Role of hearing aid bandwidth on perception of speech and music in individuals with sensorineural hearing loss

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May, 2016

CERTIFICATE

This is to certify that the dissertation entitled '**Role of hearing aid bandwidth on perception of speech and music in individuals with sensorineural hearing loss**' is the bonafide work submitted in part fulfilment for the degree of Master of Science (Audiology) of the student **Registration No. 14AUD001**. 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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DECLARATION

This masters dissertation entitled '**Role of hearing aid bandwidth on perception of speech and music in individuals with sensorineural hearing loss'** is the result of my own study under the guidance of Dr. P. Manjula, Prof. in Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysuru, and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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May 2016

Dedicated to

APPA, AMMA

and MY GUIDE

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Chapter 1

Introduction

For majority of the hearing aid users, the primary driving factor for using hearing aids is to achieve improvement in speech perception. Frequency range in the hearing aid is an important factor that affects speech perception. It depicts the range of frequencies that a hearing aid can amplify significantly. Frequency bandwidth of the hearing aid of up to 3500 Hz was considered to be sufficient, since the early studies on telephone conversations showed that for individuals with normal hearing, an upper limit of 3000 Hz was sufficient to understand the speech (Boothroyd & Medwetsky, 1992). However, the same cannot be applied to the individuals with sensorineural hearing loss, who are highly sensitive to less than ideal listening conditions such as low signal levels, noise and reverberant surroundings in addition to the audibility and processing issues due to hearing loss. The ability of these individuals is limited by the reduced ability to take advantage of linguistic and semantic cues in running speech due to the sensorineural hearing loss.

It is highly important to for the people with the hearing loss, to perceive and discriminate all speech sounds including high frequency sounds with ease and accuracy. There are three main important aspects where high-frequency hearing is highly important.

1. Speech intelligibility: Frequency content of speech has indicated that relatively large amount of important speech cues are located after 3000 Hz. For the majority of English fricatives, the voiced and voiceless cognates of‘s’, ‘f’, ‘th’, and ‘sh’ (/s, z, f, v, θ, ð, ʃ, ʒ/), the most important cues are located

above 3000 Hz. The most commonly occurring consonants in the English language, /s/ phoneme and its voiced cognate /z/ are used in a number of grammatical purposes such as for marking plurals, possessives, third person singular, tense and contractions (Yavas, 2016)

2. In a study by Jongman, Wayland, and Wong (2000), it was found that the mean spectral peak location for /s/ and /z/ were located around 7500 Hz when female speakers produced it, and was around 6200 Hz when male speakers produced it. Todd, Edwards, and Litovsky, 2011 reported an average spectral mean of approximately 7700 Hz for children aged 2 to 9 years, and in some cases spectral peaks reaching up to 10,000 Hz. In every language there are such speech sounds which can be distinguished only if the high frequency components of the signals are audible (Simpson, McDermott, & Dowell, 2005). The high frequency information is also very important in the language acquisition in children, which will help in the understanding language and reproducing it correctly.
3. Speech understanding in noise: Speech perception is affected when there is a noisy environment. Unlike low frequency components of speech which easily get masked by common types of noise (which consist of relatively of intense low frequency components), the high-frequency components are less susceptible to noise, therefore it is important for a listener to hear high frequency phonemes in order to perceive the speech in such noisy environments (Cooke, 2006).
4. Localization: The perception of high frequency characteristics gives important information about the identification and localization of sound sources (Bohnert, Nyffeler, & Keilmann, 2010). It is also very important that the high

frequency information is available for both the ears (Dubno, Ahlstrom, & Horwitz, 2002).

It is therefore very important that high frequency information must be made audible for individuals with hearing impairment especially for those with the high frequency hearing loss by providing adequate amplification.

Currently, there two methods that are used for the purpose of providing high frequencies. They are extending the conventional bandwidth and frequency lowering. Extending the bandwidth will apply amplification at high frequencies which are necessary for the perception and discrimination of high frequency phonemes. However, extending bandwidth might not help all the users because of the presence of cochlear dead regions.

The type of hearing loss has different perceptual consequences (Zeng, 2006). A conductive hearing loss which is thought to attenuate the acoustic signal reaching to the cochlea is likely to have less impact on speech perception, whereas cochlear hearing loss or sensorineural hearing loss (SNHL) would show greater deterioration in speech perception with the increase in severity of hearing loss. Individuals with cochlear or SNHL often complain of speech recognition difficulties, especially in noisy background. People with SNHL usually have auditory filters that are broader than normal (Glasberg & Moore, 1986; Tyler & Moore, 1986). This means that their ability to determine the spectral shape of speech sounds and to separate components of speech from background noise is reduced.

People with certain types of hearing impairment frequently report obtaining little or no benefit from the amplification provided by conventional hearing aids. One type of impairment in which it is difficult to fit an aid satisfactorily is characterized by a steeply sloping audiogram. Examining the works of Moore, Füllgrabe, and Stone (2011), Moore (2012) as well as Ricketts, Dittberner, and Johnson (2008), several general recommendations can be made. If the hearing loss is mild to moderate level, then a broader bandwidth is better for music. However, if the hearing loss is greater than a moderate level, then a narrower bandwidth (to avoid dead regions in the cochlea) may provide a more pleasant sound than a wider bandwidth that extends into the high frequency dead regions of the cochlea. The same can be said about the configuration of the audiogram, a person with a relatively flat audiometric configuration prefers the wider bandwidths. In contrast, if there is a sloping high frequency loss configuration then, a narrower frequency response would be ideal (Hogan & Turner, 1998).

Studies have shown that the frequency bandwidth of the hearing aid is not only important for speech understanding but also for subjectively perceived sound quality. Most individuals with hearing impairment preferred wider frequency bandwidths compared to the regular bandwidths that come in most of the hearing aids when it came to music and speech perception (Moore, 2012).

Wider bandwidths are also associated with the improved phonological development in children because of their ability to give access to the high frequency information which will help in learning language and production of speech in a child. It has been reported that reduced audibility of high frequency speech sounds due to restricted hearing aid bandwidth, as well as the common occurrence of reverberation and noise, may be contributing factors in the phonological development of the child (Moeller et al., 2007).

1.1 Need for the study

Although individuals with normal hearing can detect approximately 10 octaves, from about 20 Hz to about 20,000 Hz, the typical comprehensive audiometric evaluation rarely tests frequencies above 8,000 Hz. Until recently, hearing aids have been limited to a spectral response of up to 5,000 Hz (Pittman, 2008). Recent technological advances have allowed advanced digital hearing aids to provide extended bandwidth. Over time, there has been a speculation about the ideal bandwidth/s for hearing aid, which will take care of all kinds of hearing loss patterns and the sounds in the environment. But it is not feasible to have a single bandwidth that will serve all the listening purposes.

Grant, Tufts, and Greenberg (2007) examined the intelligibility of speech filtered into relatively narrow spectral bands for both listeners with normal hearing and those with SNHL. Hogan and Turner (1998) investigated the effects of stimulus bandwidth on phoneme recognition in listeners with steeply sloping hearing losses. Nonsense syllables were frequency shaped and low-pass filtered at 12 cut-off frequencies from 560 to 9000 Hz. The benefit of providing additional high frequency audibility was negligible or negative when the degree of loss exceeded 55 dB HL at and above 4000 Hz. In some cases, performance decreased with increases in high frequency audibility. Thus, the findings are equivocal.

Ricketts, Dittberner, and Johnson (2008) explored the sound quality as it relates to degree and slope of hearing loss and hearing aid bandwidth. They reported that there was a significant preference for the wider bandwidth among individuals with normal hearing. Subjects with slopes of less than 8 dB/octave were likely to prefer the wider bandwidth (or have no preference) and those with greater slopes (more significant high-frequency hearing loss) preferred a narrower bandwidth.

Moore and Tan (2003) evaluated perceived 'naturalness' of speech and music across a multitude of filter settings, to approximate distortions introduced via microphones, speakers, and earphones. The researchers found when approximating the bandwidth of the telephone (313 to 3,547 Hz), a very poor quality of sound was noted. The highest ratings were obtained for speech and music when the bandwidth was wide, from 123 to 10,869 Hz for speech and 55 to 16,854 Hz for music.

Studies over years on expanded bandwidth have led into mixed conclusions. Not all the individuals with sensorineural hearing impairment will benefit from the high frequency amplification. This is attributed to cochlear dead regions. Amplification in the areas of cochlear dead regions has demonstrated no change in the performances or in some cases has led into poor performance. The high frequency amplification will benefit individuals who do not have cochlear dead regions in the high frequencies and might not help the persons who have dead regions in the high frequencies (Hogan & Turner, 1998; Vickers, Moore, & Baer, 2001). Studies also have shown that listeners with steeply sloping hearing loss may not judge sound quality to be better when high frequency amplification is provided (Ricketts et al., 2008; Moore et al., 2011).

However, very few studies have been done which assess the effect of extended frequency bandwidth with respect to different pattern and type of hearing loss. There us even lesser number of studies which compared extended bandwidth effects with narrow bandwidth settings over sloping hearing impairment. The present study investigates the effect of manipulating of bandwidth of hearing aids on speech and music perception in individuals with sensorineural hearing loss. It also compares the efficacy of music program for speech and music perception.

1.2. Aim of the study

To investigate the effect of hearing aid bandwidth on speech perception and music perception, in individuals with flat and sloping SN hearing loss.

1.3. Objectives of the study

The following objectives were formulated.

1. To investigate the effect of regular and extended bandwidth settings in the hearing aid on speech and music perception, in individuals with moderate and moderately-severe SNHL.
2. To investigate the effect of regular, narrow, and extended bandwidth settings in the hearing aid on speech and music perception, in individuals with sloping SNHL.
3. To compare the quality of speech and music with the default music program, regular bandwidth program for speech in quiet and the extended bandwidth program in hearing aid.

Chapter 2

Review of literature

The sensorineural hearing loss will result in reduction in auditory perception, due to numerous challenges which will include decreased audibility, decreased dynamic range, decreased frequency resolution and decreased temporal resolution (Moore, 1996). Further, it also results in many negative social effects such as increased isolation and withdrawal from social situations (Dalton et al., 2003). Amplification from hearing aids results in addressing many of these concerns and has been a lot of help in reducing the negative effects of hearing loss (Group, 1999).

Even though, the highest frequency that can be heard by a normal hearing individual is up to 20,000 Hz, the upper frequency limit remains 4000 to 6000 Hz in hearing aids (Moore & Sek, 2013). There are a few fitting formulae, such as CAMEQ2-HF (CAM2) (Moore, Glasberg, & Stone, 2010), National Acoustic Laboratory-Non Linear 2 (NAL-NL2) (Keidser, Dillon, Carter, & O’Brien, 2012), and Desired Sensation Level method [DSLm(i/o)] (Scollie et al., 2005), require output and they prescribe high gain settings above 5,000 Hz at least to restore partial audibility. The need for high gain is because, the spectral energy of speech is lower for high frequency than for low- or mid- frequency bands (Moore, Stone, Fullgrabe, Glasberg, & Puria, 2008) and also because hearing loss tends to increase with increasing frequency. It is difficult to achieve the prescribed gain at high frequencies due to acoustic feedback problem and the problem is even more when an open-canal fitting is used.

Speech and music are complex signals. The components of speech and music vary in terms of parameters such as frequency and intensity over time. The amplification needs for both of them vary in terms of parameters in the hearing aid such as, frequency bandwidth, peak input limiting level, and threshold knee-point (Chadwick, 1973).

The following section provides a brief review of literature regarding the role of hearing aid bandwidth on perception of speech and music in individuals with SNHL. For easier conceptualization, the review has been divided perception of speech and music through extended bandwidth and narrow bandwidth.

1. Perception of speech and music through extended bandwidth

The conventional hearing aids which will have bandwidth up to 4000 to 5000 Hz Thus, it might not able to present high frequency information to the hearing aid user. Hence, the extended bandwidth came in to picture. Over the years, studies on extended bandwidth have revealed that every person with SNHL might not be benefitted from it. Thus, there is a lot of individual variability in performance as preferences for high frequency cut-off vary across users.

