Optimization of Frequency Compression

For Persons with Sloping Hearing Loss -

Application of Speech Intelligibility Index (SII)

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A Masters Dissertation Submitted in part fulfillment of final year

Master of Science (Audiology)

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May, 2014

CERTIFICATE

This is to certify that this dissertation entitled **'Optimization of frequency compression for persons with sloping hearing loss – Application of Speech Intelligibility Index (SII)'** is a bonafide work submitted in part fulfillment for the degree of Master of Science (Audiology) of the student **Registration No: 12AUD016.** This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any diploma or degree.

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CERTIFICATE

This is to certify that dissertation entitled **'Optimization of frequency compression for persons with sloping hearing loss – Application of Speech Intelligibility Index (SII)'** has been prepared under my supervision and guidance. It is also certified that this dissertation has not been submitted earlier to any other university for the award of any diploma or degree.

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DECLARATION

This is to certify that this master's dissertation entitled **'Optimization of frequency compression for persons with sloping hearing loss – Application of Speech Intelligibility Index (SII)'** is the result of my own study under the guidance of Dr. P. Manjula, Professor in Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier to any other university for the award of any diploma or degree.

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CHAPTER 1

INTRODUCTION

Hearing is an essential part of life for humans because of their unique nature of verbal communication. Verbal communication gets affected if the hearing loss accrues. The hearing loss results in a reduction in audibility, intelligibility and quality of speech. Difficulty in understanding speech is increased in the in background noise (Turner & Henry, 2002). The hearing loss not only affects the perception of speech (verbal sounds), but also the non-verbal sounds which are important for the daily living i.e., calling bell, mobile ring, alarm ring, etc. (Rileigh & Odom, 1972).

The hearing loss can occur as a result of a problem in the outer, middle or inner ear. In the inner ear, the damage is usually due to loss of cochlear hair cells (Plack, Drga, & Lopez-Poveda, 2004). The loss can be alleviated by providing external amplification of the sound.

The acoustic signals are amplified by hearing aids or amplification devices. The amplification device not only improves the audibility of acoustic signals, it also incorporates different techniques for improving the perception of speech. The technical features include enhanced speech signal, noise reduction, feedback cancellation, etc. Another technical feature incorporated in some amplification devices is frequency lowering technique. The frequency lowering provides higher frequency information by either compression or transposition of high frequency in the lower frequency region.

The hearing aid has to provide the audibility which is lost due to hearing loss, but restoration of full audibility does not take place by a hearing aid due to the restrictions such as limited bandwidth, power constrains and problem of acoustic feedback in hearing aid (Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004). In addition, the intensity of high frequencies in speech is reduced by around 9 dB per octave above the frequency 500 Hz in average speech spectrum level (ANSI, 1997). The amplification provided by a hearing aid is limited in the high frequency region. It has been reported in literature that providing higher gain in the high frequency region is also not beneficial in cochlear hearing loss which has an effect on speech intelligibility (Ching, Dillon, & Byrne, 1998; Hogan & Turner, 1998; Turner & Cummings, 1999; Ching & Dillon, 2013).

Persons with sloping hearing loss pose a challenge for audiologists as hearing aids seldom provide sufficient gain in the high frequencies to enable high frequency speech sounds to be audible (Kuk, Keenan, Peeters, Korhonen, Lau, & Andersen, 2007). This results in poor speech perception and sound quality (Hogan & Turner, 1998). Therefore, it is important to squeeze the entire spectrum of higher frequency sounds into the person's limited bandwidth of audibility (i.e., in the lower frequencies) (Simpson, Hersbach, & McDermott, 2005).

Frequency lowering techniques in hearing aids improve the audibility of high frequency information to be audible (Glista, Scollie, Bagatto, Seewald, Parsa, & Johnson, 2009). Frequency lowering is a technique of increasing access to a wider range of the spectral content of the acoustic signal. It moves the spectral content of high-frequency sounds to a region that is audible for the client.

Signal processing features used in a hearing aid of frequencies lowering technique are mainly two types, i.e., frequency transposition (FT) and non-linear frequency compression (NLFC). In FT feature the shifting of high frequencies towards lower frequencies done. This shifting of higher frequency overlaps with the lower frequency information. In non-linear frequency compression (NLFC), the high frequencies are lowering is different from FT. In NLFC, the high frequency energies are moved to lower frequency region through compressing the energy. The amount of compression of frequencies ranges from greater to lesser extent as the frequencies moved from higher to lower frequency. In yet another form of frequency lowering techniques, frequency translation is also being implemented in hearing aids. In this form, the processing technique is such that it to replicate (or translates) those high frequency features to a lower, audible frequency. In addition to lowering of the acoustic input, new features are created in real time, resulting in the presentation of audible cues while minimizing the distortion.

The main benefits of change in performance using frequency lowering techniques include speech quality and intelligibility. The two measures are independent of each other. Speech intelligibility is generally expressed as the number of words or units (or in terms of percentage) that is correctly understood. The quality of the speech signal is a subjective way of measuring which reflects the way the signal is perceived by listeners. The parameters can be expressed as loudness, pleasantness, and naturalness of the message.

1.1. Need for the Study

Frequency compression is the one of the frequencies lowering techniques (Simpson et al., 2005), which provide the algorithm where the compression of the frequency starts at a high frequency above the cut-off frequency and amount of the compression depends on the compression ratio. In non-linear frequency compression (NLFC), the processing is intended to provide increased audibility for high frequency sounds through compressing of input above a particular frequency. i. e., start frequency. This is achieved through a specific frequency compression ratio. Thus, NLFC balance for hearing loss in high frequency ranges where conventional amplification may not provide sufficient benefit (Gagana, 2013).

The frequency compression parameters, i.e., the cut-off frequency and the frequency compression ratio need to be optimized for better performance. There is a dearth of literature on optimizing the frequency compression parameters.

There are studies that have investigated the benefit of frequency lowering options in hearing aid using default settings. Such studies have reported that there was no improvement with default frequency compression option (Glista, Scollie, Bagatto, Seewald, Parsa, & Johnson, 2009). The reasons provided that include the default frequency compression is based on the audiometric configurations, so the speech intelligibility may vary from configuration. That is the reason for optimization of frequency lowering in order to provide better speech intelligibility.

In normal listeners the non-word recognition was predicted to increase along with estimated bandwidth increased for nonlinear frequency compression is at optimized condition (McCreery, Brenda, Hoover, Kopun, & Stelmachowicz, 2013). Though the result showed the befit of optimized NLFC in listeners with normal hearing, the usefulness of optimized NLFC in hearing aid cannot be acquired for person with high frequency sloping hearing loss.

In person with hearing loss the evidence of audibility based improvements for speech understanding could be used to predict performance. This also could be used for NLFC-Optimized in person with high frequency sloping hearing loss. A standardized method for approximating audibility with NLFC would allow in the selection of parameters that optimizes the outcomes.

The optimization should satisfy the perception of speech in quiet as well as in the presence of noise. In a multilingual country like India, having speech material for each language is difficult. Hence it would be useful to investigate if non-speech measures can predict the outcome with frequency lowering technique. One such technique of predicting the speech intelligibility using audibility measure is the use of speech intelligibility index (SII). Thus, the present study intends to evaluate the efficacy of SII in estimating the optimal compression parameters in order to bring about better speech intelligibility. The SII is a measure of audibility; it ranges between 0 and 1. An SII of zero indicates that speech intelligibility is very poor and an SII of one indicates that the speech intelligibility is very good.

The improvement in audibility with and without amplification can be estimated by SII (ANSI S3. 5–1997; McCreery, Brennan, Hoover, Kopun, & Stelmachowicz, 2013). On the other hand, the validity of the speech intelligibility index for signals where the spectral frequency has been altered has not been evaluated to a great extent (Bentler, 2011). Calculation of SII i.e., audible output, could be used for comparison of audibility across different conditions of varying frequency-lowering parameters (McCreery & Stelmachowicz, 2011). Even though improvements in audibility due to NLFC may result in increased exposure to high frequency acoustic cues, but these improvements could suppress by alterations to the acoustic cues that are important for speech perception (Parsa, Scollie, Glista, & Seelisch, 2013). It will be interesting to know if SII (using the frequency, importance weighted for conventional frequency range) would also be useful for setting the frequency compression parameters in a hearing aid. Thus, in the present study, the utility of SII will be investigated in selection of frequency compression parameters.

1.2. Aim of the Study

To evaluate the efficacy of SII in optimizing the frequency compression in hearing aids for sloping sensorineural hearing loss.

1.3. Objectives of the Study

The specific objectives include-

1. To evaluate the effect of the NLFC in hearing aid on speech identification, in quiet and in noise.
2. To evaluate the effect of the NLFC in hearing aid on quality of speech identification.

3. To compare the speech intelligibility (in quiet and in noise) and quality with SII in the three aided conditions, i.e., with frequency compression disabled, with NLFC set to default and with optimized NLFC settings.
4. To compare the performance on speech intelligibility in the three aided conditions, i.e., with frequency compression disabled, with NLFC set to default and with optimized NLFC settings.
5. To compare the performance on quality in the three aided conditions, i.e., with frequency compression disabled, with NLFC set to default and with optimized NLFC settings.

Hypothesis

The SII is not useful in optimization of NLFC in hearing aids for individuals with sloping sensorineural hearing loss.

CHAPTER - 2

REVIEW OF LITERATURE

A plethora of signal processing strategies is being used in hearing aids to improve the performance. The frequency lowering technique is one of them. This technique is being used for more than five decades. This technique intends to provide better speech understanding for persons with sloping hearing loss. The outcome measurement of the hearing aids is mainly done using two methods. They are subjective and objective measurements.

The speech intelligibility index (SII) has been found to be useful in selecting the hearing aid and optimizing its parameters (Studebaker & Marincovich, 1989; Sandlin, 1990; Manjula, 2008). In the present study, the efficacy of SII in optimizing the frequency compression parameter in hearing aid for sloping hearing loss was investigated. The relevant literature is being given under the headings of,

2.1. Frequency lowering techniques in hearing aids

2.2. Role of NLFC in Hearing Aid on Speech Identification in Quiet and Noise

2.3. Role of the NLFC in Hearing Aid on Quality of Speech

2.4. Role of SII in optimizing NLFC

2.1. Frequency Lowering Techniques in Hearing Aids

The conventional hearing aids fail to provide appropriate amplification for the individuals with high frequency sloping hearing loss. Altering the method of signal processing in a hearing aid helps in presenting the inaccessible high frequency information to the lower frequency region. This strategy is called frequency lowering.

There are various forms of frequency lowering such as frequency compression, frequency transposition, frequency shifting etc. (Simpson, 2009).

Early studies with frequency lowering technology (FLT) have reported unfavorable results, hence were not incorporated into hearing aids for a long time. However, as hearing aid technology became more sophisticated, FLT is being reconsidered. A variety of FLT is now available in commercial hearing aids.

