INTELLIGIBILITY AND QUALITY OF HEARING AID PROCESSED SPEECH: AN OBJECTIVE COMPARISON OF PRESCRIPTIVE FORMULAE

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CERTIFICATE

This is to certify that this dissertation entitled **"Intelligibility and quality of hearing aid processed speech: an objective comparison of prescriptive formulae"** is a bonafide work submitted as a part of the fulfillment for the degree of Master of Science (Audiology) of the student with Registration Number: 20AUD012. This has been carried out under the guidance of the faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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This is to certify that this dissertation entitled "**Intelligibility and quality of hearing aid processed speech: an objective comparison of prescriptive formulae**" is the result of my study under the guidance of Dr. Nisha K.V, Scientist-B, Department of Audiology and co-guidance of Dr. Ajith Kumar U, Professor of Audiology, All India Institute of Speech and Hearing, Mysore. The work has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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ABSTRACT

The fitting hearing aid is the process of fine-tuning the hearing aid parameters to maximize the audibility, intelligibility & quality of the speech. The present study aimed to verify the intelligibility and quality of hearing aid processed speech across companies and prescriptive formulae through objective measures such as Hearing Aid Speech Perception Index (HASPI), Hearing Aid Speech Quality Index (HASQI), Speech Intelligibility Index (SII) and Long Term Average Speech Spectrum (LTASS). The study also evaluated the objective measures of hearing aid processed speech for Kannada sentences and compared them with the International Speech Test Stimuli (ISTS) sentences.

The stimulus (Kannada sentences and ISTS) was delivered through the loudspeaker & the recordings obtained from the manikin were stored and collected through the sound level meter. The hearing aids of five companies (Oticon, Phonak, Resound, Starkey & Danavox) programmed to four formulae: Company fit, NAL NL 1, NAL NL 2 & DSLv5 were used to obtain the recordings. The results revealed that the HASPI and HASQI yielded similar values for Kannada and ISTS sentences for all the formulae across all companies. The SII values for ISTS was comparatively higher than Kannada sentences across companies in each formula. When the companies are compared, hearing aids of Danavox company consistently scored significantly higher SII values for all prescriptive formulae, while among the formulae company fit emerged with higher SII values across companies. The LTASS revealed differences for low, mid & high frequency LTASS across companies and prescriptive formulae. It can be concluded that Danavox company yielded better speech intelligibility, while among the formulas company fit can be used for better speech intelligibility (SII). The reasons for each of these findings are highlighted and recommendations for best practices on the use of objective measures for verifying the hearing aid output in clinical setups are suggested.

Keywords: Prescriptive formulae, Speech Intelligibility, Speech quality, Hearing Aid Speech Perception Index (HASPI), Hearing Aid Speech Quality Index (HASQI), Speech Intelligibility Index (SII), Long Term Average Speech Spectrum (LTASS).

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List of Acronyms:

This is a list of acronyms that are most commonly used in my study:

HA- Hearing Aid

NAL NL 1- National Acoustics Laboratory Nonlinear version 1

NAL NL 2- National Acoustics Laboratory Nonlinear version 2 (NAL-NL 2)

DSL V5- Desired Sensation Level version 5.0

PESQ-Perceptual Assessment of Speech Quality (PESQ; Hashmi, 2021),

WADA-SNR -Waveform Amplitude Distribution Analysis-Signal To Noise Ratio.

EDI- Envelope Difference Index.

ESTOI- Extended Short-Term Objective Intelligibility.

LTASS-long term average speech spectrum.

SII- Speech intelligibility index.

HASPI- Hearing aid speech perception index.

HASQI-Hearing aid speech quality index.

Chapter 1

INTRODUCTION

The fitting hearing aid is the process of fine-tuning the hearing aid parameters to maximize the audibility, intelligibility and quality of the speech for the consumer (Takagi & Ohsaki, 2007). Despite fitting digital hearing aids, not all recipients experience equivalent benefits owing to 6 reasons (Souza & Tremblay, 2006):

1. Initial representation of the acoustic content of the incoming signal by the hearing aid

2. Modification of the signal by the processing parameters of the hearing aid

3. Interaction between sound at the output of the hearing aid and the listener's ear

4. The integrity of the peripheral and central auditory system

5. Coding of available acoustic cues by the listener's auditory system

6. Correct identification of the speech sound by the listener.

While the latter three are unique to the listener's auditory physiology, the former three issues can be addressed using appropriate fitting/ programming strategies. Conventionally, over the past 60–70 years, the adoption of a prescriptive fitting strategy for hearing aid selection has been mainstream practise. Prescriptive procedure accounts for the estimated target amplification required for each individual (McCreery et al., 2013) That is, amplification characteristics were determined based on hearing characteristics of hearing-impaired individuals found using conventional audiological assessment methods. Hearing features and properties of the speech spectrum were used to develop prescriptive formula in general.