Good hearing in high frequency is very important for understanding speech (Amos & Humes, 2007; Carlile & Schonstein, 2006), sound quality (Moore & Tan, 2003), and sound localization (Best, Carlile, Jin, & van Schaik, 2005). However, the findings of the studies on the ability to make use of high frequency information , with the help of amplification for the restoration of audibility among listeners with hearing impairment are equivocal (Horwitz, Ahlstrom, & Dubno, 2007; Brian C J Moore, Füllgrabe, & Stone, 2010; Plyler & Fleck, 2006).

In a study by Turner and Henry (2002), speech recognition scores for different high frequency cut-offs across various severities of hearing loss were compared. The speech was presented to the listeners, in the background of multi-talker babble. The results showed that in all cases, regardless of hearing loss or frequency range, increasing the cut-offs resulted in better scores. Findings reported by Moore (2012) also support this contention. He investigated the effect of hearing aid bandwidth on sound quality preferences mostly for jazz and classical music stimuli. The data were obtained using method of paired comparisons and ratings of individual stimuli. In the study for individuals with normal hearing, the highest ratings were obtained for wider bandwidth, 55 to 16,000 Hz. For individuals with hearing impairment, the preferences varied across participants with respect to high frequency cut-offs. Some preferred 7500 or 10,000 Hz as the upper cut-off frequency compared to 5000 Hz; where as some subjects showed the opposite preference. Levy, Freed, Nilsson, Moore, and Puria (2015) used sentences and spatially separated masking speech in order to assess the importance of extending the audible frequency band beyond the range currently implemented in most of the hearing aids. The testing was done on subjects with normal hearing and those with hearing impairment using low filter cut-off frequencies of 4000, 6000, 8000 and 10000 Hz. He reported improvement in both normal hearing and persons with hearing impairment in the recognition of speech in the presence of spatially separated masking speech by extending bandwidth from 4000 to 10,000 Hz additionally he also reported that for persons with hearing impairment , the improvement was smaller compared to normal group. Ricketts et al. (2008) investigated the preference for bandwidth extension in hearing aid processed sounds and related it to hearing loss in individual listeners. Ten individuals with normal hearing and twenty with mild to moderate hearing loss were included in the study. Two different bandwidths with cut-off frequencies, 5500 and 9000 Hz were used. The results revealed a correlation between the preferences for either the wide or narrower bandwidth. The slope of hearing loss from 4000 to 12,000 Hz and also steep slope thresholds were associated with preferences for narrower bandwidth. He reported consistent preference for wider bandwidth in some listeners with mild to moderate hearing loss. He also reported that preference for high frequency information above 5500 Hz is related to high frequency threshold slope.

The listener will be most benefitted with high frequency amplification when he/she is bilaterally aided and under the situations with spatial separation between the target and the masking sounds, which is common in real world conditions (Carlile & Schonstein, 2006; Keidser et al., 2006). Alkaf and Firszt (2007) studied effects of hearing aid bandwidth settings on bimodal speech recognition of listeners with cochlear implant (CI) in one ear and severe to profound hearing loss in the unimplanted ear. It was made sure that the residual hearing was sufficient for wideband amplification using NAL-RP prescriptive guidelines. The subjects were given recognition of sentence material in quiet and in noise tasks. The tasks were carried in two conditions, cochlear implant alone and cochlear implant plus hearing aid. The testing were carried in different bandwidth which included upper frequency cut offs of 2000, 1000, and 500 Hz. They reported significant bimodal benefit when the amplification was given at all frequencies with aidable residual hearing. There were also no significant improvements in performance when the hearing aid bandwidth was limited to low frequency amplification, i.e., below 1000Hz.

Research also shows that children with hearing impairment are able to make use of high frequencies to improve learning of words in quiet and in noise (Pittman, 2008). Restricted stimulus bandwidth of hearing aid will have negative effect on the perception of certain phonemes such as /s/ and /z/ which serve multiple linguistic functions in the English language. This will affect the normal development of speech and language in young children with hearing loss, who miss out due to the limitations of the most of the current hearing aid due to their frequency bandwidths up to 6000-7000 Hz.

Stelmachowicz, Pittman, Hoover, and Lewis (2001) investigated effects of stimulus bandwidth on a wide range of speech material, to include a variety of auditory related tasks and also to include the effect of background noise. The assessment of effects of bandwidth as carried out with four different auditory tasks 1) nonsense syllable perception 2) word recognition 3) novel word learning, and 4) listening effort with two bandwidth settings, i.e., 5000 Hz and 10,000 Hz and were presented in noise. Children with normal hearing and hearing impairment were recruited for the study. They reported that there was a significant improvement for the perception of /s/ and /z/ spoken by female speakers. They also noted that bandwidth effects for the perception of /s/ and /z/ were very significant, and it was much greater than that seen for the group with normal hearing.

Another similar study by Stelmachowicz, Pittman, Hoover, Lewis, and Moeller, 2016 compared phonological development in the first four years of life in the three different groups of children, i.e., children with normal hearing , hearing-impairment identified and aided up to 12 months of age (early-ID group), and hearing impairment identified after 12 months of age (late-ID group). The results revealed that the acquisition of all phonemes was delayed in early-ID group compared to normal group and the delay was shortest for vowels and was longest for fricatives. The delay for late-ID group was substantially longer than the early-ID group.

2. Perception of speech and music through narrow bandwidth

Cochlear loss is generally associated with damage of hair cells in the cochlea. This can result in elevation of thresholds in two main ways. First, damage of outer hair cells (OHCs) impairs the active mechanism in the cochlea, resulting in reduced basilar membrane vibration for a given low sound level (Ruggero, 1992; Yates, 1995). Hence, the sound level must be higher than normal to give a detectable amount of vibration. Second, damage to inner hair cells (IHCs) can result in reduced efficiency of transduction. So the amount of basilar membrane vibration needed to reach threshold is larger than normal. It is possible to attribute overall hearing loss at a given frequency to damage of OHCs and damage of IHCs (and neural) (Moore & Glasberg, 1997). It is not possible to say the extent of hearing loss caused by each of these components just by measurement of absolute threshold at a given frequency.

In individuals with greater degrees of hearing loss, there is a cochlear dead region. According to Moore (2004), "a dead region is a region in the cochlea where IHCs and/or neurons are functioning so poorly that a tone producing peak vibration in that region is detected by off-place listening". Some studies have shown that hearing loss greater than 55 to 60 dB HL can be associated with cochlear dead regions. When there is a "dead region", the measured true thresholds will exceed the audiometer intensity limits (Moore, 2000). But due to the vibration pattern at the level of basilar membrane, the functioning IHCs of different frequency and of different place will respond and the audiometer tone can be detected. Due to this "off-frequency" listening, the thresholds in the audiogram can go down to as low as 40 dB HL in frequencies where cochlear dead region is present Moore, 2004.

Studies have also revealed that the presence of dead regions may limit the ability of an individual to use high frequency amplification, negating its possible effectiveness and even leading to worse performance with the amplification. Hogan and Turner (1998) investigated the benefit of providing audible high frequency speech information to listeners with hearing impairment. Nonsense syllables were low-pass filtered at different cut-off frequencies and was given for auditory identification task. Articulation index (AI) was calculated for each condition and for each listener in order to quantify the audibility for each condition. In most of the subjects with hearing impairment, providing additional high frequency information resulted in improved speech recognition. But, in some subjects with severe impairment, providing audible high frequency information resulted in no further improvement in speech recognition and in some, it resulted in decreased speech recognition. they also reported a clear pattern in results indicating that as the hearing loss increased beyond 55 dB HL at a given frequency, the efficacy of providing high audibility to that given frequency region was diminished. Further, this pattern was often seen when the hearing loss was present at frequencies 4000 Hz and above.

Vickers et al. (2001) investigated the effect of high frequency amplification on speech perception in subjects with high frequency hearing loss with and without cochlear dead regions. The dead regions were measured by psychophysical tuning curves and were confirmed using the TEN test. Nonsense syllables were used for speech recognition and the stimuli were low-pass filtered at various cut-off frequencies. For subjects without the dead regions, performances improved as the cut-off frequency increased which indicated that they got benefit from high frequency information. Whereas, two patterns were observed for subjects with dead regions. For most of the subjects, performance improved as the cut-off frequency increased till a point which was estimated to be edge frequency of dead region and hardly changed as the cut-off frequency increased further. Whereas, for the other few, the performance improved as the cut-off frequency increased and worsened with the further increase. Studies have shown that listeners with steeply sloping high frequency hearing loss might not judge the sound quality to be better when they were provided with high frequency amplification (Moore et al., 2011).

Optimization for speech inputs have remained primary concerns for hearing aid design and fitting. But there can be other kinds of inputs such as music, which is completely neglected in any kind of basic versions of a hearing aid. Music and speech are acoustically very different and the processing in the hearing aid will have different effects on music and speech. If the hearing aid user is a musician and one who professionally or for pleasure used to hear music, will have serious problems in music perception even after fitting with these kinds of hearing aids that are optimized for speech perception. However, by altering certain parameters in the hearing aid such as, frequency bandwidth, peak input-limiting level, compression characteristics - compression ratio and knee points and number of channels, can alter the way the music is perceived for better (Chasin & Russo, 2004).

Rudmin (1982) examined the effect of extended and reduced high and low frequency ranges using paired comparison and preference judgments of hearing aid processed music. The performance of subjects with mild to moderate hearing impairment was compared with those with normal hearing controls. Extended ranges for both high- and low- frequencies were perceived and preferred by subjects with normal hearing controls. However, perception and preference for high frequency ranges among subjects with hearing impairment were random. But, accurate perception and preference were noted for low frequency adjustments.

Chapter 3

Method

The main aim of the study is to investigate the role of hearing aid bandwidth on speech and music perception in individuals with flat and sloping sensorineural hearing loss. The specific objectives were to investigate the effect of conventional, narrow and extended bandwidth settings in hearing aid on perception of speech and music. In addition, the objective was also to compare the perception of quality through hearing aid programmed for speech in quiet, music and extended bandwidth.

Participants

A total number of 30 participants who were native speakers of Kannada were included in the study. Kannada is an official language spoken in the southern state of India. The mean age of the participants was 43.17 years and their age ranged from 17 to 50 years. All the participants had post-lingually acquired hearing loss. All the participants had speech identification scores (SIS) of not less than 60% on phonemically balanced bi-syllabic word list for adults, in Kannada. The test ears had ‘A’ type tympanogram and presence of reflexes, depending upon the severity of hearing loss. They did not have any significant complaint of any other neurological, otological, speech and language problems or any other associated problems.

The participants were categorized into three groups. Group I consisted of ten ears of participants having moderate flat SN hearing loss, Group II consisted of or moderately severe flat sensorineural hearing loss (SNHL). Group III consisted of 10 participants having sloping sensorineural hearing loss. The sloping hearing loss pattern was operationally defined as the air-conduction thresholds occurring at successively higher levels from 250 to 8000 Hz, and the difference between air-conduction thresholds at 250 and 8000 Hz was always >20 dB (Pittman & Stelmachowicz, 2003).

Instrumentation

The following instruments were used for collection of data:

1. A calibrated two-channel diagnostic audiometer was used for obtaining behavioural air- and bone- conduction thresholds, speech audiometry and for delivering the test stimulus during unaided and aided testing. The audiometer was connected to TDH 39 supra aural headphones housed in MX-41/AR ear cushions, Radio Ear B-71 bone vibrator, and SP90 loud speakers located at ±45^{o} Azimuth and one meter distance from the participant. An audiometric loud speaker was used to deliver speech and music stimuli during testing.
2. A calibrated clinical immittance meter was used for tympanometry and reflexometry, in order to assess the middle ear functioning of the test ears.
3. A digital behind the ear (BTE) hearing aid, which had 12 channels and sound recover feature, was used along with the stock ear tip. The other features included bass boost, whistle block technology, noise block processing, omni directional microphone, volume control switch, four programs which will also included a music program.