Ross (2009) has reviewed different techniques for frequency lowering in hearing aids. There are different techniques for frequency lowering in hearing aids. Dynamic Speech Recoding or Frequency Compression in hearing devices compresses the entire spectrum and shift the high frequencies to the lower frequencies. All energy peaks within the signal are shifted proportionately (for example, with a frequency compression ratio of 2, sounds at 6000 Hz are shifted to 3000 Hz, while 3000 Hz sounds are moved to 1500 Hz and so on).

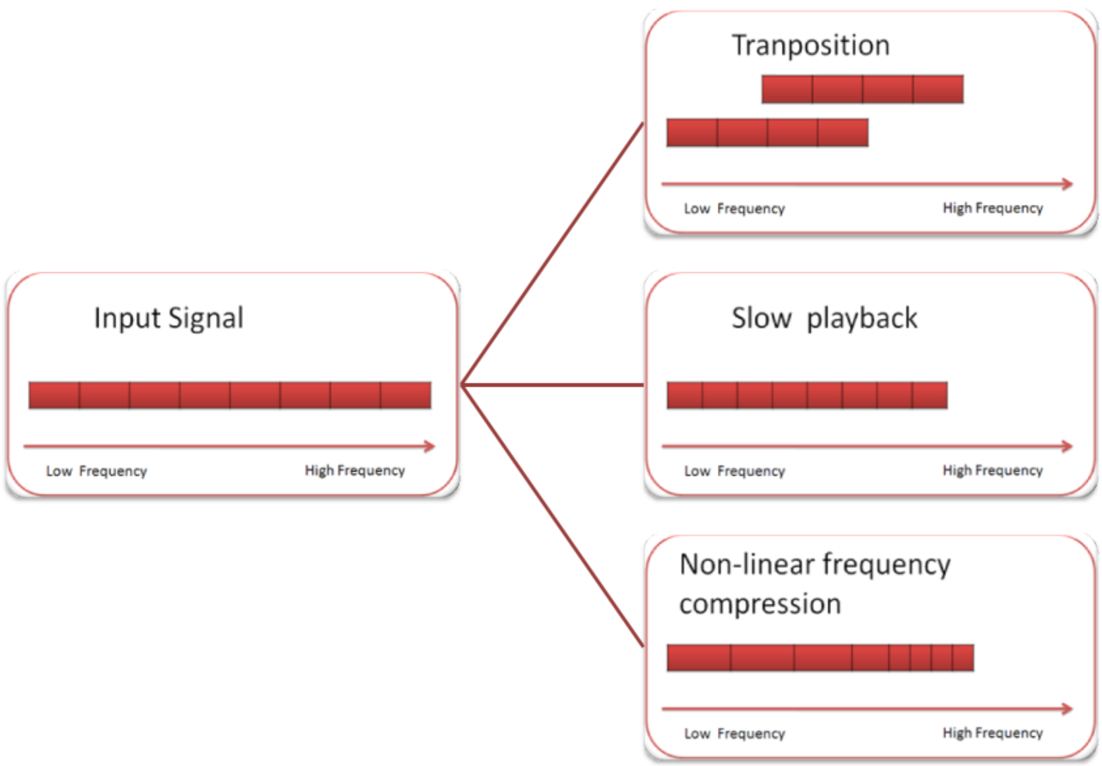
The second of such techniques is the Audibility Extender (AE) feature that transposes the unavoidable high frequency sounds to use low frequency regions. The hearing aid selects a “start” frequency, at which the AE program determines (based on the person’s stored thresholds) that aidable hearing ends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

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

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

The frequency lowering has different methods of achieving better speech identification, i.e., Slow playback, frequency transposition, and non-linear frequency compression, this is represented in Figure 2.1.

Figure.2.1. Diagrammatic representation of three methods of frequency lowering



A period of adaptation regardless of the technique used is required for realizing more benefits from such techniques. A large degree of individual variation can be expected. For reasons not fully understood, some people seem to benefit more than others. Children, perhaps because of much greater neural plasticity, seem to benefit more than adults (Ross, 2009). Other confounding variables reported in the literature include, the duration of hearing loss, and duration of hearing aid usage.

2.2. Role of NLFC in Hearing Aid on Speech Identification in Quiet and Noise

The NLFC strategy improves the speech understanding in individuals with a high frequency sloping hearing loss. This involves some amount of altering the input signal. This strategy helps in providing the high frequency components to fall within a region the low frequencies where residual hearing is better.

Nonlinear frequency lowering is one among the method of frequency lowering. In this compression of high frequency component of the incoming signal is done into a narrower bandwidth in order to maximize the use of residual low frequency hearing. Here, the high frequency elements of the incoming signal are compressed into a lower frequency range in order to maximize the use of residual low frequency hearing in individuals with a high frequency loss (Simpson, Hersbach, & McDermott, 2005).

A study to investigate the effect of NLFC on perception was conducted by Glista et al. (2009). A total of 24 participants (13 adults; 11 children) with moderate to profound sloping high frequency hearing losses took part in this study. Performance on a number of speech perception tests in quiet, including detection of /s/ and /ʃ/ and a series of phoneme recognition tasks was assessed. The testing was done in three trials, i.e., in the first trial, participants wore the hearing aid with the frequency compression disabled; in the second trial, FC was enabled; and in the third trial, where the participant can select either FC enabled or disabled. This was used for a few of weeks. The results showed that group scores in the consonant and plural recognition tasks were significantly higher when frequency compression was enabled than with conventional processing.

Group scores in the speech detection test revealed that the mean threshold at which the stimulus could be detected 50% of the time was significantly lower (i.e., better) when frequency compression was enabled than when conventional processing alone was used. Self reported preferences were also obtained, revealing that two of the adult participants favored the frequency compression setting along with seven of the child participants. Only three participants preferred the conventional setting, the rest of them showed no preference for either processing strategy.

Wolfe, John, Schafer, Nyffeler, Boretzki, & Caraway (2010) and Wolfe, John, Schafer, Nyffeler, Boretzki, Caraway, & Hudson, 2011) have reported that the use of frequency compression led to significant improvements in the perception of some high frequency speech sounds in a group of 15 children (aged 5-13 years) with moderate hearing loss. However, only group mean scores are presented so it is not possible to determine the degree of variation in benefit from frequency compression between different listeners. The results of the clinical trials mentioned above demonstrate that frequency compression may provide a significant perceptual benefit to some patients.

The perceptual performance of a number of linear and nonlinear frequency-compression schemes was evaluated by Reed et al. (1983). In a preliminary study, six subjects with normal hearing participated in experiments that investigated whether any of the schemes could improve the discriminability of consonant stimuli. Although none of the schemes provided better performance than a standard condition that applied only low-pass filtering to the stimuli, the best scheme was found to be a variant that progressively increased the amount of frequency compression for input frequencies above approximately 1200 Hz. Lower input frequencies were hardly changed by the processing.

Bohnert, Nyffeler, and Keilmann (2010) reported significant improvements in satisfaction for NLFC devices compared with their own non-NLFC devices for some self-reported measures of benefit. However, the significance of the improvements was only assessed for a subgroup of listeners who reported overall satisfaction with their NLFC device (eight out of 11 listeners), and so these findings are hard to interpret.

The majority of studies that assessed self-reported preference for NLFC over conventional processing found no significant difference in preference (Simpson, Hersbach, & McDermott, 2006; Perreau et al., 2013). However, Glista et al. (2009) found that preference for NLFC over conventional processing was significantly higher for the children that they tested, but not the adults.

The difference may also have been related to the tests used or to the duration of time that the frequency compression aid was used, which was much longer in the latter study. Another factor in which the studies differed was in their methods of determining the frequency compression settings. Specifically, when fitting the hearing aids, Glista et al. (2009) based their NLFC settings on those prescribed by the manufacturer (Phonak AG) but adjusted these settings to ensure that participants were able to correctly identify /s/ and /ʃ/ when frequency compression was enabled. If the participant was unable to identify these phonemes correctly, it was assumed that the frequency compression setting was too high and the compression ratio was reduced accordingly. Thus, the results of the different studies may not be directly comparable.

2.2.a. Role of NLFC in hearing aid on speech identification in quiet.

In a study conducted by Simpson, Hersbach, and McDermott (2005), 17 experienced hearing aid users with moderate to severe sloping hearing losses participated. All the participants had an experience of at least four to six weeks of usage of hearing aid with enabled NLFC. A recorded consonant-vowel-consonant (CVC) monosyllabic word list was used in quiet. The response was analyzed in two conditions, i.e., without frequency compression and using the experimental frequency compression scheme. They found a statistically significant ($p<0.001$) improvement of the frequency compression (FC) scheme than the conventional hearing device. In the result, even though only eight participants performed significantly better with frequency compression, but overall showed that frequency compression significantly improved detection of fricative and affricate consonants of approximately 11%, by keeping vowels and mid-frequency consonants perception intact.

The same group of authors (Simpson, Hersbach, & McDermott, 2006) investigated the effect of frequency compression on the hearing aid users with high frequency steeply sloping hearing losses. Again, the experimental devices were worn for four to six weeks and testing was conducted towards the end of the trial period. In addition to the monosyllabic word recognition task, medial consonant recognition was conducted in quiet. Results showed that there was no significant difference in group scores with and without frequency transposition in either of the tests of speech in quiet, with the group mean scores showing that frequency compression lead to a deficit in performance of 2% in the consonant recognition task and of 6% in the monosyllabic word recognition task.

The high frequency VCV recognition in quiet was done using NLFC by Ellis and Munro (2012). An inspection of the group means indicate that performance with FC enabled was better than that without FC, with a mean percentage correct of 83.3 (SD = 18.54) with FC enabled compared to 78.4 (SD = 19.82) with FC disabled. The results of a paired samples t-test confirmed that there was a significant effect of signal processing strategy on performance [$t(47) = -5.87$, $p = 0.001$]. The individual data indicate that 8 participants performed better with FC enabled than without FC, 4 participants obtained similar results (with a difference of less than 1.5%) with both signal processing strategies and none of the participants performed poorly with FC than without FC.

Glista, Scollie, Bagatto, Seewald, Parsa, and Johnson (2009) evaluated the efficacy of NLFC in children and adults with high frequency hearing loss by using speech recognition, functional performance and preference. The participants were 24 adults with hearing impairment and children with sloping high frequency hearing losses, ranging from moderately severe to profound in the better ear. The participants were familiarized with the study aid programmed with conventional processing (CP) and NLFC. Individual cut-off frequencies and compression ratios were determined based on individual preference and verified to ensure comfort, audibility and no confusion of speech sounds due to overlapping signals from frequency compression. The test battery: (1) speech sound detection of can adaptive version of the Ling's six-sound test, (2) consonant recognition using a modified version of the University of Western Ontario, Distinctive Features Differences test, (3) plural recognition, and (4) vowel recognition. All the speech tests used to record stimuli to reduce variability between tests and participants. The presentation level was varied to accommodate individual hearing losses with a testing level varying from 50 dB SPL up to 65 dB SPL for some participants. Both group-level and individual-level results were analyzed using single subject design methods due to small sample size and variability of testing levels. Contributing factors to test results of the participant were explored using multiple regression analysis.