Prescription formulae most commonly used are based on hearing thresholds, but some are based on supra-threshold loudness judgments. According to Tobin (1997) the main aims of prescriptive approaches are:

i) to provide an appropriate gain to achieve normal hearing,

ii) to present an average speech spectrum at a comfortable level to the ear,

iii) to provide the maximum dynamic range,

iv) to provide signals to restore equal loudness function,

v) to provide aided speech signals at MCL in the speech frequencies,

vi) to provide gain based on the size and shape of the dynamic range, and

vii) to provide gain based upon the discomfort level.

Whatever may be the aim of the prescriptive method selected, advancements in hearing aid technology, greater understanding of hearing characteristics and factors affecting hearing aid effectiveness, have altered the tested prescriptive methods over time. In the recent years the use of the other validated methods like National Acoustics Laboratory Nonlinear version 1 (NAL-NL1), National Acoustics Laboratory Nonlinear version 2 (NAL-NL 2) and Desired Sensation Level version 5.0 (DSL V5) have gained momentum over the manufacturers' proprietary algorithms (Mueller, 2005).

NAL-NL1 evolved as a compression- based method (Humes et al., 1999), derived from the older NAL-R method (Mueller, 2005). NAL-NL1 aims for equal loudness of all speech frequency bands, along with maximal speech intelligibility. NAL NL-1 has more than one target, because hearing aid compression offers different gain for different input levels. NAL- NL1 targets refer to gain rather than output. The evaluation of the NAL-NL1 showed that the prescribed overall gain was slightly too high for adults, particularly, for higher input levels, and slightly too low for lower input levels for children (Keidser et al., 2012).

On comparison of NAL-NL1 with default manufacturer's algorithm of six premium hearing aids configured for a flat 50 dB HL hearing loss (Mueller, 2005), showed that manufacturer's algorithms differ significantly from the gain specified by the NAL-NL1, and that the recommended gain for the important frequencies of 1500 Hz to 3000 Hz varies by up to 15 dB amongst products (Mueller, 2005).

Another variant of NAL, is the NAL-NL2 hearing aid prescription (Keidser et al., 2011). Extensive studies conducted by National Acoustic Laboratories indicated that different populations preferred different gain settings relative to that provided by NAL-NL1 (Keidser et al., 2012). A number of changes were implemented in NAL-NL2 to address this finding which included 3 dB less overall gain at the input level of 65 dB SPL for adults with a mild or moderate hearing loss, a 2 dB increase in the overall gain prescribed for children and in-built gain corrections for gender, aid configuration and prior experience with amplification. Adjustments were also made to compression ratios and compressor speeds for those with severe to profound hearing loss.

According to the study by Ching, Johnson, and Hou et al. (2013), calculated SII and loudness for NAL-NL2 and DSLv5 gain targets differed significantly when prescriptive targets were compared, with hearing aid users preferring DSLv5 for low input levels but NAL-NL2 for medium and high input levels. When estimated loudness was compared, it became clear that the two prescriptions came close to being typical for low-level input. However, for medium and high-level inputs, the computed loudness for DSLv5 was substantially higher than NAL-NL2 (Ching et al., 2013).

The DSL method is widely used for hearing aid fitting for infants, young children, and adults whose instruments have comprise of technology such as multichannel compression, expansion, and multimemory. The DSL version 5.0 (Scollie et al., 2005) iteration expands the DSL version to accommodate for adult-child variances in listening preferences and requirements, avoiding loudness discomfort, selecting a frequency response and compression characteristics which appropriately match technology to the user's needs.

According to the study by Ching et al. (2015) on fitting hearing aids to kids with moderately severe to profound hearing loss revealed that the overall gain prescribed by the NAL-NL1 and DSL v5 was significantly different, with effects on anticipated speech intelligibility and loudness. The computed SII values are consistent with observed gains in children's speech perception in quiet environments with DSL v5 relative to NAL-NL1 and show that improved audibility at low input levels (higher gain than that recommended by NAL-NL1) is advantageous (Ching et al., 2015). When using the DSL v5 prescription rather than the NAL NL1 prescription in real-world settings, children reported more loudness discomfort, which is consistent with the loudness calculations (Ching et al., 2015).