   In the present study, Sound Recover, Bass Boost, Whistle Block and Noise Block were switched off before starting with the aided evaluations. NAL-NL2 prescriptive formula, at acclimatization level of 2, was used for target gain match.
4. Appropriate sized ear tips were used to couple the test hearing aid to the test ear of the participant.

5. A personal computer installed with NOAH (4.0 version) software, connected to HiPro, was used. The hearing aid programming software was also installed into this computer for programming the hearing aid for each test ear. The same computer was used to present the recorded speech and music stimuli that was routed through the sound field audiometer.

Test environment:

All audiological evaluations were carried out in air-conditioned, sound treated single/double room suite. The ambient noise levels were within permissible limits.

Test material:

The following test material were used for the evaluations in the unaided and aided conditions

1. Paired word lists, developed at the Department of Audiology, All India Institute of Speech and Hearing were used for establishing speech reception threshold (SRT). The PB word lists in Kannada (Yathiraj & Vijayalakshmi, 2005) were used for obtaining speech recognition score (SRS) for selection of participants, in Phase I. The recorded PB word lists for adults in Kannada developed by Manjula, Kumar, Geetha, and Antony (2013) were used for SRS and SNR-50 in aided conditions of Phase II.
2. A Kannada passage (Sairam, 2002) was used for assessment of quality of speech.
3. Stimuli from the music perception test battery (MPTB) (Das, 2010) were used to check the quality of music processed through the hearing aid.

Procedure:

Testing involved two phases. In Phase I, evaluations were done in order to select the participants for the study. Phase II involved data collection for the purpose of verifying the objectives of the study.

Phase I: The following audiological evaluations were carried out for selection of participants.

1. Case history: A detailed case history was taken for all the participants before the routine audiological assessment to confirm the inclusion criteria.
2. Pure tone audiometry: The testing was done using a calibrated dual channel audiometer. Calibrated headphones were used to deliver air-conduction stimuli and calibrated bone vibrator was used to deliver bone-conduction stimuli. Pure tone thresholds were obtained for each test ear using modified version of Hughson-Westlake procedure (Carhart & Jerger, 1959) at octave frequencies between 250 Hz to 8000 Hz for air-conduction stimuli and between 250 Hz to 4000 Hz for bone-conduction stimuli.
3. Speech audiometry: The speech identification score (SIS) were obtained for each of the test ears. This was done at 40 dB SL (re: SRT). Phonemically balanced word lists in Kannada developed by Yathiraj and Vijayalakshmi (2005) were used to obtain the SIS. The total number of correctly identified words, out of the total 25 words present in the list, was noted down to represent the SIS.
4. Uncomfortable loudness level: The speech stimulus was presented through head phones to the participant at a comfortable loudness level. The intensity of the stimulus was gradually increased in 5 dB steps. The participant was

instructed to indicate when the experience of loudness became uncomfortable. The test was repeated once to check reliability. The level at which the participant indicated that the loudness of speech stimuli became uncomfortably loud was taken as the uncomfortable loudness level (UCL) for the test ear of that participant. All of them had an UCL of greater than 100 dBHL.

5. Immittance evaluation: This was done with a probe tone frequency of 226 Hz (Brooks, 1968; Holte, Margolis, & Cavanaugh, 1991) at 85 dB SPL. Tympanogram and acoustic reflex thresholds (ipsilateral and contralateral) for 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz were measured. Using this, the middle ear pathology in the test ears was ruled out.

Phase II: In this phase, the test hearing aid was programmed for three (for Groups I and II) or four (for Group III) different programs. This phase involved administration of TEN test for test ears (of Group III only), programming of hearing aid, and aided testing for evaluation of perception of speech and music.

Administrating TEN test:

Audiometric TEN HL (threshold equalizing noise) test (Moore, 2004; Moore, 2000) was used to find out cochlear dead regions in participants with sloping hearing loss (Group III). The Threshold Equalizing Noise (Hearing Level) CD was played using a computer and stimuli were presented via the AudioStar Pro through TDH-39 ear phones. The stimuli for TEN test consists of pure tones at 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz frequencies and TEN noise. The TEN (HL) level is specified as the level of a one-ERBn wide centered at 1 kHz. ERBn stands for Equivalent Rectangular Bandwidth noise of the auditory filter determined by using young individuals with normal hearing at moderate sound levels (Glasberg & Moore, 1990; Moore, 1997).

To perform a TEN test, first pure-tone thresholds between 500 and 4000 Hz were obtained using the tones on the TEN HL CD as described by (Moore, Glasberg, & Stone, 2004), using a procedure similar to manual audiometry, that is modified Hughson-Westlake procedure (Carhart & Jerger, 1959), except that masked thresholds were obtained using a 2-dB final step-size as recommended by Moore, Glasberg, and Stone, 2004. The levels of the signal and the TEN were controlled using the attenuators in the audiometer.

The TEN noise and pure tones were played in the same channel of the audiometer. Calibration was done prior to the testing, in which the individual with normal hearing was supposed to detect the tone in noise presented at 50 dB HL. The noise level was kept constant at 50 dB HL. The level of tone was adjusted using the level adjustment knob of the audiometer. The individual with normal hearing was asked to indicate whether he/she heard the tone in the presence of TEN which was presented continuously at a fixed level of 50 dB HL and the intensity of the tone was varied, for equal loudness. The level adjustment knob for the tone was decreased if the participant was able to hear the tone and the level adjustment knob was increased if the participant was not able to hear the tone. An up and down procedure for changing the level adjustment knob of the audiometer was done until the participant was able to detect the tone in the presence of TEN when both the tone and Ten were presented at 50 dB HL. The TEN noise was presented ipsilaterally, and masked thresholds were obtained for each test frequency.

Once the calibration was performed, the masked thresholds were compared to ascertain the presence of cochlear dead regions. The presence or absence of a cochlear dead region was based on the criteria suggested by Moore, Glasberg, and Stone, 2004. For frequencies where hearing loss was less than or equal to 60 dB HL, the TEN level was presented at 70 dB HL initially. When hearing loss at frequency was 70dB HL or more, the TEN level was set 10 dB HL above audiometric threshold at that frequency. If the TEN was unpleasantly loud, or if the maximum level of 90 dB HL was reached, then the TEN level was set to audiometric threshold. Initially, the TEN level was varied in 5 dB steps, later was varied in 2 dB steps to get precise thresholds. The criteria to signify a dead cochlear region were:

1. If the masked threshold in the TEN was 10 dB HL or more than the TEN level/ERBn and the TEN elevated the absolute threshold by 10 dB or more, then a dead region was assumed to be present at that frequency.
2. If the masked threshold in the TEN was less than 10 dB above the TENlevel/ERBn, and the TEN elevated the absolute threshold by 10 dB or more, then a dead region was assumed to be present.
3. In case the TEN (HL) level could not be made high enough to elevate the absolute threshold by 10 dB or more, then the results were considered inconclusive. This would happen because the noise that would have been required was judged as too loud or because the maximum output of the audiometer was reached. A "no response (NR)"was recorded when the participant did not indicate hearing at the maximum output level of the audiometer.

The TEN (HL) test was administered for all the participants having sloping hearing loss. Edge frequency (fe), that is, the frequency from which the cochlear dead region starts, was noted down for all the participants.

Programming of the hearing aid:

The participants were fitted with test hearing aid using appropriate programming cables. The hearing aid was connected to HiPro which in turn was connected to the personal computer having the programming software (NOAH 4.0 and Hearing aid software). The details of participant, including the results of hearing evaluation such as pure tone thresholds of each participant from 250 Hz to 8000 Hz for air-conduction and from 250 Hz to 4000 Hz for bone-conduction of the test ear, were entered into the software. From the home page hearing aid detection was accessed. Special features like Sound Recover, Bass Boost, Whistle Block and Noise Block were disabled. The hearing aid was programmed using NAL-NL2 prescriptive formula with acclimatization level 2. The aided testing was carried out in the following 3 (for Groups I and II) or 4 (for Group III) hearing aid programs, depending upon the configuration of hearing loss.

1. Regular bandwidth program (Program 1): The hearing aid in set ‘speech in quiet’ program with frequency-gain characteristics as prescribed by NAL-NL2 (acclimatization level 2). The gain setting in the regular bandwidth program setting (Program 1) was present only till 5000 Hz, which is the upper frequency cut-off of most hearing aids. Optimization for frequency gain was done for audibility of Ling’s six sounds.
2. Extended Program (Program 2): In this program, the hearing aid was set to similar setting as in Program 1, except for the extended frequency bandwidth setting of the hearing aid. The upper cut-off frequency of the hearing aid was

extended up to 8000 Hz. Optimization for frequency gain was done for audibility of Ling's six sounds.

3. Program 3: In this program, the hearing aid was set to similar setting as in Program 1 except for the narrow bandwidth. That is, the setting of the upper cut-off was based on the edge frequency (F_e). The cut-off was derived from 1.7×F_e, where 'F_e' is the lower edge frequency of cochlear dead region in the high frequency region. The F_e was found out using TEN (threshold equalizing noise) HL as described earlier (Baer, Moore, & Kluk, 2002). This program was used during aided testing only for participants having sloping configuration of hearing loss.
4. Program 4: In this program, the hearing aid was set to similar setting as in Program 1, except that the hearing aid was set to default music program.

The aided testing was carried out to obtain the following measures in each of the three (Groups I1 and II) or four (Group III) programs:

1. Speech identification scores (SIS) in noise for recorded phonemically balanced word list (Manjula, Kumar, Geetha, & Antony, 2013) was obtained in two-room air-conditioned sound treated room. The list consisted of 25 words. The participant was made to sit comfortably on a chair in the test room at a distance of one meter from the loud speaker of the audiometer at 45˚A on the aided ear side. The recorded word list was presented in quiet through the computer routed through the auxiliary input of the calibrated two-channel audiometer in the control room. The presentation level was set at 40 dB HL. Level adjustment was done for the calibration tone so that the VU-Meter deflections averaged zero.

   The participant was instructed to repeat the words that he/she heard. The response considered incorrect if he/she failed to repeat or if it was repeated incorrectly. Each correct response was given a score of ‘one’. The total number of correct responses was calculated for each aided condition for each test ear of the participant. The maximum score was 25 as the list consisted of 25 words.

2. SNR-50: The signal to noise ratio (SNR) required for 50% performance is termed as SNR-50 (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004). Each participant was made to sit comfortably in the test room. A computer containing recorded speech material (phonemically balanced word list by Manjula, Kumar, Geetha, & Antony, 2013) was connected to auxiliary input of audiometer. The PB word list was presented at a constant level of 40 dB HL, in the presence of speech noise, through the audiometric loud speaker kept in front of the participant at a 0˚ Azimuth and one meter distance. The initial level of speech noise through the same loud speaker was kept at 10 dB HL below that of the speech (i.e., 30 dB HL). An adaptive method was utilized in which the level of speech noise was varied systematically in order to establish the SNR-50.

   The participant was instructed that he/she will be hearing words in Kannada in the presence of noise. The participant was informed to listen to the words and repeat them while ignoring the noise. Gradually, level of speech noise was increased and they were instructed to try and repeat back the words. The level of the noise was increased in 5 dB steps, till the participants repeated two out of four words (i.e., 50%) being presented. At this point, the noise was varied in 2 dB steps in order to obtain a more precise level of speech noise level at which 50% of the words were correctly repeated. At this instance, the difference in level of the speech and noise was noted as the SNR-50 measure. This procedure of obtaining SNR-50 was repeated for all the participants.

3. Perceptual quality measurement

Quality of speech and music was evaluated separately. Separate quality perception scales were used for the purpose.