In the group-level analysis, a repeated measures ANOVA was completed with Processor type (CP versus NLFC) and phoneme (/s/ versus /sh/) as within subject variables, and age group (adult versus children) as a between subjects variable. Significant main effects were found for the processor type as well as the phoneme type, $F(1, 22)=42.97$, $p<.001$; $F(1, 22)=6.84$, $p=.02$. Aided thresholds were lower when NFC processing was activated for both the /s/ and /sh/ phonemes, indicating that NFC tended to improve high frequency audibility.

For speech recognition, repeated measures ANOVA was performed with processor type (CP versus NLFC) and test type (consonant, plural, or vowel recognition) as within subject variables and age group (adults versus child) as a between subjects variable. The results suggest a significant interaction between test and processor type. A Bonferroni comparison was employed; analyses indicate that scores were significantly higher with NFC activated for the consonant and plural recognition tasks [$t(23)=3.40$, $p=.002$; $t(23)=5.15$, $p<.001$]. On average, high frequency speech recognition scores increased with the use of NFC, while vowel perception did not change significantly.

Wolfe et al. (2010, 2011) have reported that the use of frequency compression led to significant improvements in the perception of some high frequency speech sounds in a group of 15 children (aged 5-13 years) with moderate hearing loss. However, only group mean scores were presented so it is not possible to determine the range in benefit from frequency compression between different listeners.

Hurtig (1991) found excellent recognition of vowels by normal hearing listeners after only 15 min of practice when proportional frequency shifting was used to lower the frequency of the speech tokens. Simpson, Hersbach, and McDermott (2005) have considered 17 subjects, the majority of them having moderate to severe hearing losses. A recorded consonant vowel consonant (CVC) monosyllabic word list was used in quiet. The response was analyzed in two conditions, i.e., Using conventional device and using the experimental frequency compression scheme. They found a statistically significant ($p<0.001$) improvement of the frequency compression scheme than the conventional hearing device (CD). A similar study was reported by Hornsby et al., (2011). In their study, speech perception increased as the audibility provided increased in the high frequency region for the person with high frequency hearing loss.

Another issue of interest is the discrepancy between the results of Simpson et al. (2006) and Glista et al (2009). Simpson et al. (2006) found no benefit of frequency compression to participants with a steeply sloping hearing loss. However, Glista et al. (2009) found that participants with such a loss were the most likely to receive benefits from a frequency compression hearing aid. There are a number of possible reasons for this difference in findings. One explanation is that the discrepancy may be due to differences in the hearing aids used in the two studies, those used by Glista et al. (2009) being more technologically advanced than those used by Simpson et al. (2006). The difference may also have been related to the outcome measures used or to the duration of time that the frequency compression aid was used, which was much longer in the later study. Another factor in which the studies differed was in their methods of determining the frequency compression settings. Specifically, when fitting the hearing aid, Glista et al. (2009) ensured that participants were able to correctly identify /s/ and /ʃ/ when frequency compression was enabled. If the participant was unable to identify these phonemes correctly, it was assumed that the frequency compression setting was too high and the compression ratio was reduced accordingly.

The study by McDermott and Henshall (2010) involved eight adult cochlear implant users with hearing aid in the other ear. Moderate to profound hearing loss was checked with default frequency compression and the result showed no benefit with the frequency compression due to the contralateral cochlear implant because the implant is already giving information on high frequency.

The study by Dubno et al. (2005) reported that as the intensity increases the speech recognition reduces in person with reduced hearing loss. Bandwidth controls are not possible in case of the population with hearing impairment due to the setting used for frequency lowering due to varying audiometric configurations.

The similar results were found by Bohnert et al. (2010), Souza et al. (2013). That is, significant improvements in speech recognition for eight of the seventeen participants with the experimental NFC device was reported.

Nyffeler (2008) examined the effects of multi-channel NFC and its ability to boost speech intelligibility in individuals with high frequency hearing loss. This study

Looked at eleven participants with moderately severe to profound sensorineural hearing loss. Subjects were fitted binaurally with prototype Naida Ultra-power hearing aids with NFC turned on. Subjective comparisons of participants' own hearing instruments Versus newly fitted conventional hearing instruments were made.

A non-significant improvement in speech reception threshold was found. However, when combined with subjective findings the author felt a significant benefit from the Naida with NFC was found over the children's own hearing instruments. Subjective measures also found an acclimatization effect over a short period of time. Fricatives were reported to sound different to the participants, with sound quality ratings improving over time. Participants also rated their own voice sound quality as more pleasant with NFC 'on'. This article demonstrates support for NFC benefit. Comparison of own devices, along with lack of electroacoustic characteristics of the subjects own devices, poor and incomplete explanation of methodologies, along with a lack of sensitive testing materials are all contributing confounds which reduce the evidence of this study provide support for NFC benefit.

The results of the study showed that the use of NLFC led to significant improvements in all measures of speech perception compared to performance with conventional amplification. Measures included a consonant in a noise recognition task. In addition, this study was the first to report a significant improvement to sentence in noise recognition with the use of frequency compression. This novel finding is likely to be related to differences in the nature of the sentence stimuli used in this and earlier studies.

The difference in findings, relating to sentence in noise perception, between the present study and earlier studies may also relate to variations in the selection of frequency compression parameters. The results of the first experiment to investigate the effect of NLFC on categorical perception in listeners with normal hearing indicated that NLFC affects the identification of high frequency phonemes rather than the ability to discriminate between them. The decision to incorporate this finding into the NLFC fitting process resulted in the application of stronger NLFC settings than those prescribed by the manufacturer. It is possible that these settings facilitated greater benefit to speech in noise perception by making audible higher frequencies (important for separating speech and noise) than the prescribed setting would allow. These findings suggest that, for some individuals, it may be beneficial for clinicians to apply stronger NLFC settings than the default prescription but further research is needed to identify which listeners are likely to benefit from the application of stronger NLFC settings. However, improvements in audibility of high frequency information should be considered alongside a possible reduction in sound quality if the settings applied are too high. Further research is needed to identify which listeners are likely to benefit from the application of stronger NLFC settings and to determine the impact of stronger settings on sound quality.

The results of this study also provide preliminary evidence that NLFC may not lead to self reported improvement in benefit, even if improvements are apparent on lab-based speech measures. If this finding were replicated in a study of large scale, the implication would be that clinicians should be aware that even if a listener does not report any additional benefit from NLFC, improvements in speech perception may have actually taken place.

The study by McCreery, Brenda, Hoover, Kopun, and Stelmachowicz (2013), showed that non-word recognition was anticipated to increase as estimated bandwidth increased for all conditions in normal listeners. The benefits are reported in individuals with normal hearing.

2.2. b. Role of NLFC in hearing aid in speech identification in noise.

A study by Ellis, 2010, showed limited evidence of acclimatization, with observed changes being specific to a reduction in confusions between phonemes which were adversely affected by NLFC at the initial fitting session. There were no large decreases in the correct identification of any phoneme but changes in the pattern of confusions between some lower frequency consonants were observed, when stimuli were presented in a background of noise. The results provide no further evidence of changes over time to speech processed by NLFC. The clinical implication of this is that if a patient fails to perform well with NLFC initially, they are unlikely to obtain much additional benefit over time, at least in the first six weeks post fitting. It is possible that greater evidence of acclimatization would be seen if participants were tested after a few months of NLFC use or if different outcome measures were used.

Hopkins, Khanom, Dickinson, and Munro (2014) studied benefits of frequency compression in high frequency hearing loss participants in conventional hearing aid setting and default frequency compression setting. The results showed that there was a benefit with the consonants (formant transition) in quiet and no benefit for speech recognition in noise. The study reported that the default setting of frequency compression is not always beneficial for high frequency hearing loss.

In Nyffeler's (2008) study, subjects were asked to critically compare their own current instrument to the test instrument with sound recover (SR). In quiet, the device with SR on produced significantly increased subjective satisfaction rates. A similar picture emerged in noisy environments. The satisfaction rating after 2 weeks of use indicates that subjects needed to acclimatize to SR. Further improvements in satisfaction over time reflect the effects of acclimatization to the new hearing instrument in general and to the SR signal processing in particular.

Bohnert et al. (2010) reported that seven out of the 11 participants that they tested had improved speech recognition in noise with NLFC enabled, but they did not report whether these improvements were statistically different. Similar results were reported by Simpson, Hersbach, and McDermott (2006), where they had used CVC stimuli.

Wolfe et al. (2011) found that for children fitted with NLFC for six months, speech recognition was improved when compared with the disreputably new measure without NLFC which was taken at least six months earlier. The authors interpreted this as evidence for benefit from NLFC for speech recognition in noise. However, as acknowledged by the authors, the study did not include a control group, so it is possible that the apparent benefit from NLFC for speech recognition in noise could be attributed to auditory maturation, or simply an improvement on the test due to practice.

2.3. Role of the NLFC in Hearing Aid on Quality of Speech

The speech quality assessment was done to see the outcome by Bohnert et al. (2010). In their study, 11 adults with severe to profound hearing loss rated the speech quality on a 7-point scale. Here, also there was a benefit with the default frequency, but could not account for significant differences. They have also concluded that the default frequency compression need not provide benefit for all individuals.

McDermott and Henshall (2010) used the strongest possible frequency compression parameters, unless the participant complained about the sound quality using this setting, in which case the default setting prescribed by the fitting software was used. Parsa, Scollie, Glista, and Seelish (2013) did a study to find the effect of nonlinear frequency compression on speech as well as music sound quality for children and adult with and without hearing losses. The interaction of processing setting with hearing group indicates that the NH (Normal hearing) listeners distinguished between the sound quality changes introduced by different frequency compression settings, while the HI (Hearing impaired) listeners did not. The quality scores from NH listeners in general decreased with an increase in the amount of frequency compression, whereas HI listeners provided higher and more similar sound quality ratings for a larger range of frequency compressed stimuli. Post-hoc contrasts indicated that NH listeners provided significantly different sound quality ratings across frequency compression strength for all but two settings; while the HI listeners provided different ratings for only one third to one half of the stimuli. These results indicate that HI listeners may be less sensitive to the sound quality effects of frequency compression compared to listeners with normal hearing.

2.4. The role of SII in optimizing NLFC

The speech intelligibility index (SII) is a modified version of the articulation index (AI) (ANSI-S3.5 in 1997). This index gives information about the audibility of the speech, and it ranges from either 0-1 or 0%-100%. The SII has various applications. This includes prediction of speech identification and hearing aid selection. The SII utilizes additional correction factors such as speech level distortion (SLD; Ching, Dillon, & Byrne, 1998) and hearing loss desensitization (HLD; Sherbecoe & Studebaker, 2003) in order to improve the prediction of speech identification (ANSI – S3.5, 1997).