In contrast to the prescriptive formulas, many practitioners prescribe hearing aids based on the manufacturer’s first-fit. The reason for this, is that the advent of novel hearing aid technology, fitting of which are claimed by companies as issues that are not addressed by the generic prescriptive formulas discussed above (Curran & Galster, 2013).Hearing aid manufacturers, therefore, have introduced their own proprietary fitting algorithms for the optimal fitting of their devices. These algorithms have been developed based on the research done by the respective manufacturers.

Manufacturer's proprietary software used to program hearing aids provide estimations of real-ear hearing aid responses associated with company-specific fitting algorithm. Many hearing practitioners tend to believe that software simulations indicate the values that are directly reflective of a particular hearing instrument being programmed and the particular patient getting fitted. It is possible that for some patients, the simulations may be beneficial or work out quite well, but for others they may be significantly different from the required gain, particularly in high frequencies where important speech information is present.

In order to quantify the efficacy of the fitting rationale, Audiologists traditionally use the probe-microphone verification techniques and perceptual ratings. The perceptual ratings always come with inherent limitation of subjective bias, while lack of infra-structure and the time constraints restrict the use of probe-microphone verification (Walker et al., 2013). A potentially useful tool which could overcome the above limitations, is the use of the objective metrics which can evaluate intelligibility and quality of the hearing aid processed stimuli (programmed to different generic formula). The objective measures like Perceptual Assessment of Speech Quality (PESQ; Hashmi, 2021),Waveform Amplitude Distribution Analysis-Signal To Noise Ratio (WADA-SNR; Kim & Stern, 2008), Envelope Difference Index (EDI; Fortune et al., 1994), Extended Short-Term Objective Intelligibility (ESTOI; Jensen & Taal, 2016), long term average speech spectrum (LTASS; Byrne et al., 1994), Speech intelligibility index (SII; Kates & Arehart, 2005), hearing aid speech perception index

(HASPI; Kates & Arehart, 2021) and hearing aid speech quality index (HASQIv2; Kates & Arehart, 2014b) can be employed to understand and empirically validate the salient acoustic features in the hearing aid processed speech output.

In the present study we have used LTASS, SII, HASPI & HASQI v2 as they are more efficient (Kates et al., 2018). LTASS accurately reflects the acoustic characteristic of the speech signal actually received at the hearing aid microphone (Cornelisse et al., 1991). The Speech Intelligibility Index (SII) is a measure, ranging between 0.0 and 1.0, which is highly correlated with the intelligibility of speech. (Hornsby, 2004). The HASPI (Kates & Arehart, 2021) is a metric for predicting monaural speech intelligibility. The Hearing-Aid Speech Quality Index (HASQI) Version 2 is a quality index for hearing aids output which predicts the trade-offs between signal distortion and audibility (Kates & Arehart, 2014b)

For HA users in complex listening environments comprising noise, reverberation, and noise-plus-reverberation, it was observed that HASPI, a metric tailored for intelligibility prediction, outperformed HASQI (its quality predictor counterpart) and all other metrics (Falk et al., 2015). HASPI and HASQI measures are efficient than PESQ measure in predicting the speech intelligibility in noisy conditions (Websdale et al., 2015). Hou et al. (2018) found that when distortion measurement of clean and hearing aid enhanced speech were done, better performance was found in HASPI & HASQI than PESQ & ESTOI measures. While we could not use the other objective measures like PESQ, EDI & ESTOI due to there limitations related to each measure such as high reliability of PESQ and ESTOI for subjective quality evaluations of NH listeners for speech intelligibility prediction of

HA processed outputs (Falk et al., 2015), they were not used in the present study. On other hand we used standard measures such as LTASS and SII. In terms of correlation and prediction error, HASQI and HASPI have been best-performing metrics (Kressner et al., 2013), hence used in the study.

1.1. Need for the Study:

For an optimal fitting solution to be achieved, prescribing the prescriptive formulae will be more important. To satisfy the user at the first fitting itself, we will have to be aware of the changes that have to be brought with the prescribed formulae. In order to enhance the speech intelligibility and there by the quality of speech perception using the Hearing aid. Therefore, it becomes imperative on our part to know the deviations that occur based on the needs of the user and the degree of hearing loss. Hence, based on the above-mentioned data, it becomes all the more important to study the differences between the company fit settings and the prescribed formulae i.e., NAL-NL1, NAL-NL2 and DSL v5.

1.2. **Aim of the Study**: To study the effect of different prescriptive formulae on hearing aid processed speech using objective assessment methods. The study also aimed to understand the language-based differences in hearing aid processed speech across different companies and prescriptive formulae.