3. a. Perception of quality of speech:

The parameters for evaluating quality were adapted from the quality rating scale for speech developed by Eisenberg and Dirks (1995) for this study. For this, the recorded story in Kannada language developed by Sairam (2003) was routed through the audiometer at 45 dB HL through the loudspeaker of the audiometer placed at a distance of one meter at 45˚ Azimuth. The participant was asked to rate the recorded speech stimulus on the six parameters of quality of speech, using a five-point rating scale, while listening to different hearing aid program conditions. The six parameters included loudness, clearness, sharpness, fullness, naturalness and overall impression. The five-point rating scale for each of these six parameters was 1 for 'Very Poor', 2 for 'Poor', 3 for 'Fair', 4 for 'Good', and 5 for 'Excellent'. The participant was explained about the six parameters of quality in simple Kannada and practice trials were given before the actual testing. The instructions were made simple in Kannada. The parameters included,

1. Loudness: The story given was sufficiently loud, in contrast to soft or faint.
2. Clearness: How clear the story sounded in contrast to blurred or distorted speech.
3. Sharpness: The story was audible with respect to its unevenness.
4. Fullness: The story is full in contrast to thin.

5. Naturalness: The story seems to be as if there is no hearing aid, and the story sounds just like original.
6. Overall impression: The reproduction of sound was with little distortion, giving results very similar to original sounds.

3.b. Perception of quality of music:

For assessing of perception of quality of music while listening through the different hearing aid programs, a five-point perceptual rating scale was used which is the modification of the work of Gabrielsson, Rosenberg, and Sjögren (1974). For this, music sample from the Music Perception Test Battery (MPTB) was routed through the audiometer at 40 dB HL through the loudspeaker of the audiometer placed at a distance of one meter at 45° Azimuth. The participants were asked to rate the sound quality, on five parameters, while listening to different hearing aid program conditions using a five-point rating scale. The five parameters included:

1. Loudness: The music is sufficiently loud, in contrast to soft or faint
2. Fullness: The music is full, in contrast to thin
3. Crispness: The music is clear and distinct, in contrast to blurred, and diffuse
4. Naturalness: The music seems to be as if there is no hearing aid, and the music sounds as "I remember it" and
5. Overall Fidelity: The dynamics and range of the music is not constrained or narrow.

The five-point rating scale for each of the five parameters included 1 for 'Very Poor', 2 for 'Poor', 3 for 'Fair', 4 for 'Good', and 5 for 'Excellent'. Each of the participants were asked to rate the five parameters of quality on a five-point rating scale for the music stimulus. The participants were given explanation about the five parameters of quality and instructed. The practice trials were given before the actual testing. It was ensured that all the participants had no tolerance problem with the hearing aid in any of the programs.

For Group I, the data on SIS, SNR-50, quality perception of speech and music with hearing aid programmed to regular bandwidth (Program 1), extended bandwidth setting (Program 2), and music program (Program 4) were obtained for each participant and tabulated. For Group II, the data on SIS, SNR-50, perception of speech and music with the hearing aid in regular bandwidth (Program 1), extended bandwidth setting (Program 2), narrow bandwidth program (P3), and music program (Program 4) were obtained for each participant and tabulated.

Statistical Analysis

Data on SIS, SNR-50 and quality perception of speech and music were collected for each test ear. These data were tabulated for analysis. At the end of data collection, appropriate statistical procedures were used to obtain different statistical measures for the data from the participants. The mean, median, and standard deviation (SD) were obtained for SIS, SNR-50 and perceptual quality rating for both speech and music, in different hearing aid programs. This was carried out for all the groups in different programs. The scores obtained for different programs were also compared for significance of difference between the hearing aid programs, if any.

Chapter 4

Results

The aim of the present study was to investigate the effect of varying the frequency bandwidth of the hearing aid on the speech and music perception. The objectives were

1. To investigate the effect of regular and extended bandwidth settings in the hearing aid on speech and music perception, in individuals with moderate and moderately-severe SNHL.

a. To investigate the effect of regular, narrow, and extended bandwidth settings in the hearing aid on speech and music perception, in individuals with sloping SNHL.

b. To compare the quality of speech and music with the default music program, regular bandwidth program for speech in quiet and the extended bandwidth program in hearing aid.

Perception of speech and music through hearing aid was evaluated using Speech Identification Scores (SIS), SNR-50 and quality perception ratings. The parameters mentioned above were evaluated in three groups, Group I with moderate flat sensorineural hearing loss, Group II with moderately-severe flat sensorineural hearing loss and Group III with sloping sensorineural hearing loss.

The data for the different parameters for the three groups of participants were tabulated and statistically analyzed using the Statistical Package for Social Sciences (SPSS, version 21). The following statistical tools were used to analyze the statistical data obtained through the study.

1. Descriptive analyses: Mean, median and standard deviation for the scores on SIS, SNR-50 and quality perception ratings were obtained for each of the three groups.
2. Non-parametric analysis: Non-parametric tests were performed. Friedman's test and Wilcoxon Signed Ranks Test (when indicated) were used to compare the performance of the participants on the SIS, SNR-50 and quality ratings while listening to different hearing aid programs.

The results are being discussed under different headings based on the objectives of the study.

I. Effect of regular bandwidth, extended bandwidth and music program settings in hearing aid on speech and music perception in individuals with moderate and moderately-severe SNHL

Data were collected and tabulated on SIS, SNR-50, quality of speech, and quality of music from participants with moderate (Group I) and moderately-severe (Group II) hearing loss. This was done while the participants listened through three different hearing aid programs (i.e., regular bandwidth - P1; extended bandwidth - P2; and music program - P4). The mean, median and the standard deviation (SD) of the SIS and SNR-50 are given in the following tables for Group I and Group II respectively. Table 4.1 represents the mean, median and standard deviation of SIS scores and SNR-50 for Group I, which includes the participants with moderate flat SNHL, for regular bandwidth (P1), extended bandwidth (P2), and music program (P4).

Table 4.1 Mean, median and standard deviation (SD) of SIS and SNR-50 with hearing aid in regular (P1), extended bandwidth (P2) and music program (P4), in Group I.

Hearing aid setting	SIS*			SNR-50		
	Mean	**Median**	**SD**	**Mean**	**Median**	**SD**
Regular Bandwidth (P1)	23.10	23.50	1.10	10.20	11.0	3.12
Extended Bandwidth (P2)	24.20	24.00	0.63	8.40	10.0	2.63
Music program (P4)	22.60	23.00	1.77	9.40	10.00	2.67

Note: * = Max. score being 25.

From Table 4.1, it can be seen that the mean SIS was best with extended bandwidth program (P2) followed by regular program (P1) and music program (P4). The performance in noise was best with P2 followed by P4 and then P1. It must be noted here that, smaller the value of SNR-50, better is the performance. That is, the participants required lesser difference between the speech and noise levels for comparable performance on speech perception. Friedman's test was administered in order to check if the difference in mean SIS, while listening through different hearing aid settings, was statistically significant. The results of Friedman's test for performance in SIS across P1, P2, and P4 programs revealed a statistically significant difference [χ^2 (2) = 11.556, p = 0.003]. In order to know which of these pairs differed significantly, post-hoc analysis with Wilcoxon signed-rank test was applied. This revealed a statistically significant improvement in SIS with extended bandwidth program (P2) compared to regular program (P1) (Z = -2.428, p = 0.015) and music program (P4) (Z = -2.379, p = 0.017). However, the difference was not significant between the SIS with regular program (P1) and music program (P4) (Z = -1.518, p = 0.129).

Friedman's test was also administered in order to check if the difference in mean SNR-50, obtained while listening to different hearing aid programs, was statistically significant. The results of Friedman's test for performance in SNR-50 across P1, P2, and P4 revealed a statistically significant difference [χ^2 (2) = 8.313, p = 0.016]. In order to know which of these pairs differed significantly, post-hoc analysis with Wilcoxon signed-rank test revealed a statistically significant improvement in SNR-50 with extended bandwidth program (P2) compared to the regular program (P1) (Z = -2.460, p = 0.014). There was no significant difference between the regular program (P1) and the music program (P4) (Z = -1.414, p = 0.157); and the music program (P4) and extended bandwidth program (P2) (Z = -1.890, p = 0.059).

For Group II, mean, median and SD were obtained for SIS and SNR-50 (Table 4.2). From Table 4.2, it can be noted that the mean SIS was highest for extended bandwidth (P2) followed by regular bandwidth (P1) and music program (P4). This pattern was observed for SNR-50 also, i.e., the performance in noise was better with extended bandwidth (P2) followed by regular bandwidth (P1) and music program (P4).

Table 4.2 Mean, median and standard deviation (SD) of SIS and SNR-50 with hearing aid in regular (P1), extended bandwidth (P2) and music program (P4), in Group II.

Hearing aid setting	**SIS ***			**SNR-50**		
	Mean	**Median**	**SD**	**Mean**	**Median**	**SD**
Regular bandwidth (P1)	21.10	21.0	2.13	14.40	15.00	2.50
Extended bandwidth (P2)	22.30	22.50	1.56	12.80	13.00	2.57
Music program (P4)	20.80	21.00	2.15	14.80	15.00	2.57

Note: * = Max. score being 25

Friedman’s test was administered in order to check if the difference in mean SIS while listening through different programs in the hearing aid was statistically significant. The results of Friedman’s test on SIS across P1, P2, and P4 revealed a statistically significant difference [χ^2 (2) = 12.743, p = 0.002]. Hence, post-hoc analysis with Wilcoxon signed-rank test was applied to know the hearing aid setting that brought about significantly better performance. This test revealed a statistically significant improvement in SIS with regular program (P1) compared to extended bandwidth program (P2) (Z = -2.585, p = 0.010); extended bandwidth program (P2) when compared to music program (P4) (Z = -2.714, p = 0.007). There was no significant difference between regular program (P1) and music program (P4) (Z = -0.905, p = 0.366).

Friedman’s test was also administered in order to check if the difference in mean SNR-50 with different hearing aid settings was statistically significant. The results of Friedman’s test for performance in SNR-50 across P1, P2, and P4 revealed a statistically significant difference [χ^2 (2) = 16.800, p = 0.000]. Post-hoc analysis with Wilcoxon signed-rank test revealed a statistically significant improvement in SNR-50 with extended bandwidth program (P2) compared to regular program (P1) (Z = -2.828, p = 0.005); and in extended bandwidth program (P2) compared to music program (P4) (Z = -3.162, p = 0.002). Further, there was no significant difference between regular program (P1) and music program (P4) (Z = -1.414, p = 0.157).

The quality rating for speech and music was obtained and tabulated on different quality parameters for speech and music, on a five-point rating scale (1 to 5). Quality rating for speech was analyzed for Group I. The mean rating for different parameters of quality of speech is given in Figure 4.1.

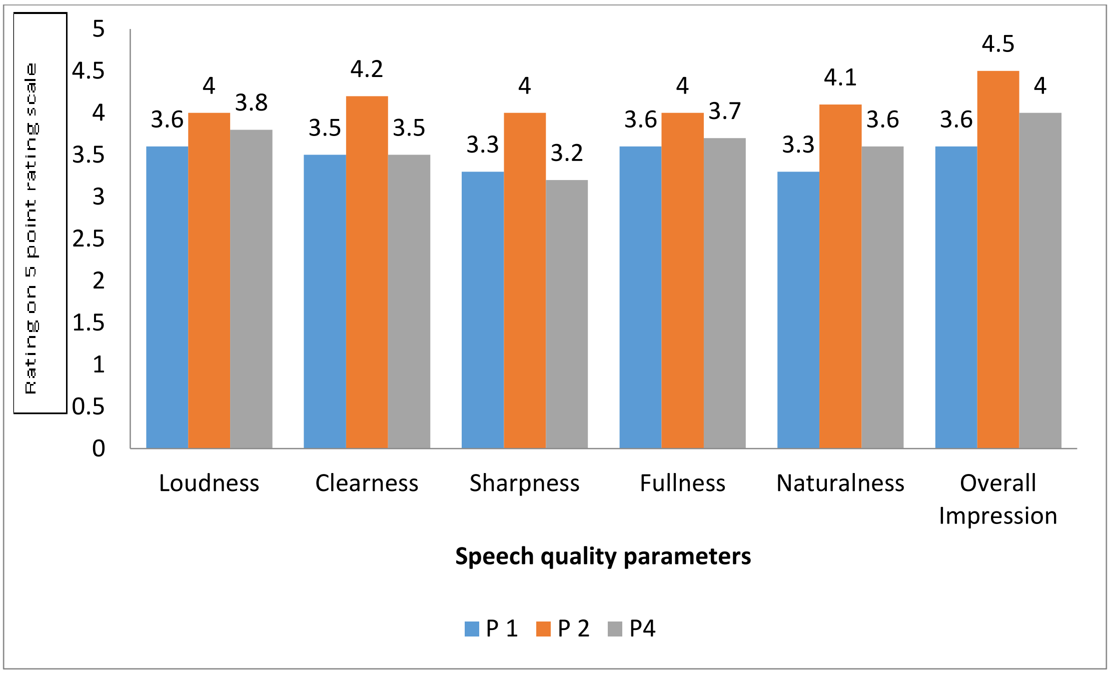

Figure 4.1: Mean rating (1 to 5) on different parameters of quality of speech with hearing aid in regular bandwidth (P1), extended bandwidth (P2) and music program (P4), in Group I.