The SII is calculated by determining the proportion of speech information that is audible across a specific number of frequency bands and the spectrum are divided into 20 bands To determine this, comparison of the level of speech peaks to either auditory threshold or the RMS level of the noise (if present), in frequency-specific bands are done.

The proportion of audible speech, in a frequency region, is then multiplied by the relative importance of that frequency region and estimating the weighted average of the signal to noise ratio (SNRs) in each band. The SNRs in each band are weighted by the band importance functions (BIFs) which is different across speech material. Finally, the resulting values are summed across the total number of frequency bands used to make the measures and the value ranges from 0 to 1. The formula to calculate SII is given as:

$$SII = \sum_{i=1}^{n} I_i A_i$$

Where,

Ai is the band audibility. That is the proportion of the speech signal within the band, that is above the hearing threshold level or interference level (noise) whichever was higher.

Ii is the band weightage or importance. That is, the number that was related to the importance of speech frequency band to the speech intelligibility (High frequency band weightage is greater than for low frequency band).

n is the number of frequency bands (ranging from 4 to 20)

Calculation of SII is complicated, but software is readily available to simplify the computation (e.g., www.sii.to). To obtain the SII, the frequency spectrum between 100 and 9500 Hz is divided into speech bands, either by octaves, one-third octaves, or critical bands. One calculates the product of the audibility function and the frequency band importance function for each speech band and adds the resulting products together. The SII ranges from zero (no audibility of the speech spectrum) to one (full audibility of the speech spectrum). The SII may be occasionally expressed on a scale from 0 to 100 to express the percentage of accessible speech. According to the ANSI 1997 standard, a good communication system has a SII >0.75 and a poor communication system has a SII <0.45 (ANSI S3.5-1997). Critical to the study of ototoxic hearing loss, the SII has more emphasis on the high frequencies (6000 and 8000 Hz.) than the AI (Killion & Mueller, year).

The variations made in SII mainly depend on the different listening situations. These modifications made it possible in predicting speech intelligibility.

2.5. Utility of SII in optimization of hearing aid

Audibility within speech spectrum is used as a guiding principle for setting the hearing aid gain (Sandlin, 1990; Studebaker & Marincovici, 1989). Berger, 1992 as reported that AI or SII can be used to objectively select optimtimul frequency gain of the hearing aid. It helps the audiologist to decide how the hearing aid gain should be changed to increase speech recognition.

In a study by Bentler, Cole, and Wu (2011), it was reported that the SIS could be predicted by SII, with frequency lowering hearing aids. In the light of this finding, it would be interesting to investigate if SII can predict the SIS in frequency lowering hearing aids. In another study by Brennan and McCreery (2014), they have compared SII (value ranging from 0 to 100%) obtained with NLFC in a hearing aid being enabled or disabled. The SII was 12% points higher when a classroom teacher was four meters from the listener with NLFC enabled (SII = 98%) than without-NLFC condition (SII = 86%).

Thus, it would be interesting to investigate the relationship of SII with other behavioral and objective measures.

CHAPTER - 3

METHOD

The aim of the present study was to evaluate the efficacy of the Speech Intelligibility Index in optimizing the frequency compression in hearing aids for sloping sensorineural hearing loss. The process for collecting information to realize the objectives of the study followed a protocol. The information about the selection criteria of the participants, test environment, procedure of data collection and statistical analysis is given in detail.

3.1. Participants

The data were collected from 14 ears of 9 participants with sloping hearing loss from moderate to severe. The participants who satisfied the inclusion criteria were included in the study.

3.1.1. Inclusion criteria.

Participants with sloping sensorineural hearing loss in either one or both ears were considered. In the study, sloping is defined as thresholds occurring at equal or successively higher levels from 250 Hz to 8000 Hz and the difference between the thresholds at 250 Hz to 8000 Hz is greater than 20 dB (Pittman & Stelmachowicz, 2003). The degree of hearing loss ranged from moderate to severe degree, with the threshold at 2000 Hz not exceeding 70 dBHL. The participants had post-lingually acquired hearing impairment. They were in the age ranging from 20 to 60 years. The participants were native speakers of Kannada language and naïve hearing aid users.

Written consent was taken from the participants before starting the test and ethical committee guidelines were followed.

3.1.1. Exclusion criteria.

The participants with other otological, neurological, cognitive or psychological problems were not included in data collection. The cognition deficits and speech-language deficits were ruled out by administering questionnaire, Mini Mental Status Examination (MMSE; Kurlowicz & Wallace, 1999).

3.2. Test Environment

All the testing was carried out in an air-conditioned, sound treated double room, with the permissible limits of ambient noise levels within permissible limits

3.3. Instrumentation

- A calibrated 0^0 Azimuth diagnostic sound field audiometer Madsen ORBITER 922 (version 2) was used to evaluate the hearing, aided performance and speech identification scores. The loudspeaker was located at. The participant was made to sit one meter away from the loudspeaker (Martin Audio, London-C 115).

- A calibrated immittance meter (GSI Tympstar, version-2) was used to rule out the presence of the middle ear pathology. Tympanometry performed using 226 Hz probe frequency, sweeping pressure from +400 to -200 daPa. Acoustic Reflexes were measured and were present at least in one of the four frequencies.

- The commercially available digital BTE hearing aid with frequency compression (sound recover feature) facility having six channels, with gain up to 75 dB was used. The frequency of Non-linear Frequency Compression (NLFC) ranged from 1.5 kHz to 6 kHz. The NLFC could be either enabled or disabled.

- A personal computer with NOAH-3 software and hearing aid specific software connected to the Hearing Instrument Programmer (HI-PRO) interface was used to program the digital BTE hearing aid. The programming was done based on the hearing threshold with NAL- NL1 fitting formula with an acclimatization level of 2. The hearing aid verification was performed using the insertion gain measurement system, Affinity 2.0, by considering the prescriptive formula NAL-NL1.

- Using the Affinity 2.0, insertion gain measurement was performed for the verification of gain, with an input level of 60 dB SPL, according to NAL-NL1 formula. The verification of gain was done for the hearing aid without NLFC feature.

- The SII was computed using a computer software program (Manjula, 2008). Here the aided thresholds at nine frequencies, i.e., 250 Hz, 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz, were considered to find out the predicted speech intelligibility.

- Fonix 7000 real ear measurement instrument was used for finding out the output of the hearing aid in all three hearing aid programming conditions. The digispeech was used as stimulus at the level of 60 dB SPL in a HA2 coupler.

3. 4. Test Material

- Recorded PB word lists in Kannada for adults developed by Manjula, Kumar, Geetha and Anthony (2013) was used for SIS and SNR-50 in three aided conditions. Each list consisted of 25 words.
- Recorded Monosyllable PB list (Mayadevi, 1974) having 20 monosyllables was used to find out speech identification scores in all three aided conditions. The recording of monosyllable list was done by a native Kannada female speaker with normal voice effort. A condenser microphone was used for recording, along with audio interface MOTU Microbook II. The recording done in a soundproof room, microphone placing at 6-7 cm away from the mouth of the speaker. The recorded material was normalized using Adobe Audition 3.0.
- Recorded in high frequency (HF) word list (Mascarenhas, 2001) was used for finding out speech identification scores in all three aided conditions.
- The recorded Kannada story sample of 300 words of a female speaker is used for assessment of the quality of speech. The six parameters of quality were considered, i.e., Loudness, Clearness, Sharpness, Fullness, Naturalness and Overall impression. The ten-point rating scale ranging from 0 to 10 was used very poor to excellent except for Loudness parameter. For the Loudness parameter the rating scale considered is from 0 to 10 representing no speech sound to the most comfortable speech level.

3.5. Procedure

The procedure included two stages – Stage I and Stage II.

Stage I involved selection of participants and programming the digital BTE in three different conditions / modes, i.e., conventional frequency bandwidth, default frequency compression and optimized frequency compression. The programming involved Insertion Gain (IG) measurement for verification of programming of the hearing aid.

Stage II involves collection of data for the purpose of the study. The data included aided thresholds, speech identification score (SIS) in quiet, speech reception in noise (SNR-50), speech quality judgement and speech intelligibility index (SII).

3. 5. 1. Stage I.

The participants were selected based on pure tone audiometry, speech audiometry and immittance evaluation. Whenever possible, reflex decay was measured at one frequency or STAT has done to rule out the presence of retro-cochlear pathology. The participants satisfying the inclusion criteria were considered for the study. The steps involved Stage I were as follows:

1. Hearing aid programming was done by providing the NAL NL-1 as a prescriptive formula with acclimatization level 2. The first aided condition was conventional frequency response with NLFC disabled (Program 1). The gain is optimized by asking five questions to the participants in live voice and verified with the insertion gain measurement.

2. In the second, aided condition, the hearing aid was programmed with NLFC feature enabled in default settings (Program 2). This was done by enabling sound recover option in the fitting screen and the compression ratio was also programmed to default setting as determined by the fitting software provided by the manufacturer.
3. In the third, aided condition, the hearing aid was programmed with NLFC feature is enabled in optimized settings (Program 3). For optimizing the frequency compression, audibility of the /s/ and / ʃ/ sounds were produced in live voice. The cut-off frequency of sound recovery and the ratio were varied till the participant repeated the sibilants correctly.
4. *Insertion gain measurement:* Otoscopy was done before placing the probe tube to rule out any contraindication for the real ear measurement. The insertion gain measurement is selected for the measurement, real ear target curve as prescribed by the non-linear prescriptive formula recommended by NAL-NL1 was obtained. Prior to initiating the measurement, calibration of the system was ensured. Tube calibration was performed as the instruction given by the software.

Later, the participant was made to sit around 30 cms away from the loudspeaker. The stimulus is presented at 0^0 Azimuth with the intensity level of 60 dB SPL for obtaining the real ear unaided response (REUR) and real ear aided response (REAR). The measurement of the REAR was done at 60 dB SPL level and the gain matched with that of the target curve of the REAR. The gain where the REAR curve approximates the target curve was considered for verification of hearing aid programming.

3. 5. 2. Stage II.

The details of various measures for data collection in the three aided conditions are given below.

3. 5.2. Stage II. Aided threshold measurement.

The participant was made to sit one meter away from the loudspeaker kept at 0^0 azimuth. He/she was instructed to listen to the warble tone and raise the finger as soon as they hear, even when they hear the soft sound. They were asked to pay attention for the faint sound also.

The warble tone was presented at 45 dBHL through the loudspeaker of the audiometer. The level was adjusted to find out the minimum level at which the participant responded at each of the nine test frequencies. The bracketing method is followed in considering the threshold. That is, a +5 dB and -10 dB steps were used. Two positive responses out of three presentations at a minimum level was considered as the threshold at a particular test frequency.