Table 4.3: Friedman's test results for significance difference for speech quality rating between the three programs, i.e., regular bandwidth (P1), extended bandwidth setting (P2) and music program (P4), in Group I and Group II.

Speech Quality Parameters	**Group I**		**Group II**	
	χ^2	**p**	χ^2	**P**
Loudness	6.00	> 0.05	0.00	> 0.05
Clearness	14.00	0.001 *	12.28	0.002 *
Sharpness	11.84	0.003 *	10.33	0.006 *
Fullness	3.71	> 0.05	6.00	> 0.05
Naturalness	11.27	> 0.05	12.00	0.02 **
Overall Impression	13.55	0.01 *	6.00	> 0.05

Note: * = p < 0.01; ** = p <0.05

Table 4.4: Wilcoxon signed-rank test results for the significance difference between the programs, i.e., regular bandwidth (P1), extended bandwidth (P2) and music program (P4), on three parameters, in Group I and Group II speech quality rating.

Speech Quality Parameters	**Group I**			**Group II**		
	P			**P**		
	P2 vs. P1	P4 vs. P1	P4 vs. P2	P2 vs. P1	P4 vs. P1	P4 vs. P2
Loudness	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05
Clearness	0.008* (Z=-2.46)	>0.05	0.008* (Z=-2.64)	0.008* (Z=-2.64)	>0.05	0.014** (Z=-2.44)
Sharpness	0.008 * (Z=-2.64)	>0.05	0.011 ** (Z=-2.53)	0.025 ** (Z=-2.23)	>0.05	0.014 ** (Z=-2.44)
Fullness	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05
Naturalness	>0.05	>0.05	>0.05	0.014 ** (Z=-2.44)	0.014 ** (Z=-2.44)	>0.05
Overall Impression	0.003 * (Z=-3.00)	0.046 ** (Z=-2.00)	0.025 ** (Z=-2.23)	>0.05	>0.05	>0.05

Note: * = p < 0.01; ** = p <0.05

Friedman's test was carried out to know is the three programs differed significantly, i.e., regular bandwidth (P1), extended bandwidth setting (P2) and music (P4). As shown in the Table 4.3, the results revealed that, there was statistically significant among the ratings for "Clearness" (χ^2 (2) = 14.00, p= 0.001), "Sharpness" (χ^2 (2) = 11.840, p= 0.003), and "Overall Impression" (χ^2 (2) = 13.556, p= 0.001) in above mentioned programs. Thus, Wilcoxson signed-rank test was administered.

From Figure 4.1, Table 4.3 and Table 4.4, the following observations were made for Group I:

- For “Loudness”, “Fullness”, and “Naturalness”, there was no significant difference between the extended bandwidth setting (P2), regular bandwidth (P1) and music program (P4).
- For “clearness”, extended bandwidth setting (P2) yielded significantly better ratings than regular bandwidth (P1) as well as music program (P4). Regular bandwidth (P1) and music (P4) program yielded similar ratings.
- For “Sharpness”, extended bandwidth setting (P2) yielded significantly better ratings than regular bandwidth (P1) and music program (P4). The regular bandwidth (P1) yielded slightly better ratings than music program (P4). Further, there was no significant difference between the regular and music programs.
- For “Naturalness”, extended bandwidth setting (P2) yielded slightly better ratings than regular bandwidth (P1) and music program (P4). Music program (P4) yielded slightly better ratings than the regular bandwidth (P1). Further, there was no significant difference between all the three programs.
- For “Overall Impression”, extended bandwidth setting (P2) yielded significantly better ratings than regular bandwidth (P1) and music program (P4. Music program (P4) yielded significantly better ratings than the regular bandwidth (P1).

Quality rating for speech was analyzed for Group II. The mean rating for different parameters of quality of speech is given in Figure 4.2. Friedman’s test was carried out to know is the three programs differed significantly, i.e., regular bandwidth (P1), extended bandwidth setting (P2) and music (P4). As shown in the Table 4.3, the results revealed that, there was statistically significant among the ratings for “Clearness, “Sharpness”, and “Naturalness” in above mentioned programs. Thus, Wilcoxson signed-rank test was administered.

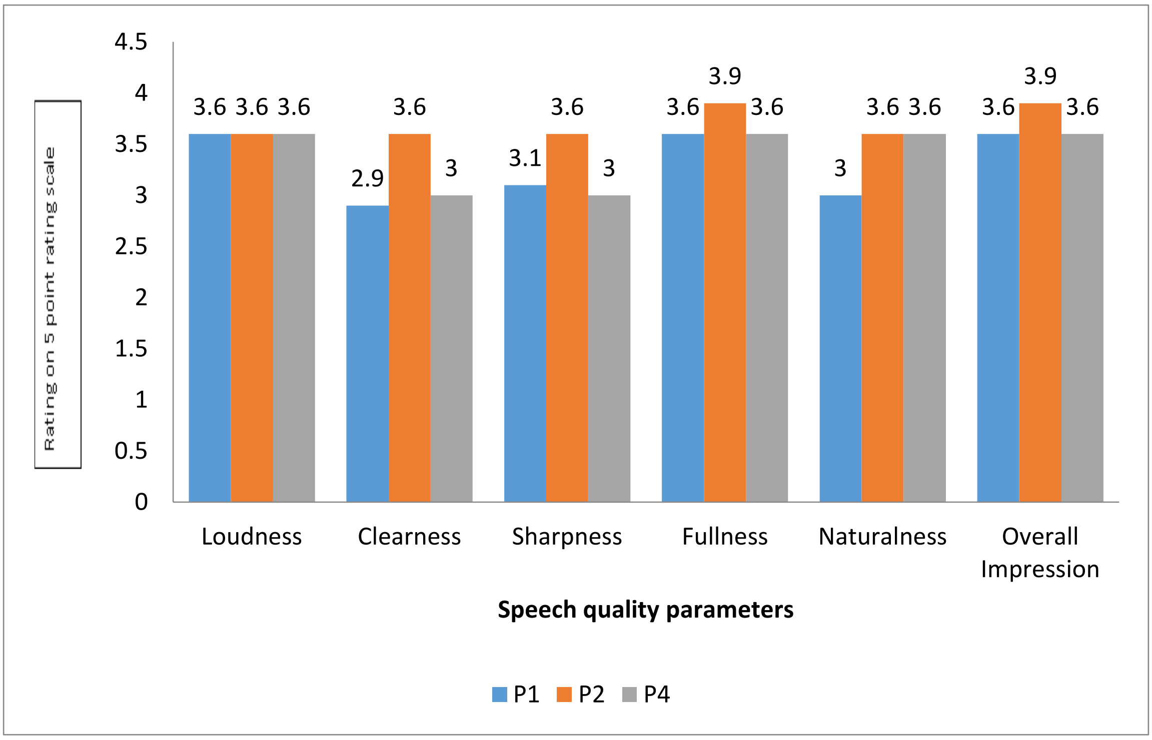

Figure 4.2: Mean rating of quality (1 to 5) of speech with hearing aid in regular (P1), extended bandwidth (P2) and music program (P4), in Group II.

From Figure 4.2, Table 4.3 and Table 4.4, the following observations were made for Group II:

- For “Loudness”, regular bandwidth (P1), extended bandwidth setting (P2), and music program (P4) yielded same ratings for quality.
- For “Clearness”, extended bandwidth setting (P2) yielded significantly better ratings than regular bandwidth (P1) as well as music program (P4). Further, music (P4) resulted in significantly better rating than the regular bandwidth

*(P1). There was no significant difference between the regular (P1) and music (P4) programs.

- For “Sharpness”, extended bandwidth setting (P2) yielded significantly better ratings than regular bandwidth (P1) and music program (P4). The Regular bandwidth (P1) yielded slightly better ratings than music program (P4). Further, there was no significant difference between the regular and music programs.
- For “Naturalness”, extended bandwidth setting (P2) and music program (P4) yielded similar ratings and were better than regular bandwidth (P1).
- For “Fullness” and “overall impression”, there was no significant difference between the extended bandwidth setting (P2), regular bandwidth (P1) and music program (P4).

The quality rating of music on a five-point scale was analyzed for different parameters while listening to different programs, in Group I. Figure 4.3, Table 4.5 and Table 4.6 provide the details of the mean and significant difference between the hearing aid programs. Friedman’s test was carried out between all three programs, i.e., regular bandwidth (P1), extended bandwidth setting (P2) and music (P4) in Group I. The results revealed that, there was statistically significant among the ratings for all the music quality parameters in Group I, as shown in the Table 4.5.

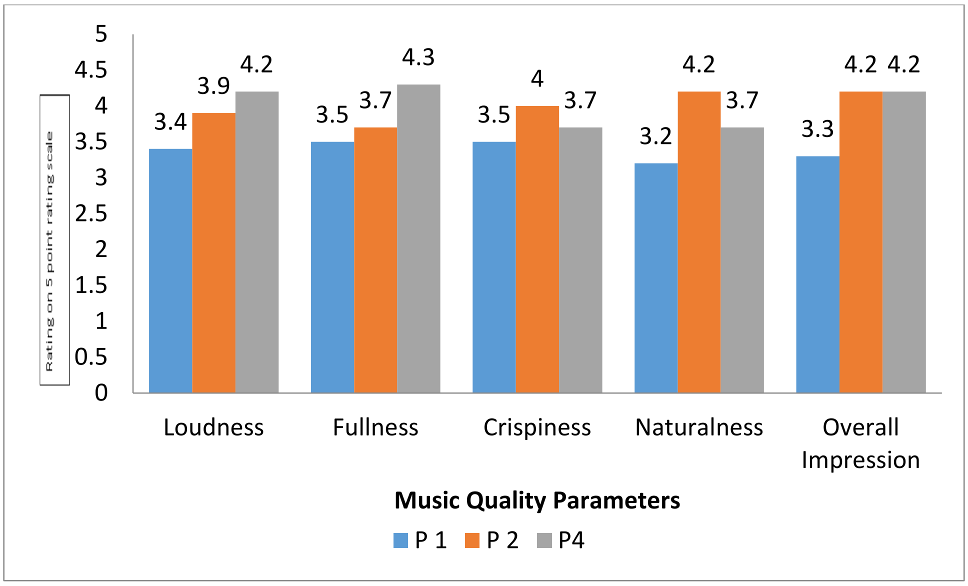

Figure 4.3: Mean rating (1 to 5) on parameters of quality of music with hearing aid in regular (P1), extended bandwidth (P2) and music program (P4), in Group I.

Table 4.5: Friedman's test results for significance difference among the three programs, i.e., for five parameters of music in regular bandwidth (P1), extended bandwidth setting (P2) and music (P) in Group I and Group II.