The hearing thresholds for warble tones were measured in the unaided and three aided conditions (P1, P2, and P3). The thresholds were obtained at 500 Hz, 750 Hz, 1000 Hz, 2000 Hz, 3000 Hz 4000 Hz and 6000 Hz. Later these thresholds in the three aided conditions were used for computation of speech intelligibility index (SII). This procedure was repeated for each test ear.

3. 5. 2. Stage II. Speech identification scores in quiet.

The recorded PB word lists in Kannada for adults (Manjula et al., 2013), Monosyllable PB list (Mayadevi, 1974) and high frequency word list (Mascarenhas, 2001) were presented separately, in quiet condition, through the laptop connected to the auxiliary input of the audiometer.

1. The stimuli were presented through the loudspeaker of the audiometer from 0^0 Azimuth at a distance of 1 meter from the head of the participant.
2. The recorded speech material was presented at 45 dBHL in the sound field of the audiometer. The level of speech was monitored through VU meter.
3. The participants were instructed to listen to each word carefully and repeat them back.
4. The number of words correctly repeated was considered by asking for repetition mode.
5. The scoring was done based on the number of words repeated correctly out of the total number of words being presented. This was considered as the Speech Identification Score (SIS). That is the number of words repeated correctly out of 25 words in high frequency word list, out of 25 words in the PB word list and 20 monosyllables from the monosyllable list.
6. The SIS for each type of speech material was obtained in three aided conditions, for each test ear.

3. 5.2. Stage II. Assessment of Quality of speech.

The recorded Kannada story was presented at 45 dB HL through the loudspeaker of the audiometer kept at 0 degree Azimuth and at a distance of 1 meter. The presentation is done in quiet condition and the participant is instructed to listen to the full story. Later the participant is asked to rate the intelligibility of the speech in terms of six parameters of quality, as very poor, poor, fair, good, very good and excellent in a 6 point rating scale from 0 to 10 in increasing order respectively except for Loudness parameter. For the Loudness parameter the rating scale considered as

0 - No speech sound

2- Very soft speech sound

4- Soft speech sound

6- Moderate level speech sound

8- Comfortable speech level

10- the most comfortable speech level.

And also the rating between two points are allowed if the participant feels so.

The speech qualitative judgement was done at the end of the stimulus presentation for each of the three aided conditions. The rating was done for each condition.

3. 5. 2. Stage II. Measurement of SNR-50.

Speech is presented at a constant level, i.e., at 45 dBHL, in the presence of varying levels of speech noise. The signal to noise ratio (SNR) required for 50% performance is termed SNR-50 (Killion, Niquette, & Gudmundsen, 2004). For example, if a participant requires about + 3 dB SNR (i.e., target speech 3 dB louder than the background speech noise) to correctly repeat 50% of the key words, then the SNR-50 is +3dB. The recorded Kannada PB word list for adults was used as stimulus to obtain the SNR-50.

The participant was instructed that the stimulus would be presented through the loudspeaker along with noise. The participant was asked to concentrate on the speech stimulus and repeat the words which are heard in the presence of noise. The procedure for SNR-50 is given below.

1. The level of speech, through the audiometric loud speaker kept in front of the speaker (0^{o} Azimuth at 1 m distance); was kept constant at 45 dB HL. The PB word list developed by Manjula, Kumar, Geetha, and Anthony (2013) was used. The initial level of speech noise presented through the same loudspeaker, was set at 30 dB HL.
2. The level of speech noise was increased, in 5-dB steps, till the participant repeated two out of four (i.e., 50%) words being presented.

3. From this level, the speech noise was varied in 2 dB steps in order to obtain a more precise level of speech noise at which 50% of the words were correctly repeated.
4. At this point, the difference in intensity of speech and the intensity of speech noise, in dB, was noted as the SNR-50.

The value of the SNR-50 in each of the three aided conditions, for each test ear, was tabulated.

3. 5. 2. Stage II. Computation of SII.

The calculation of the speech intelligibility index (SII) was done using the software program (Manjula, 2008) based on the procedure derived from those adopted by Popelka and Mason (1987) and Pavlovic (1991). To obtain this, the aided thresholds at frequencies 250 Hz, 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz were obtained for three aided conditions. The SII was calculated by feeding the aided thresholds into the software program written on an Excel spread sheet. The SII incorporate

The SII was calculated by using the software:

$$\textbf{SII} = \sum_{i=1}^{n} Ii\ Ai$$

Here, *I* represent frequency band, *and* represents the number of frequency bands included in the summation. Ii and Ai represent the importance and audibility coefficients for each frequency band, which were multiplied and summed to produce a single value of SII, varying from 0 to 1. An SII of 0 indicates that none of the speech signal is audible and 1 represents a speech signal is fully audible to the listener. Further, the correction factors such as hearing loss desensitization (HLD) (Sherbecoe & Studebaker, 2003) and speech level distortion (SLD) (Ching, Dillon, & Byrne, 1998).

The overall SPL values and output of the hearing aid was measured using Fonix 7000 instrument.

- The hearing aids were programmed for the different conditions.
- The hearing aid was connected to one end of the HA-2 2cc coupler, the other end of the HA2 coupler was connected to the microphone of the instrument.
- The hearing aid microphone was placed in the reference position in the sound box.
- The digispeech was used as a signal and was presented at 60 dBSPL through the loudspeaker in the sound box.
- The measured output of the hearing aids was displayed on the screen. The overall SPL value as well as the output values at different frequencies was measured.
- These values were utilized for entered for the calculation of SII_{SLD}.
- The measurements were done for all three aided conditions.

The SII was computed by feeding the aided threshold as well as the output SPL values of frequencies 250 Hz, 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 6000 Hz. The SII values were calculated automatically as the data was entered into the SII excel sheet.

The SII values were calculated for three aided conditions and the values were compared with the subjective methods in quiet and noise as well as with the qualitative measurement In addition, prediction of speech intelligibility from SII was also investigated.

The data were obtained and tabulated. Statistical analysis was performed using the software, i.e., Statistical Package for Social Sciences or SPSS (version-17) for calculation of descriptive statistics (mean, standard deviation, median and range) were calculated for SIS for monosyllables list, PB word list, HF word list, SNR -50, speech quality parameters and SII.

The repeated measures ANOVA was done to compare significance different across aided conditions, if the significant difference was observed in all three conditions the post-hoc Boferroni test was performed for pair-wise comparison. The non-parametric, Friedman test was performed on SNR-50 and speech quality rating in order to know if the aided conditions differed significantly. If the significance different found, then post-hoc test Wilcoxon was carried out to see which pair was significantly different from each other. The correlation was performed by using Pearson and Spearman correlation for analyzing the relationship between speech identification in quiet and noise with SII, and speech quality with SII.

CHAPTER - 4

RESULTS AND DISCUSSION

The aim of the present study was to evaluate the effect of non-linear frequency compression (NLFC) on intelligibility and quality of speech. To realize this, the data were collected on speech identification and quality. This was done in three aided conditions, i.e., without NLFC, with NLFC in default setting, and with NLFC in optimized setting. Statistical analysis was performed using the Statistical Package for Social Sciences (SPSS for Windows, version 20). The results have been presented under the following headings.

4.1. The effect of the NLFC in hearing aid on speech identification in quiet and noise

4.2. The effect of the NLFC in hearing aid on quality of speech

4.3. Comparison of speech identification (in quiet and noise) and quality with SII

4.4. Comparison of the performance on speech identification and quality in three aided conditions

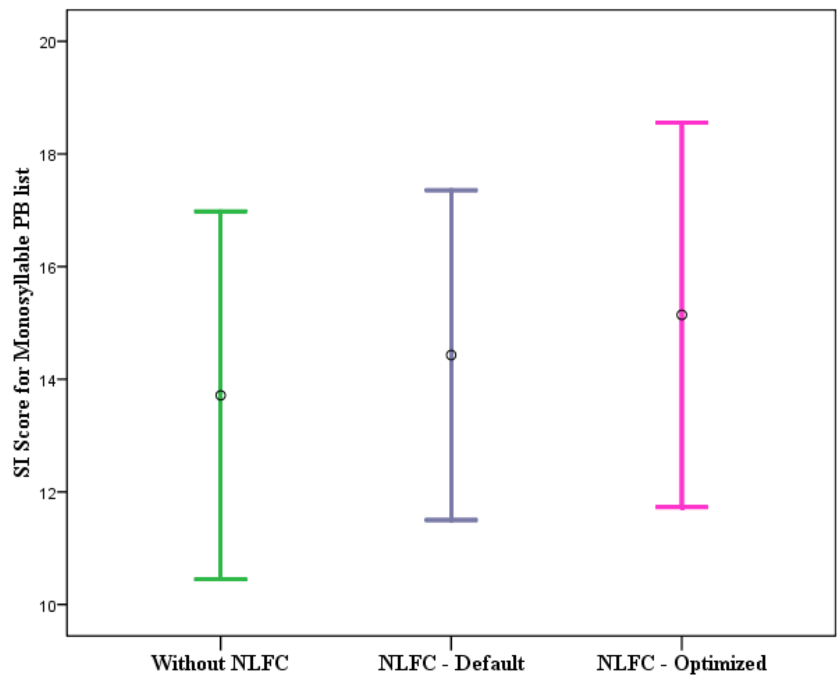
4.5. Comparison of the performance on speech quality in three aided conditions

4.1. Effect of the NLFC in Hearing Aid on Speech Identification in Quiet and in Noise

The data on speech identification (SI) for monosyllables, PB word lists, and high frequency word list in quiet were collected in the three aided conditions, i.e., hearing aid without NLFC feature, hearing aid with NLFC set to default condition and the hearing aid set to NLFC in the optimized condition. The mean and standard deviation (SD) of the

SIS in three aided conditions for monosyllable list are represented using Error bar graph in Figure 4.1. The maximum score for SIS using the monosyllables is 20.