Music Quality Parameters	**Group I**		**Group II**	
	χ^2	**P**	χ^2	**P**
Loudness	10.88	0.004 *	4.00	0.135
Fullness	12.09	0.002 *	2.00	0.368
Crispiness	6.33	0.042 **	16.80	0.00 *
Naturalness	15.00	0.001 *	7.40	0.025 **
Overall Impression	18.00	0.000 *	10.00	0.007 *

Note: * = p < 0.01; ** = p <0.05

Table 4.6: Results of Wilcoxon signed-rank test for the significance difference in music quality parameters between different programs, i.e., regular bandwidth (P1), extended bandwidth setting (P2) and music program (P4), in Group I and Group II. Numbers within brackets indicate Z value.

Music Quality Parameters	**p value**					
	Group I			**Group II**		
	P2 vs P1	P4 vs P1	P4 vs P2	P2 vs P1	P4 vs P1	P4 vs P2
Loudness	>0.05	0.005	>0.05 (Z=-2.82)	>0.05	>0.05	>0.05
Fullness	>0.05	0.011** (Z=-2.53)	0.014** (Z=-2.44)	>0.05	>0.05	>0.05
Crispiness	0.025** (Z=-2.23)	>0.05	>0.05	0.002* (Z=3.16)	>0.05	0.005* (Z=-2.82)
Naturalness	0.002* (Z=-3.16)	0.025** (Z=-2.23)	0.025** (Z=-2.23)	0.008* (Z=2.64)	>0.05	>0.05
Overall Impression	0.003* (Z=-3.00)	0.003* (Z=-3.00)	>0.05	0.025** (Z=2.23)	0.025** (Z=-2.23)	>0.05

Note: * = p < 0.01; ** = p <0.05

From Figure 4.3, Table 4.5 and Table 4.6, the following observations were made, in Group I:

- For "Loudness", music program (P4) yielded better ratings among three programs tested and it yielded significantly better ratings than regular (P1) (Z = -2.828, p = 0.005). Extended bandwidth setting (P2) slightly better ratings than regular (P1). Further, there was no significant difference between the regular (P1) and extended bandwidth setting (P2).
- For "Fullness", music program (P4) yielded significantly better ratings than both regular bandwidth (P1) (Z=-2.530, p= 0.011) and extended bandwidth

setting (P2) (Z=-2.449, p= 0.014). The extended bandwidth setting (P2) yielded slightly better ratings than regular bandwidth (P1). Further, there was no significant difference between the regular (P1) and extended bandwidth setting (P2).

- For “Crispiness”, extended bandwidth setting (P2) yielded better ratings among three programs tested and it yielded significantly better ratings than regular (P1) (Z = -2.236, p = 0.025). The music program (P4) yielded slightly better ratings than regular bandwidth (P1). Further, there was no significant difference between the regular (P1) and music program (P4).
- For “Naturalness”, extended bandwidth setting (P2) yielded significantly better ratings than regular bandwidth (P1) (Z=-3.162, p= 0.002) and music program (P4) (Z=-2.236, p= 0.025), also music program (P4) yielded significantly better ratings than the regular bandwidth (P1) (Z=-2.236, p= 0.025).
- For “Overall Impression”, extended bandwidth setting (P2) and music program (P4) yielded similar ratings and they gave significantly better ratings than regular bandwidth (P1) [(Z=-3.000, p= 0.003) & (Z=-3.000, p= 0.03)

Quality rating for music was analyzed for participants with moderately-severe SNHL (Group II). The mean rating for different parameters of quality of music is given in Figure 4.4. Friedman’s test was carried out between all the three programs, i.e., regular bandwidth (P1), expanded bandwidth setting (P2) and music (P4). The results revealed that there was statistically significant ratings on “Crispiness” (χ^2 (2) = 16.800, p= 0.000), “Naturalness” (χ^2 (2) = 7.400, p= 0.025), and “overall impression” (χ^2 (2) = 10.000, p= 0.007) in above mentioned programs.

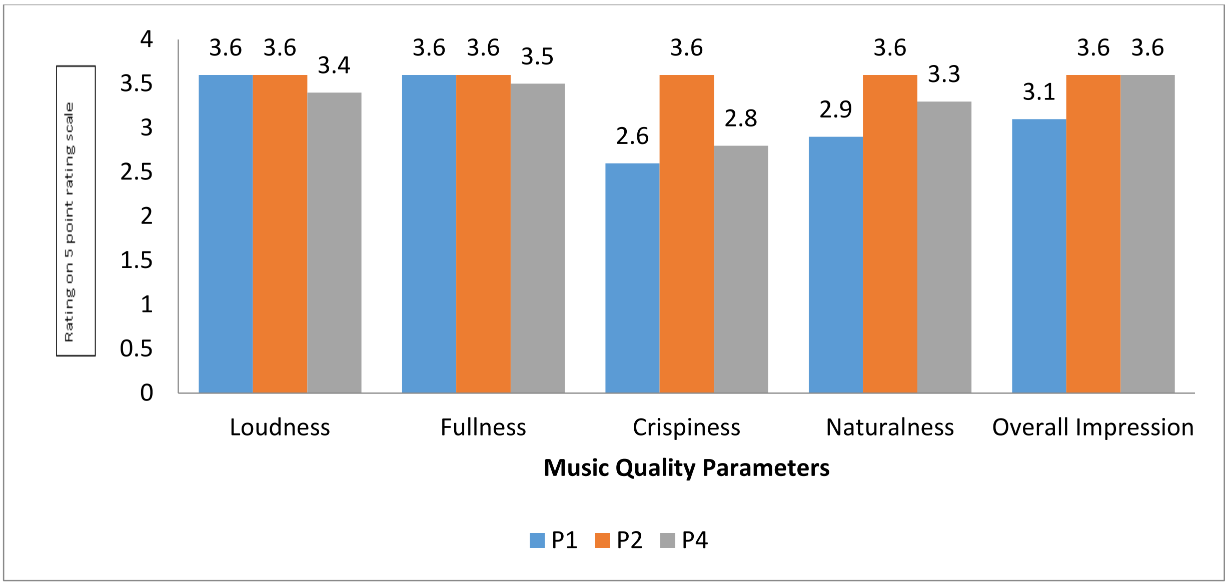

Figure 4.4: Mean rating (1 to 5) on different parameters of quality of music, with hearing aid in regular (P1), extended bandwidth (P2) and music program (P4), in Group II.

On the basis of observation of the Figure 4.4, Table 4.5 and Table 4.6, the following were noted, in Group II:

- For "Loudness", and "Fullness", there was no significant difference between the extended bandwidth setting (P2), regular bandwidth (P1) and music program (P4).
- For "Crispiness", extended bandwidth setting (P2) yielded significantly better ratings than regular bandwidth (P1) (Z=-3.162, p= 0.002) and music program (P4) (Z=-2.828, p= 0.005); also music program (P4) yielded significantly better ratings than the regular bandwidth (P1) (Z=-1.414, p= 0.157).
- For "Naturalness", extended bandwidth setting (P2) yielded better ratings among three programs tested and it yielded significantly better ratings than regular (P1) (Z = -2.646, p = 0.008). The music program (P4) yielded slightly

better ratings than regular bandwidth (P1). Further, there was no significant difference between the regular (P1) and music program (P4).

- For "overall impression", extended bandwidth setting (P2) and music program (P4) yielded similar ratings and they gave significantly better ratings than regular bandwidth (P1) [(Z=-2.236, p= 0.025) & (Z=-2.236, p= 0.025).

Effect of regular, narrow, extended bandwidth and music program settings in the hearing aid on speech and music perception, in individuals with sloping SNHL.

Data were collected and tabulated on SIS, SNR-50, quality of speech and quality of music from participants with sloping SN hearing loss (Group III). This was done while the participants listened through four different hearing aid programs (regular bandwidth - P1, extended bandwidth - P2, narrow bandwidth - P3, and music program - P4). The mean, median and standard deviation (SD) of the SIS and SNR-50 are given in Table 4.7 for Group III, which includes the participants with sloping hearing loss. This is given for regular bandwidth (P1), extended bandwidth (P2), narrow bandwidth program (P3) and music program (P4). The narrow bandwidth setting was possible for six among the ten participants with sloping SNHL, since4only six of them had cochlear dead regions. Hence, Wilcoxson's signed-rank test was performed and not Friedman's test.

Table 4.7: Mean, median and standard deviation (SD) of SIS and SNR-50 with hearing aid in regular (P1), extended bandwidth (P2), narrow bandwidth (P3) and music program (P4), in Group III

Hearing aid setting	SIS *			SNR-50		
	Mean	Median	SD	Mean	Median	SD
Regular Bandwidth (P1)	20.50	21.00	1.90	11.70	12.50	3.09
Extended Bandwidth (P2)	20.70	20.50	2.91	11.80	12.50	5.27
Narrow Bandwidth (P3)	19.83	19.50	1.17	13.17	13.00	1.84
Music program (P4)	20.20	20.00	2.25	13.30	13.50	3.65

Note: * = Max. score being 25

From Table 4.7, it can be noted that the mean SIS was highest for extended bandwidth program (P2) followed by regular program (P1), music program (P4), and narrow bandwidth program (P3). The performance in noise, i.e., SNR-50, was best with regular program (P1) followed by extended bandwidth (P2), narrow bandwidth program (P3), and music program (P4).

Table 4.8: Wilcoxon signed-rank test for the significance difference in SIS for different programs, i.e., regular bandwidth (P1), extended bandwidth setting (P2), narrow bandwidth setting (P3) and music program (P4), in Group III.

Difference between programs for SIS	Z	p
P2-P1	-4.91	0.623
P3-P1	-1.342	0.180
P4-P1	-1.134	0.257
P3-P2	-1.725	0.084
P4-P2	-1.186	0.236
P4-P3	-2.121	**0.034****

Note: ** = p <0.05

Because of the fewer participants in the Group III who had cochlear dead region and hence tested with narrow bandwidth program (P3), Friedman's test for checking significance difference could not be carried out. Thus, Wilcoxon signed-rank test was applied. Table 4.7 show cases the paired comparison of programs for performance with SIS in Group III. This revealed a statistically significant improvement in SIS with music program (P4) compared to narrow bandwidth program (P3) (Z = -2.121, p = 0.034). However, there was no significant difference between the other programs.

Table 4.9: Results of Wilcoxon signed-rank test for the significance difference in SNR-50 between different programs, i.e., regular bandwidth (P1), extended bandwidth setting (P2), narrow bandwidth setting (P3) and music program (P4), in Group III.

Difference between programs for SNR-50	**Z**	**P**
P2-P1	0.000	1.000
P3-P1	-1.000	0.317
P4-P1	-2.124	0.034**
P3-P2	-1.667	0.096
P4-P2	-1.687	0.092
P4-P3	-2.333	0.020**

Note: ** = p <0.05

From Table 4.9, it can be noted that the performance in noise, i.e., SNR-50, was best with regular program (P1) followed by extended bandwidth (P2), music program (P4), and narrow bandwidth program (P3).

The mean, median and standard deviation values of the rating on quality parameters of music are depicted in Figure 4.4. Further, because there were fewer participants in the Group III (6 among 10 had cochlear dead region) who got programmed for Program 3, Friedman's test could not be done for all the four programs. Thus, Wilcoxon signed-rank test was applied. Table 4.10 showcases the paired comparison of SNR-50 obtained for different programs, in Group III. This revealed a statistically significant improvement in SNR-50 with regular program (P1) compared to music program (P4) ($Z = -2.124$, $p = 0.034$); and narrow bandwidth program (P3) compared to music program (P4) (Z = -2.333, p = 0.020). However, there was no significant difference found between other programs.

As shown in Table 4.10, the results of Wilcoxson's signed-rank test for rating of six parameters across P1, P2, P3, and P4 revealed that only "Sharpness" and "Fullness" had statistically significant difference. All the other parameters did not show any significant difference between programs.

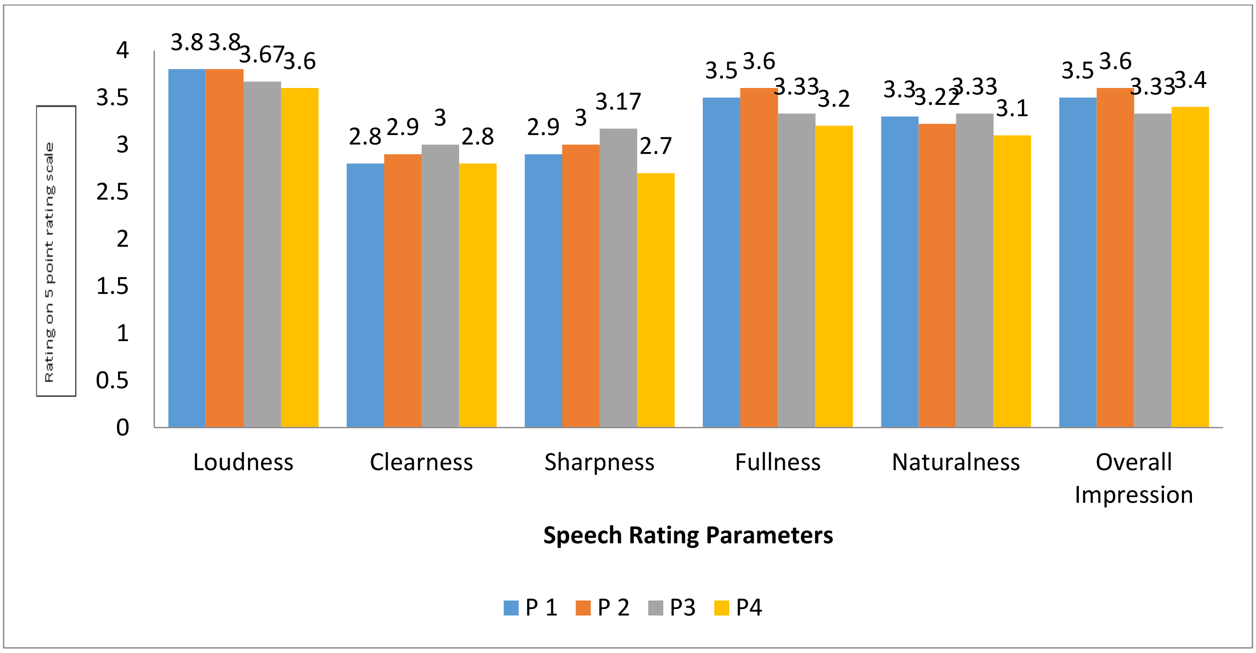

Figure 4.5: Mean rating (1 to 5) on different parameters of quality of speech with hearing aid in regular (P1), extended bandwidth (P2), narrow bandwidth (P3) and music program (P4), in Group III.

Table 4.10: Results of Wilcoxon signed-rank test for significance difference in speech quality parameters between the programs, i.e., regular bandwidth (Program 1), expanded bandwidth setting (Program 2), narrow bandwidth (P3) and music (Program 4), in Group III.

Speech Quality Parameters	P					
	P2 vs. P1	P3 vs. P1	P4 vs. P1	P3 vs. P2	P4 vs. P2	P4 vs. P3
Loudness	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05
Clearness	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05
Sharpness	>0.05	>0.05	>0.05	0.046** (Z=-2.00)	>0.05	>0.05
Fullness	>0.05	>0.05	>0.05	0.025** (Z=-2.23)	0.046** (Z=-2.00)	>0.05
Naturalness	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05
Overall Impression	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05

Note: ** = p <0.05

From Figure 4.4 and Table 4.10, the following observation were made:

- For "Loudness", "Naturalness" and, "Overall Impression", there was no significant difference between the regular bandwidth (P1), extended bandwidth setting (P2), narrow bandwidth program (P3), and music program (P4).
- For "Clearness", narrow bandwidth program (P3) yielded slightly better ratings compared to regular bandwidth (P1) and music program (P4).

However, narrow bandwidth program (P3) yielded significantly better ratings compared to extended bandwidth setting (P2).

- For “Sharpness”, narrow bandwidth program (P3) yielded slightly better ratings compared to regular bandwidth (P1) and music program (P4). However, narrow bandwidth program (P3) yielded significantly better ratings compared to extended bandwidth setting (P2).
- For “Fullness”, extended bandwidth setting (P2) slightly better ratings compared to regular bandwidth (P1) and narrow bandwidth program (P3). However, extended bandwidth setting (P2) yielded significantly better ratings compared to music program (P4) ($Z = -2.000$, $p = 0.046$).

Quality rating for music was analyzed for Group III. The mean rating for different parameters of quality of music is given in Figure 4.6. Since there were fewer participants in the Group III who had cochlear dead regions and hence programmed for narrow bandwidth, Friedman’s test could not be performed. As shown in the Table 4.13, the results of Wilcoxon’s test for ratings on five parameters across P1, P2, P3 and P4 revealed that only “Naturalness” had statistically significant difference. All the other parameters did not show any significant difference among programs.

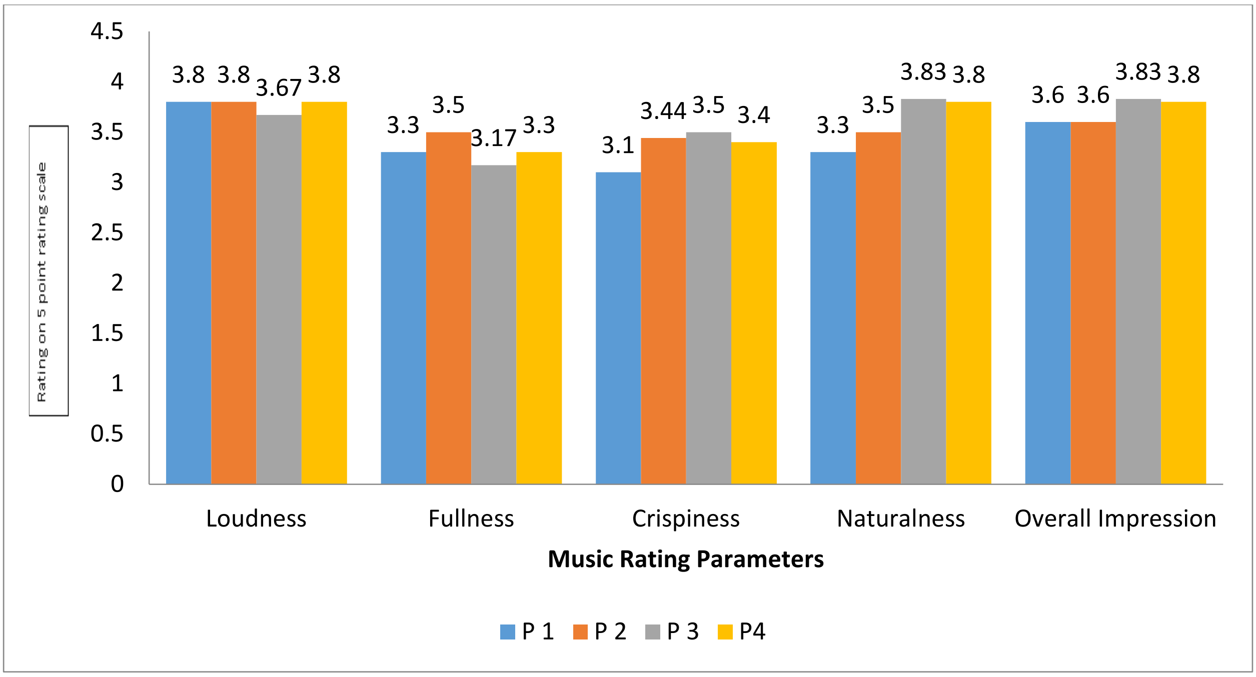

Figure 4.6: Mean rating of quality (1 to 5) for music quality parameters with hearing aid in regular (P1), extended bandwidth (P2), narrow bandwidth (P3) and music program (P4), in Groups III.

Table 4.11: Results of Wilcoxon signed-rank test for the significance difference on parameters of quality of music between different programs for five parameters of music quality, i.e., regular bandwidth (P1), expanded bandwidth setting (P2), narrow bandwidth (P3) and music (P4), in Group III.

Music Quality Rating Parameters	P					
	P2 vs P1	P3 vs P1	P4 vs P1	P3 vs P2	P4 vs P2	P4 vs P3
Loudness	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05
Fullness	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05
Crispiness	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05
Naturalness	>0.05	>0.05	0.025** (Z=-2.23)	0.046** (Z=-2.00)	>0.05	>0.05
Overall Impression	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05

Note: ** = p <0.05

- For “Loudness”, “Fullness”, “Crispiness”, and “overall Impression”, there was no significant difference between the regular bandwidth (P1), extended bandwidth setting (P2), narrow bandwidth program (P3), and music program (P4).
- For “Naturalness”, narrow bandwidth program (P3) and music program (P4) yielded similar ratings and were slightly better than regular bandwidth (P1), and extended bandwidth setting (P2). However, music program (P4) yielded significantly better ratings compared to regular bandwidth (P1) (Z=-2.236, p= 0.025) and narrow bandwidth program (P3) yielded significantly better ratings compared to extended bandwidth setting (P2) (Z=-2.000, p= 0.046).

Chapter 5

Discussion

The aim of the present study was to investigate the effect of varying the frequency bandwidth of the hearing aid on the speech and music perception in three groups of participants with sensorineural hearing loss. Results obtained from those three groups will be discussed under different headings.

Effect of regular bandwidth, extended bandwidth, and music program settings in hearing aid on speech and music perception, in ears with moderate (Group I) and moderately-severe SNHL (Group II).

Speech identification scores were better in quiet as well as noise with hearing aid in extended frequency bandwidth setting than the regular frequency bandwidth setting and music program. This finding of the present study agrees with that reported by previous investigators where they showed that extension of audible frequency in the hearing aid will improve the performance in terms of speech recognition tasks in quiet as well as in noise (Turner & Henry, 2002; Carlile & Schonstein, 2006; Alkaf & Firszt, 2007; Ricketts, Dittberner & Johnson, 2008; Levy et al., 2015).

In order to get good speech recognition scores, it is highly important that the hearing aid provide access to all the speech frequencies, present in the input, to the hearing aid user so that he/she can perceive and discriminate all speech sounds including high frequency sounds with ease and accuracy. It has been reported that relatively large amount of important speech cues are located after 3000 Hz. In a study by Yavas, 2016 on acoustic characteristics of English speech sounds, it was reported that most important cues are located above 3000 Hz in English. This is because in majority of English fricatives, the voiced and voiceless cognates of‘s’, ‘f’, ‘th’, and ‘sh’ (/s, z, f, v, θ, ð, ʃ, ʒ/), and especially the most commonly occurring consonants in the English Language, /s/ phoneme and its voiced cognate /z/, are used in a number of grammatical purposes such as for marking plurals, possessives, the third person singular, tense and contractions. The average spectral location for /s/ and /z/ were located around 7,500 Hz when female speakers produced it and was around 6,200 Hz when male speakers produced it. In another study, Todd, Edwards, and Litovsky, 2011 reported that it can go up to 10,000 Hz when children produce it. It is very evident that high frequency components are very essential in order to distinguish such sounds.

Regular bandwidth hearing aids, which will have a bandwidth up to 4000 - 5000 Hz, might not help the hearing aid user in providing high frequency information. Thus might end up giving poor speech recognition scores. But, when the extended bandwidth program is used, it gave amplification till 8000 Hz which made certain high frequency sounds audible giving better results compared to regular bandwidth settings. Recently, it has been shown that increasing the frequency bandwidth resulted in improved speech recognition in listeners with hearing thresholds as poor as 85 dB HL (Hornsby & Ricketts, 2006).

The SNR-50 measure yielded better results with extended bandwidth than the regular and music program in both the groups. The high frequency components are less susceptible to noise unlike the low frequency components of speech which get masked easily by common types of noise which majorly consist of relatively intense low frequency components. So it is highly important that high frequency components are audible to the hearing aid user so that he / she can differentiate between the speech and noise with the help of high frequency information.