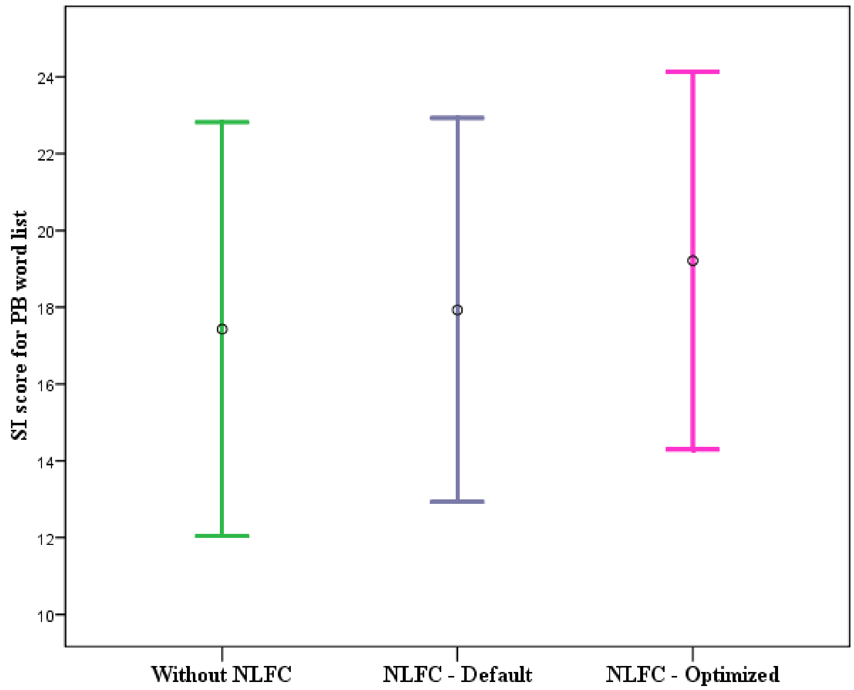
Figure.4.1. Mean and SD of SIS in three aided conditions for monosyllables



As shown in the Figure.4.1, the mean and SD of SIS was13.71 ± 3.27 in the aided condition without NLFC; 14.43 ± 2.93with NLFC-Default condition; and 15.14 ± 3.42 with NLFC-Optimized condition. The SIS ranged from 9 to19 in without NLFC; 11 to19 in NLFC in default; and 8 to 20 in NLFC optimized conditions.

The Mean and SD of SIS in three aided conditions for the PB word list has shown in the Figure.4.2.The maximum score for SIS using the PB list is 25.

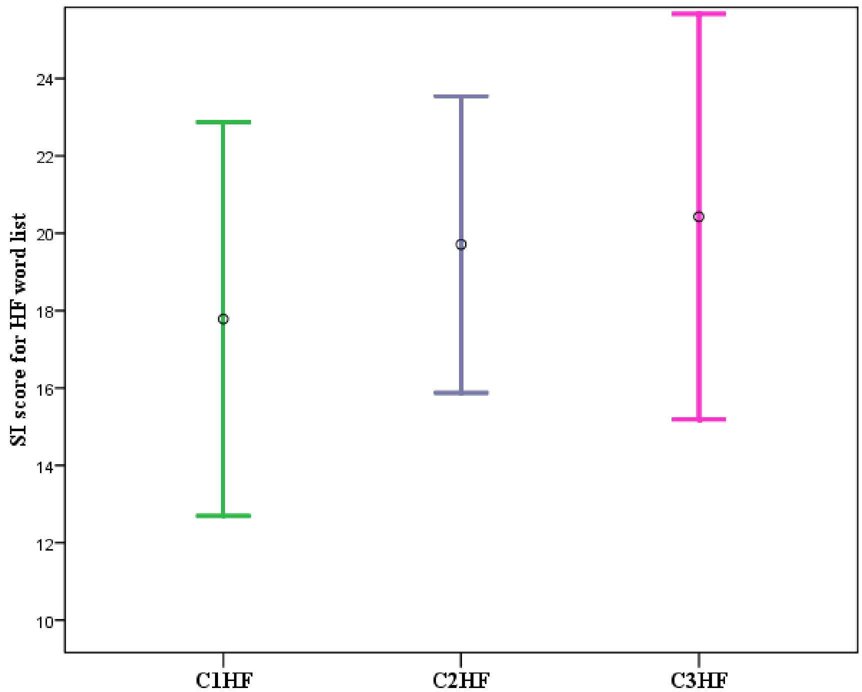
Figure.4.2. Mean and SD of SIS in three aided conditions for PB word list



As shown in the Figure 4.2, the mean and SD of SIS were 17.43 ± 5.39 in the aided condition without NLFC; 17.93 ± 5 with NLFC-Default condition; and 19.21 ± 4.92 with NLFC-Optimized condition. The SIS ranged from 7 to 23 in without NLFC; 8 to 23 in NLFC in default; and 12 to 25 in NLFC optimized conditions.

The mean and SD of SIS in three aided conditions for HF word list has shown in the Figure.4.3. The maximum score for SIS using HF word list is 25.

Figure.4.3.Mean and SD of SIS in three aided conditions for HF word list

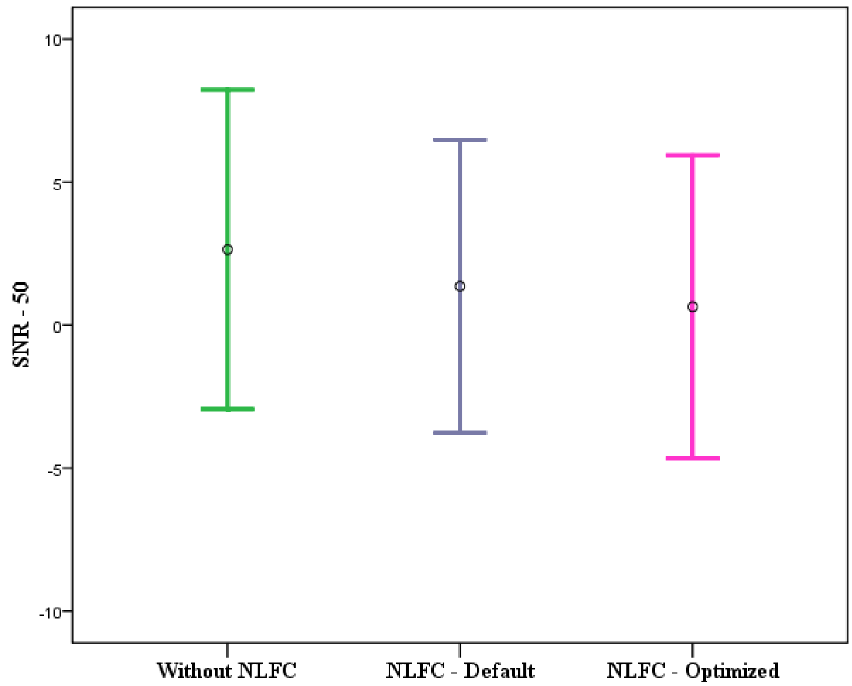


As shown in the Figure.4.3, the mean and SD of SIS were 17.79 ± 5.09 in the aided condition without NLFC; 19.71 ± 3.83 with NLFC-Default condition; and 20.43 ± 5.24 with NLFC-Optimized condition. The SIS ranged from 7 to 24 in without NLFC; 13 to 24 in NLFC in default; and 8 to25 in NLFC optimized conditions.

From Figures 4.1, 4.2 and 4.3, it can be noted that the speech identification improved as the aided conditions moved from NLFC disabled to default to optimized. This same pattern was noted for SIS in quiet for monosyllables, PB word lists, and high frequency word lists. The SD of the SIS in quiet condition overlapped. In order to know if there was any significant difference between the SIS in the three aided conditions differed significantly, repeated measures ANOVA was done. This is given in details later.

The data on speech identification in noise, i.e., SNR-50 was analyzed. Figure 4.4 depicts the mean and SD of the SNR-50 in the three aided conditions.

Figure.4.4. Mean and SD of SNR-50 values in three aided conditions



In Figure.4.4, the mean and SD of SNR-50 in the three aided conditions is shown. As can be seen in the Figure.4.4, the mean and SD were 2.64 ± 5.58 in without NLFC condition; 1.36 ± 5.12 in NLFC-Default; and 0.64 ± 5.3 in NLFC-Optimized condition. The SNR-50 ranged from -5 to 14 without NLFC, -7 to 11 in NLFC-Default; and -7 to 11 in NLFC-Optimized condition.

The SNR-50 reduced as the aided conditions moved from NLFC disabled to default to optimized. Here, it should be noted that lesser the value of SNR-50 (i.e., the individual performs well even when the difference between the noise and speech is less) or more negative the value of SNR-50 (i.e., when the noise level is higher than the speech level), better is the performance.

4.2. Effect of the NLFC in Hearing Aid on Quality of Speech

The data on quality of speech was assessed for six parameters, i.e., loudness, clearness, sharpness, fullness, naturalness and overall impression were tabulated for analysis. The rating of each of these parameters was done from 0 to 10; where 0 represents 'very poor' and 10 represents 'excellent'. However, for Loudness parameter, the rating ranged from the 0 representing 'no speech heard' to 10 being 'most comfortable level'. The mean, SD, median and range of the rating on six parameters of quality, in three aided conditions, are tabulated in Table.4.

Table.4.1

Mean, SD, median and range of rating on six parameters of quality, in three aided conditions

Parameters of Quality	*Aided Conditions*	*Rating (Range:0-10)*		
		Mean ± SD	*Median*	*Range*
Overall Impression	Without NLFC	6.79 ± 1.48	7.00	4 – 9
	NLFC-Default	6.93 ± 1.73	7.50	3 – 9
	NLFC-Optimized	7.43 ± 1.45	8.00	4 – 10
Loudness	Without NLFC	6.43 ± 1.79	6.00	3 – 9
	NLFC-Default	6.79 ± 1.85	6.50	3 – 10

	NLFC-Optimized	6.71 ± 1.54	6.50	4 – 9
Clearness	Without NLFC	6.43 ± 1.87	6.00	3 – 10
	NLFC-Default	6.50 ± 1.40	6.00	3 – 8
	NLFC-Optimized	7.21 ± 1.53	7.50	4 – 10
Sharpness	Without NLFC	6.21 ± 1.53	6.00	4 – 8
	NLFC-Default	6.50 ± 1.79	6.00	3 – 10
	NLFC-Optimized	6.71 ± 1.27	7.00	4 – 8
Fullness	Without NLFC	6.07 ± 1.82	6.00	3 – 10
	NLFC-Default	6.36 ± 1.78	6.00	2 – 9
	NLFC-Optimized	6.71 ± 1.77	6.00	3 – 10
Naturalness	Without NLFC	6.57 ± 1.60	6.00	4 – 9
	NLFC-Default	7.00 ± 1.70	7.50	3 – 9
	NLFC-Optimized	7.29 ± 1.44	8.00	4 – 9

As can be noted in Table 4.1, the rating on most of the parameters of quality showed an improvement, as the conditions moved from without NLFC to NLFC-Default to NLFC-Optimized.

4.3. Comparison of Speech Identification (in Quiet and in Noise) and Quality with SII

The mean and SD of SIS, SNR-50, quality rating, and SII are given in Table 4.2. The value of SII ranged from 0 to 1.

Table.4.2.

Mean, SD, median and range for without NLFC, NLFC – Default and NLFC – Optimized aided conditions

	Without NLFC			NLFC-Default			NLFC-Optimized		
	Mean ± SD	Median	Range	Mean± SD	Median	Range	Mean ± SD	Median	Range
					SIS				
Monosyllable (Range=0-20)	13.71 ± 3.27	13	9-19	14.43±2.9	14	11-19	15.14 ±3.42	15	8-20
PB word list (Range=0-25)	17.43 ± 5.39	20.5	7-23	17.93 ± 5	20.5	8-23	19.21 ±4.92	22	12-25
HF word list (Range=0-25)	17.79 ± 5.09	19.5	7-24	19.71±3.8	21.5	13-24	20.43 ± .24	23	8-25
					SNR-50				
SNR-50	2.64 ± 5.58	2.5	-5 – 14	1.36 ±5.12	1.5	-7 – 11	0.64 ± 5.3	1	-7 – 11
					Quality rating				
Loudness	6.43 ± 1.79	6.00	3 – 9	6.79 ± 1.85	6.50	3 – 10	6.71 ± 1.54	6.50	4 – 9
Clearness	6.43 ± 1.87	6.00	3 – 10	6.50 ± 1.40	6.00	3 – 8	7.21 ± 1.53	7.50	4 – 10
Sharpness	6.21 ± 1.53	6.00	4 – 8	6.50 ± 1.79	6.00	3 – 10	6.71 ± 1.27	7.00	4 – 8
Fullness	6.07 ± 1.82	6.00	3 – 10	6.36 ± 1.78	6.00	2 – 9	6.71 ± 1.77	6.00	3 – 10
Naturalness	6.57 ± 1.60	6.00	4 – 9	7.00 ± 1.70	7.50	3 – 9	7.29 ±1.44	8.00	4 – 9

Overall Impression	6.79 ± 1.48	7.00	4 – 9	6.93 ± 1.73	7.50	3 – 9	7.43 ± 1.45	8.00	4 – 10
				SII value					
SII	0.76 ± 0.07	0.76	0.60-0.89	0.78 ± 0.07	0.80	0.61-0.88	0.79 ± 0.07	0.80	0.63- 0.89

From the Table.4.2, it can be observed that the SII values are showing an improvement as the aided condition changed from without NLFC to NLFC-Default to NLFC-Optimized. Further, comparison of the dependent variables such as SIS in quiet, SNR-50, quality and SII was performed using repeated measures ANOVA and correlation analysis.

4.3.1. Comparison of SII in three aided conditions.

From the present study (Table 4.2), it can be noticed that the mean SII value is highest with NLFC-Optimized condition, followed by NLFC-Default condition and then by the condition without NLFC. In order to know if this difference in the mean SII values between the three aided conditions is significant, repeated measures ANOVA was done. The result showed a significant effect of the aided condition, $F(2, 26) = 19.48$, $p < 0.05$. In order to know the aided condition that brought about the significant difference, pair-wise comparison was done using post-hoc Bonferroni test. It was found that the mean SII without NLFC condition was significantly different from that of NLFC-default condition ($p = 0.001$) and NLFC-Optimized condition ($p = 0.000$). However, though the mean SII of the NLFC-default condition was lower than that of NLFC-Optimized condition, it was not significantly different ($p = 0.067$).

From this, it is inferred that the NLFC-Optimization would bring about better performance compared to NLFC-Default condition. This fact is reflected in the SIS scores which are best in the NLFC-Optimized condition. Hence, from the present study it can be construed that there is a necessity to provide optimized NLFC for better perception of speech.

This is supported in a study by Brennan and McCreery (2014), where they have compared SII (value ranging from 0 to 100%) obtained with NLFC in a hearing aid being enabled or disabled. The SII was 12% points higher when a classroom teacher is four meters from the listener with NLFC enabled (SII = 98%) than without-NLFC condition (SII = 86%).

4.3.2. Comparison of speech identification (in quiet and in noise) and quality with SII in three aided conditions.

The Pearson's correlation was carried out to compare SII with Monosyllable PB list, PB word list, and HF word list. For comparison between SII with SNR-50 and parameters of quality rating, the Spearman correlation was carried out.

4.3.2.1. Comparison of speech identification in quiet with SII.

The Pearson's correlation of SII with SIS obtained in three aided conditions was done in quiet. This is given in Table.4.3.

Table.4.3.

Pearson's correlation of SII with SIS in three aided conditions, in quiet

		Pearson's Correlation	
	Monosyllable PB list	R	P
SII v/s SIS	Without NLFC	0.424	0.131
	NLFC-Default	0.554*	0.040
	NLFC-Optimized	0.518	0.058
	PB word list		
SII v/s SIS	Without NLFC	0.358	0.209
	NLFC-Default	0.584*	0.028
	NLFC-Optimized	0.366	0.198
	HF word list		
SII v/s SIS	Without NLFC	0.575*	0.031
	NLFC-Default	0.479	0.083
	NLFC-Optimized	0.577*	0.031

Note: * = significant difference at $p < 0.05$

Table.4.3 depicts that there is a positive moderate correlation between the SII and SIS, in most of the aided conditions. This correlation was significant only for the aided condition in which the hearing aid was set to default setting for monosyllables and PB word list; and for optimized condition for HF word list. Thus, from the results of the present study, it is implied that the SII and the speech recognition score depend highly upon the type of the speech material used.

In a study by Bentler, Cole, and Wu (2011), it was reported that the SIS could be predicted by SII, with frequency lowering hearing aids. In the light of this finding, it would be interesting to investigate if SII can predict the SIS in frequency lowering hearing aids.

4.3.2. 2. Comparison of speech identification in noise with SII.

The correlation of the SII values with the speech recognition in noise was investigated for all three aided conditions. The correlations are tabulated in the Table.4.4.

Table.4.4.

Spearman correlation of SII with Speech recognition in noise

		Spearman's correlation	
		Rho	P
SII v/s SNR-50	Without NLFC	-0.529	0.052
	NLFC-Default	-0.451	0.105
	NLFC-Optimized	-0.39	0.168

Note: * = significant difference at $p < 0.05$

From Table 4.4, it can be observed that there is a negative moderate correlation between the SII and the SNR-50. This implies that as the SII increased, the SNR-50 reduced indicating a better performance in noise. However, this moderate correlation was not significant.

4.3.2.3. Comparison of speech quality with SII.

The correlation of the SII values with the speech quality rating was evaluated for all the three aided conditions. The correlations are tabulated in the Table.4.5.

Table.4.5.

Spearman correlation of SII with Speech Quality

Speech Quality		Spearman's Correlation	
		Rho	P
SII v/s Overall Impression	Without NLFC	0.322	0.261
	NLFC-Default	0.452	0.105
	NLFC-Optimized	0.602*	0.023
SII v/s Loudness	Without NLFC	0.408	0.147
	NLFC-Default	0.434	0.121
	NLFC-Optimized	0.430	0.125
SII v/s Clearness	Without NLFC	0.417	0.138
	NLFC-Default	0.108	0.714
	NLFC-Optimized	0.408	0.148
SII v/s Sharpness	Without NLFC	0.585*	0.028
	NLFC-Default	0.397	0.160
	NLFC-Optimized	0.393	0.165

SII v/s Fullness	Without NLFC	0.441	0.115
	NLFC-Default	0.408	0.147
	NLFC-Optimized	0.267	0.357
SII v/s Naturalness	Without NLFC	0.506	0.065
	NLFC-Default	0.487	0.077
	NLFC-Optimized	0.513	0.061

Note: * = significant difference at $p < 0.05$

The individual parameters of quality were not significantly correlated with SII for all the conditions considered, except that the overall impression of quality and sharpness of perception had a significant correlation with SII.

4.4. Comparison of the Performance on Speech identification in three aided conditions

The comparison of mean SIS for the monosyllables PB list, PB word list and HF word list in quiet was performed using repeated measures of ANOVA. Later Bonferroni post-hoc test was conducted to see if there was a significant difference between the three conditions. I.e., without NLFC, NLFC-Default, and NLFC- Optimized conditions Similarly, nonparametric Wilcoxon's test was done for SNR-50 to see the significant difference between the three conditions.

4.4.1. Comparison of the performance on speech intelligibility in quiet for three aided condition.

From Figures 4.1, 4.2, and 4.3, the mean and SD of SIS for the monosyllables, PB word list, High Frequency word list, and PB word list in quiet reflect slight changes in values of SIS. To know if these variations between the aided conditions were significant, repeated measures ANOVA was. It was seen that there was a significant difference between the aided conditions for monosyllables [$F (2, 26) = 4.19$, $p < 0.05$], PB word list [$F (2, 26) = 6.59$, $p < 0.05$] and HF word list [$F (2, 26) = 8.33$, $p < 0.05$].

As there was s significant difference in all the three conditions, the post-hoc Bonferroni test was performed for pair-wise comparison. The SIS in the aided condition without NLFC condition was significantly lesser than that in NLFC-Optimized condition for all the types of speech material, i.e., for monosyllables ($p= 0.031$), PB word list ($p=0.004$) and HF word list ($p=0.000$).

There was a significant difference between the SIS in NLFC-default condition from NLFC-Optimized condition for PB word list ($p=0.030$). The NLFC-default condition is not significantly different from NLFC-Optimized condition for monosyllables ($p = 0.117$) and HF word list ($p = 0.377$).

There was a significant difference between the SIS without NLFC condition from NLFC-Default condition ($p=0.015$) for HF word list. And there was no significant difference for monosyllables ($p = 0.136$) and PB word list ($p = 0.325$) in the SIS.

In the present study, the improvement in speech identification showed for optimized NLFC over without NLFC. There was an improvement of speech identification for optimized NLFC over default setting of NLFC for Monosyllables and HF PB word list. The default NLFC also improves the speech identification over without NLFC for PB word list. So, for the better speech recognition, the optimized NLFC will be useful for individuals with sloping sensorineural hearing loss.

A similar study was done by Shruthi (2009), where the fine tuning NLFC (where the start frequency selected based on /s/ and /ʃ/ sound discrimination) showed improvement in word as well as in sentences in person with cochlear dead region. And also ling six sound identification maximum score for fine tuning NLFC.

In the study by Simpson, Hersbach, and McDermott (2005), a recorded consonant-vowel-consonant (CVC) monosyllabic word list was used in quiet. The response was analyzed in two conditions, i.e., without frequency compression and using the experimental frequency compression scheme. They found a statistically significant ($p<0.001$) improvement for the frequency compression (FC) scheme than the conventional hearing device.

The study by Munro and Lutman (2003) used high frequency VCV recognition in quiet. An inspection of the group means indicate that performance with FC enabled was better than that without FC, with a mean percentage correct of 83.3 (SD = 18.54) with FC enabled compared to 78.4 (SD = 19.82) with FC disabled.

Glista, Scollie, Bagatto, Seewald, Parsa, and Johnson (2009) evaluated the efficacy of NLFC in children and adults with high frequency hearing loss. Individual cut-off frequencies and compression ratios were determined based on individual preference and verified to ensure comfort, audibility and no confusion of speech sounds due to overlapping signals from frequency compression. A Bonferroni correction was employed; analyses indicate that scores were significantly higher with NFC activated for the consonant and plural recognition tasks [$t(23) = 3.40$, $p=.002$; $t(23) = 5.15$, $p<.001$]. On average, high frequency speech recognition scores increased with the use of NFC, while vowel perception did not change significantly.