In a study by (Turner & Henry, 2002), the performance in the presence of background noise improved with the addition of high frequency audible information in all cases of their study, irrespective of their degree of the hearing loss. The result of the present study with respect to the improvement of performance in noisy or complex listening situations is consistent with the previous studies by (Turner & Henry, 2002; Hornsby & Ricketts, 2003; Hornsby & Ricketts, 2006; and Plyler & Fleck, 2006).

Extended bandwidth yielded better ratings in terms Loudness, Clearness, Sharpness, Fullness, Naturalness, and Overall Impression with respect to speech quality perception in both the groups compared to regular bandwidth and music program settings. This difference was significant in certain parameters such as Clearness, Sharpness, Naturalness and Overall Impression.

These findings are consistent with previous investigators (Franks, 1982; Moore & Tan, 2003; Ricketts, Dittberner & Johnson, 2008), who advocated the importance of high frequency cut-off for better speech and music quality. It is reported that perceived sound quality depends majorly on audible frequency bandwidth and smoothness of frequency response amplification systems. The preference for a wide, audible bandwidth appears to be most important for signals containing frequency information across entire audible bandwidth, as evident in some music and environmental signals, but also for band-limited signals such as speech. (Moore & Tan, 2003) reported that perceived sound quality of speech signals, a significant degradation in sound quality was noted when the upper cut-off frequency was decreased below 10,869 Hz and when the lower cut-off frequency was increased from 123 to 208 Hz. Most modern hearing aids do not provide useful gain above about 6,000 Hz. However, the ability to achieve a much wider bandwidth in hearing aids was demonstrated more than two decades ago (Killion & Tillman, 1982). This preference is important because it is possible that perceived poor sound quality resulting from limited bandwidth might be a factor contributing to the non-acceptance or limited use of hearing aids by listeners.

Extended bandwidth also yielded better ratings in terms of Loudness, Fullness, Crispiness, Naturalness, and Overall Impression with respect to music quality perception in both groups compared to regular and music program settings. There was significant improvement in the performances on certain parameters such as Crispiness, Naturalness, and Overall Impression.

These findings are consistent with previous investigators (Franks, 1982; Moore & Tan, 2003; Ricketts, Dittberner & Johnson, 2008), who also reported that extension of audible frequency bandwidth would result in better music perception. According to Chasin, 2003, ideal hearing aid for music perception can be programmed to have good speech intelligibility but the vice versa is not true because speech and music differ from each other in terms mainly four factors, namely (1) the long-term spectrum (2) differing overall intensities, (3) crest factors, and (4) phonetic vs. phonemic perceptual requirements. Moore & Tan, 2003 evaluated perceived 'naturalness' of speech and music across a multitude of filter settings, to approximate distortions introduced via microphones, speakers, and earphones. The researchers found when approximating the bandwidth of the telephone (313 to 3,547 Hz), a very poor quality of sound was noted. The highest ratings were obtained for speech and music when the bandwidth was wide, from 123 to 10,869 Hz for speech and 55 to 16,854 Hz for music. There was also a study by Moore (2012) which supports this findings, he investigated the effect of hearing aid bandwidth on sound quality preferences mostly for jazz and classical music stimuli. The data were obtained using method of paired comparisons and ratings of individual stimuli. In the study, for individuals with normal hearing, the highest ratings were obtained for wider bandwidth, 55 to 16,000 Hz. For individuals with hearing impairment, the preferences varied across participants with respect to high frequency cut-offs. Some preferred 7,500 or 10,000 Hz as upper cut-off frequency over 5,000 Hz; where as some subjects showed the opposite preference.

It is well established that bandwidth for speech and music vary significantly. The bandwidth of speech is fixed over narrower frequency range compared to the bandwidth for music. The latter varies with the singer and the instrument. Generally, the goal of fitting a hearing aid is mainly for improvement in perception of speech. Thus, the hearing aids selected may not be optimal for music perception. Even though there is a 'music program' in some models of hearing aids, the efficiency of it remains to be explored.

Effect of regular bandwidth, extended bandwidth and narrow bandwidth settings in the hearing aid on speech and music perception, in individuals with sloping SNHL.

In the present study, unlike the Group I and Group II, the speech recognition scores did not improve significantly with extended bandwidth, which implies that high frequency amplification did not improve the performance of the participants who had cochlear dead region. Extended bandwidth setting yielded slightly better speech recognition scores than the other three programs. But in the presence of competing noise, the regular bandwidth yielded better performance than the other programs.

Recent studies on the extension of audible frequency range in individuals with hearing impairment have been equivocal (Plyler & Fleck, 2006; Horwitz Alhstrom & Dubno, 2007; Moore, Fullgrabe & Stone, 2010). Moore, 2004 reported that hearing impairment greater than 55 to 60 dB, can be associated with cochlear dead regions, which may limit the ability to make use of high frequency amplification, negating its possible effectiveness and even leading to worse performance with amplification (Hogan & Turner, 1998; Vickers, Moore & Baer, 2001; Baer, Moore & Kluk, 2002). Recent studies have revealed consistent finding on listeners with high frequency SNHL and indicated that improvements in speech recognition from amplification of high frequency components were related to presence or absence of a dead region, whether listening in quiet or in noise (Vickers, Moore & Baer, 2001; Baer, Moore & Kluk, 2002).

Although transducer limitations do exist, speech recognition data, particularly for those listeners with high frequency hearing thresholds in excess of 55 dB HL and those with high frequency ‘dead regions’, have been used to support bandwidth limitations (Amos, 2001; Baer, Moore & Kluk, 2002; Ching, Dillon, & Byrne, 1998; Hogan & Turner, 1998). In summary, these studies suggest that for some listeners, little or no additional speech recognition or sound quality benefit is found when increasing the high frequency cut-off frequency beyond 3-4 kHz. However, these studies also revealed that for many other listeners, particularly those without high-frequency dead regions, improvements in speech recognition can be associated with increasing the high frequency cut-off.

All the three bandwidth settings yielded comparable and better ratings in most of the parameters, both for Speech and Music, in Group 3

There was no significant difference between regular bandwidth (P1), extended bandwidth (P2), narrow bandwidth (P3) and music program (P4) for most of the parameters tested in Group III. The extended bandwidth which had improved perceptual qualities for both speech and music was found with no effect over perceptual qualities of speech and music in Group III. The results are consistent with the findings by Ching, Dillon & Byrne, 1998; Hogan & Turner, 1998; Ricketts, Dittberner & Johnson, 2008. Examining the work of this author, several general recommendations can be made. If the hearing loss is mild to moderate level, then a broader bandwidth for music is better. If however, the hearing loss is greater than a moderate level, then a narrower bandwidth (to avoid dead regions in the cochlea) may provide a more pleasant sound than a wider bandwidth that extends into the high frequency region. The same can be said about the configuration of the audiogram, a person with a relatively flat audiometric configuration prefers the widest bandwidth possible. In contrast, if there is a precipitous high frequency loss configuration then, a narrower frequency response would be ideal.

Ricketts, Dittberner and Johnson, 2008 explored the sound quality as it relates to degree and slope of hearing loss and hearing aid bandwidth. They reported that there was a significant preference for the wider bandwidth among individuals with normal hearing. Subjects with slope of less than 8 dB/octave were likely to prefer the wider bandwidth (or have no preference) and those with greater slopes (more significant high frequency hearing loss) preferred a narrower bandwidth.

Chapter 6

Summary and conclusions

It is highly important for the people with the hearing loss to perceive and discriminate all speech sounds, including high frequency sounds, with ease and accuracy in order to understand speech in quiet as well as in noise, and also to help in localization. Most of the sensorineural hearing losses result in poor high frequency hearing sensitivity, and, as such, the hearing aid should be able to provide amplification for heard. Most of the speech sounds (consonants) necessary for understanding of speech have their energy regions in the high frequencies. Therefore, this frequency region should be compensated for (amplified) when affected by a hearing loss. But most of the hearing aids available in the market tend to have frequency bandwidth limited around 5000 Hz.

Currently, high frequency information can be made audible to the hearing aid user by various techniques, such as frequency lowering and extended frequency bandwidth. Frequency lowering involves transposing high frequency information to the low frequency region which is audible to the user. Extended frequency bandwidth, where high frequency components are made audible to the user by providing amplification to them. In the present study, the effect of extended frequency bandwidth over speech and music perception, in persons having sensorineural hearing loss, was investigated.

Most of the studies in the literature have talked about effect of frequency bandwidth over both speech and music perception in individuals with sensorineural hearing impairment. The results of these studies over years have led to mixed conclusions. There were group of individuals with hearing impairment who benefitted from high frequency amplification and there were also people whose performance did not change with high frequency amplification; and in some cases the performance reduced with high frequency amplification. However, very few studies have been done which assess the effect of extended frequency bandwidth with respect to different pattern and degree of hearing loss. And there were even lesser number of studies which compared extended bandwidth effects with narrow bandwidth settings in persons with sloping hearing impairment.

The present study therefore compared effect of extended bandwidth over speech and music perception in sensorineural impaired. Three groups were made wherein, Group I consisted of ten ears with moderate SNHL of flat configuration, Group II consisted of ten ears with moderately severe SNHL of flat configuration, Group III consisted of ten ears with sloping SNHL. The test ears in Group I and Group II were tested with regular bandwidth (Program 1), extended bandwidth (Program 2) and default music program (Program 4) of a digital BTE hearing aid connected to ear tip. In addition to these three programs, the test ears in Group III were tested with narrow bandwidth (Program 3).

The participants from all groups were tested with PB word lists for adults in Kannada (Manjula, Kumar, Geetha, & Antony, 2013) for obtaining speech identification scores (SIS) in quiet and for SNR-50 (for assessment in noise). The perceptual quality was assessed for both speech and music with the help of five-point rating scale where they rated speech for six parameters (Loudness, Clearness, Sharpness, Fullness, Naturalness, and Overall Impression) and music for five parameters (Loudness, Crispiness, Fullness, Naturalness and Overall Impression). A Kannada passage (Sairam, 2002) and stimuli from the music perception test battery

(MPTB) (Das, 2010) were used as stimuli for rating the quality of speech and music respectively.

Statistical analyses were carried out using descriptive analysis and non-parametric tests. The descriptive analysis was carried out in order to get mean, median, and standard deviation (SD) for the scores on SIS, SNR-50 and quality perception ratings in all three groups. Friedman’s test and Wilcoxon Signed Ranks Test were used to compare the performance of the participants on the SIS, SNR-50 and quality ratings while listening to different hearing aid programs.

Results revealed better scores for extended bandwidth for both SIS and SNR-50 compared to regular bandwidth and music program, in Group I and Group II. Thus, the performance improved in speech recognition both in quiet as well as in noise with extended bandwidth. Extended bandwidth yielded better ratings in terms Loudness, Clearness, Sharpness, Fullness, Naturalness, and Overall Impression with respect to speech quality perception in both the groups compared to regular and music program settings. Expanded bandwidth also yielded better ratings in terms of Loudness, Fullness, Crispiness, Naturalness, and Overall Impression with respect to music quality perception in both groups compared to regular bandwidth and music program settings.

In Group III, extended bandwidth setting yielded slightly better speech identification scores than the other three programs. But in the presence competing noise as in SNR-50, the regular bandwidth yielded better performance than the other programs. Further, all the four programs yielded comparable quality ratings for speech as well as music.

Clinical Implications:

The present study recommends the use of extended frequency bandwidth in hearing aid to help the users of hearing aid in terms speech recognition (in quiet and noise) and improve the perceptual quality of speech and music. Additionally, it also recommends the use of regular bandwidth in cases steeply sloping hearing loss with cochlear dead regions for better speech recognition.

Future Directions for Research:

There are many areas where further research can be carried out,

1. Studies on effect of extended bandwidth can be done on different types and degrees of hearing loss.
2. Studies can be done on effect of extended bandwidth on localization in SNHL.
3. Effect of narrow bandwidth on speech and music perception in persons with and without cochlear dead region.

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