The study by Simpson, Hersbach, and McDermott (2006) examined the performance of an NFC device in quiet and noisy conditions by comparing speech-understanding abilities of seven hearing impaired listeners with steeply sloping hearing losses. No statistically significant differences were found between the NFC and the CP devices (p=.186), although a significant interaction term was present. Therefore, subject data was analyzed separately with pair-wise comparisons using the Holm-Sidak method. The authors concluded that listeners with steeply sloping audiograms received limited benefit from the experimental NFC scheme. Many of the subjects presented with very severe hearing losses, consistent with significant dead regions throughout the cochlea; however, no dead region testing was performed in this study. The use of NAL-NL1 as a fitting strategy for these individuals likely reduced high frequency gain, possibly even with NFC enabled. Cut-off frequencies were not employed based on individual reference, but set to a strong setting and scaled back if subject dissatisfaction occurred. Therefore, this study does not support the use of NFC for subjects with steeply sloping audiograms.

Simpson, Hersbach and McDermott (2006) the individual data showed that 9 participants performed better with FC enabled than without it and 2 participants performed more poorly with FC when compared to their performance in the No FC condition.

4.4.2. Comparison of the performance on speech intelligibility in noise for three aided condition.

Friedman test was carried out to find out the significance difference with in test conditions. Then post-hoc Wilcoxon test was carried out to see which pair was significantly different.

From the Figure.4.4 Speech identification in noise (SNR-50) was considered and Friedman test was carried out for finding out the presence of significant difference between the three conditions. The result showed that the χ^2 (2) = 17.89 and significant level at 0.000 ($p < 0.05$). As the Friedman test showed the presence of significant difference the post-hoc Wilcoxon test was performed to find out pair-wise significant difference. Without NLFC condition is significantly different from NLFC-Default at the significance level of 0.010 and NLFC-Optimized condition ($p = 0.003$). NLFC-default condition is significantly different from NLFC-Optimized condition at a level of 0.025.

From the present study, the speech identification in noise improved significantly with the NLFC-optimized over NLFC-Default and without NLFC. The noise level was not affected for the speech identification in NLFC- Optimized condition. There was a significant improvement in speech identification in noise for NLFC-Default over the without NLFC. So from the present study SNR- 50 is improved, i.e., performance improves, by providing the optimized NLFC.

Supporting study by Hopkins, Khanom, Dickinson, and Munro (2014) showed that the sentence intelligibility in noise test. On an average, the performance was similar with NLFC on and off (median SRTs of 2.0 and 2.4 dB Speech to babble ratio or SBR, respectively), and a Wilcoxon signed rank test confirmed that the difference between conditions was not statistically significant ($|Z| = 1.0$, $p = 0.30$).

The findings of the present study support the work by Ellis, 2010 on NLFC acclimatization, here they have found that the performance in background noise was showed no difference between NLFC disabled as well as in enabled at the initial fitting. Later with the exposure with NLFC enable in hearing aid, the result showed better performance in background noise.

4.5. Comparison of the Performance on Speech Quality in three aided condition

From the Table.4.1, comparison of parameter of quality rating was done. There was no significant difference between the three aided conditions for loudness parameter [χ^2 (2) = 3.18, p =0.204] and sharpness parameter [χ^2 (2) = 4.00, p=0.135]. In other parameters, the significance levels for clearness was [χ^2 (2) = 9.00, $p < 0.05$], fullness [χ^2 (2) = 5.89, $p < 0.05$], naturalness [χ^2 (2) = 7.92, $p < 0.05$], and overall impression [χ^2 (2) = 6.08, $p < 0.05$]. The condition without NLFC is significantly different from NLFC-Optimized condition for clearness (p=0.016), fullness (p=0.030), naturalness (p=0.026) and overall impression (p=0.047). The condition without NLFC is not significantly different from NLFC- Default condition for clearness (p=0.595), fullness (p=0.248), naturalness (p=0.058) and overall impression (p=0.577). The NLFC-default condition was not significantly different from NLFC-Optimized condition for fullness (p=0.059) and naturalness (p=0.157). The NLFC-default condition was significantly different from NLFC-Optimized condition for clearness (p=0.039) and overall impression (p=0.053).

The NLFC-Optimized condition showed good perception in terms of speech quality over without-NLFC for parameter of clearness, fullness, naturalness and overall impression. But then there were no significant improvement in speech quality perception for loudness and sharpness for NLFC-Optimized condition.

The study by Parsa, Scollie, Glista, and Seelisch (2013) revealed that the mean quality scores from children with hearing impairment (HI) differed across most frequency compression conditions while ratings by the adults did not. The strongest frequency compression condition used in this study was a Compression Ratio (CR) of 2.1 and Cut-off (CF) of 2 kHz. This strong condition was rated as having sound quality that was not significantly different than the peak clipped stimulus by all groups. Statistically, this condition was not significantly different than the 2 kHz low pass stimulus as rated by the HI groups.

The speech quality assessment done to see the outcome by Bohnert et al, 2010. Where the 11 Adults with severe to profound hearing loss. Sound quality rating of 7-pointing was done for recognition of speech. Here also there was a benefit with the default frequency but could not account for significant difference. They have concluded that the default frequency compression need not provide benefit for all individual.

The data for speech identification in quiet and noise were analyzed using descriptive statistics to find out the mean, SD, median and range of SIS (for the monosyllables PB list, PB word list, HF word list), SNR-50, quality of speech. Comparison of speech identification (in quiet and noise) and quality with SII was done using Pearson's correlation and Spearman's correlation. Comparison of the performance on speech identification in three aided conditions was done using repeated measures

ANOVA and post-hoc Bonferroni's test (if indicated). Comparison of the performance on speech quality in three aided conditions was carried out by using Friedman's test along with the Wilcoxon test (if indicated).

The SII had a correlation with the behavioral measures such as SIS in quiet, SNR-50 and overall impression of quality. Hence the SII can be utilized to optimize the NLFC parameter in a hearing aid. Thus, the null hypothesis was rejected.

CHAPTER - 5

SUMMARY AND CONCLUSION

The present study aimed at investigating the efficacy of SII in optimizing the frequency compression in hearing aids for sloping sensorineural hearing loss. The objectives were:

1. To evaluate the effect of the NLFC in hearing aid on speech identification, in quiet and in noise.
2. To evaluate the effect of the NLFC in hearing aid on quality of speech.
3. To compare the speech identification (in quiet and in noise) and quality with SII in the three aided conditions, i.e., with frequency compression disabled, with NLFC set to default and with optimized NLFC settings.
4. To compare the performance on speech identification in three aided conditions, i.e., with frequency compression disabled, with NLFC set to default and with optimized NLFC settings.
5. To compare the performance on quality in the three aided conditions, i.e., with frequency compression disabled, with NLFC set to default and with optimized NLFC settings.

The procedure involved two stages, Stage I and Stage II. In stage I, selection of participants and programming the digital BTE in three different conditions / modes was carried out, i.e., conventional frequency bandwidth or without NLFC, default frequency compression or NLFC-Default and optimized frequency compression or NLFC-Optimized. The programming involved Insertion Gain (IG) measurement for verification of programming of the hearing aid in conventional mode. In Stage II, collection of data was done for the purpose of the study. The data included measurement of aided thresholds for computing the SII, speech identification score (SIS) in quiet for monosyllable list, PB word list and HF word list; and SNR-50.

The data were collected and statistical analyses were executed with the help of software (Statistical Package for Social Sciences or SPSS, version-17). For parametric analyses, i.e., SIS for monosyllable list, PB word list, HF word list and SII, the repeated measures ANOVA was done to compare the SIS for different speech material in three aided conditions. The post-hoc Bonferroni test was performed for pair-wise comparison. For the non-parametric analyses, i.e., SNR-50 and speech quality rating, the Friedman's test were done to find out if there was a significant difference between the aided conditions. The data showing a significant difference were further subjected to post-hoc Wilcoxon test. The correlation analysis was performed by using Pearson's and Spear man correlation. The representation of the numerals was done using tabulation and figures wherever required.

The findings of the present study are given below.

1. The mean value of speech identification in quiet improved as aided condition changed from without NLFC to NLFC-Default to NLFC-Optimized conditions. This difference in mean was statistically significant only for without NLFC and NLFC-Optimized condition. This was true for all types of speech material, i.e., monosyllable list, PB word list and HF word list.

2. The mean value of SNR-50 reduced as the aided condition changed from without NLFC to NLFC-Default to NLFC-Optimized conditions. The performance in noise was significantly different between each of the aided conditions. Here, it should be noted that lesser the value of SNR-50 (i.e., the individual performs well even when the difference between the noise and speech is less) or more negative the value of SNR-50 (i.e., when the noise level is higher than the speech level), better is the performance.
3. The quality rating improved significantly on parameters such as overall quality, clearness, sharpness, fullness, naturalness as the aided condition changed from without NLFC to NLFC-Default to NLFC-Optimized conditions.
4. The mean SII values improved as the aided condition changed from without NLFC to NLFC-Default to NLFC-Optimized conditions. This improvement was significant between the aided condition without NLFC and NLFC-Default; and without NLFC and NLFC-Optimized conditions.

From the above findings, it is construed that the NLFC-Optimized condition brings about improvement in speech identification in quiet and in noise, SII, and quality compared to NLFC-Default settings and without NLFC condition. Hence, optimization of NLFC brings about improvement in performance and better acceptance of the device.

5. A positive moderate correlation was obtained between the SII and SIS in quiet, in most of the aided conditions. This correlation was significant (p,0.05) only for aided condition in which the hearing aid was set to Default settings for monosyllables and PB word list; and for Optimized condition for HF wordlist.

6. A moderate negative correlation was obtained between SII and SNR-50. This implies that as the SII increased, the SNR reduced or the performance in nose improved. However, this correlation was not significant ($p>0.05$).
7. The individual quality parameters were not significantly correlated with SII, except for the overall impression and sharpness of perception. These two parameters of quality showed a significant moderate correlation ($p<0.05$).

The present study highlights the importance of optimization of NLFC for the better understanding of speech in quiet as well as noise. The optimized NLFC condition brought about an improvement in quality and SII. The SII being a non-language measure, this can be used for optimization of NLFC.

Clinical Implications

The clinical implications of the present study include:

- The study provides evidence to optimize the NLFC parameters in order to maximize performance.
- SII can be used to optimize the NLFC parameters. This will be highly useful, especially in a multi-lingual country like India. This is because, it is not practically feasible to have speech material in all the languages and also it is not possible for the audiologist to learn all the languages for testing.

5.2. Future Directions for Research

The present study directs more studies in implementing the frequency compression strategy and application of the SII for persons with high frequency sloping hearing loss.

- There is a need to find the regression equation for the prediction of speech intelligibility from SII using non-linear frequency compression.
- Investigating the benefit with optimizing non-linear frequency compression in the light of variables such as different degree of hearing loss, different durations of hearing loss, different durations of hearing aid experience.

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