1.3. Objectives:

- To document and compare the speech intelligibility and speech quality of hearing aid processed speech across companies (five companies) and fitting rationales (company first fit, like National Acoustics Laboratory Nonlinear version 1 (NAL-NL1), National Acoustics Laboratory Nonlinear version 2 (NAL-NL 2) &Desired Sensation Level version 5.0 (DSL V5) using hearing aid speech perception index (HASPI v2), hearing aid speech quality HASQIv2 and Speech intelligibility index (SII).

- To document and compare the spectral variations in the hearing aid processed speech using Long term average speech spectrum (LTASS) for low-, mid-, and high-frequencies
    - across companies (5 companies) within a fitting rationale (NAL-NL1, NAL-N2 and DSL v5).
    - across fitting prescriptive formulae (company first fit, NAL-NL1, NAL-N2 and DSL v5) within each company
- To compare the speech intelligibility, quality and spectral variations in hearing aid processed speech for Kannada and international speech test stimuli (ISTS) sentences.

CHAPTER 2

REVIEW OF LITERATURE

The World Health Organization (WHO) defines a disabling hearing loss as a loss in better ear that is greater than 40 dB HL in adults and greater than 30 dB HL in children (Olusanya & Newton, 2007). There are approximately 465 million people in the world who have disabling hearing loss, which is approximately 5% of the global population (Shakespeare & Alana, 2018). Out of the two types of hearing loss (Zahnert, 2011) sensorineural hearing loss (SNHL) caused due to permanent damage of the hair cells in the inner ear accounts for almost 90% of hearing loss (Li et al., 2017). There is currently no known cure for the damage to hair cells in the ear, so amplification devices such as hearing aids may be one of the most effective ways to manage the condition (Zahnert, 2011). The outcomes of the hearing aids are verified conventionally using perceptual measures in clinical practice. Prescriptive procedure for non-linear hearing devices are broadly classified into suprathreshold based formulas and hearing threshold based formulas. Threshold based procedures include National Acoustic Laboratory Non-Linear, version 1 (NAL-NL1, Byrne et al., 2001), National Acoustic Laboratory Non-Linear, version 2 (NAL NL 2, Keidser et al., 2011), and Desired Sensation Level version 5.0 (DSL v5, Scollie et al., 2005).

Nonlinear prescription can be viewed as specifying the gain-frequency response for various input levels. Average gain and frequency responsiveness both change as input level changes. In other words, prescriptive formulae specify specific gain resulting in input specific output curves at various frequencies. However, it is completely impracticable to recommend a hearing aid based entirely on prescriptive approaches because evaluation of the final outcomes, such as customizing the device to each person's needs, is always necessary (Byrne et al., 2001). The following section highlights a brief description of the various prescriptive formulae.

2.1. Prescriptive Procedures:

2.1.1. NAL NL 1:

Its an extension of the National Acoustic Laboratory -Revised (NAL-R). The goal of this approach is to maximize the speech intelligibility at all input levels and to make sure that the overall speech loudness is not exceeding the overall normal loudness (Byrne et al., 2001). It provides different prescriptive targets as a function of input level. It optimizes the anticipated speech intelligibility for a given loudness, it does a calculations using a loudness model (Moore and Glasberg, 1997) and a modified form of the Speech Intelligibility Index (SII). NAL-NL1 aims for equal loudness of all speech frequency bands, along with maximal speech intelligibility. A distinctive feature of NAL-NL1 is that it may not deliver a prescription at the most extreme frequencies. If you have severe hearing loss, this is especially likely to happen at high frequencies. The reason for this is that amplified signals at such frequencies can only contribute a little amount to predicted speech intelligibility. This is due to a combination of factors, including a limited ability to employ high-frequency information (i.e. hearing loss desensitisation) and the fact that even the maximum contribution of those frequencies to the SII is tiny (Byrne et al., 2001).

2.1.2. NAL NL 2:

Similar to NAL-NL1, the optimization technique used in the NAL-NL2 procedure, uses intelligibility and loudness to calculate the perceived loudness by the hearing-impaired person (Keidser et al., 2011). On two points, the theoretical derivation of NAL-NL2 differs from that of NAL-NL1. First, the intelligibility model (ANSI, 1997) was modified, which is a revised version of the speech intelligibility index (SII) formula. The audibility factor differs between the original SII formula and the speech intelligibility model used to produce NAL-NL1 and NAL-NL2. The audibility factor in the original SII formula assumes that speech is fully understood when all speech components are audible, regardless of the degree of hearing loss (Keidser et al., 2011). An overview of changes made to NAL-NL2 relative to NAL-NL 1 across different input levels is highlighted in Figure 2.1.

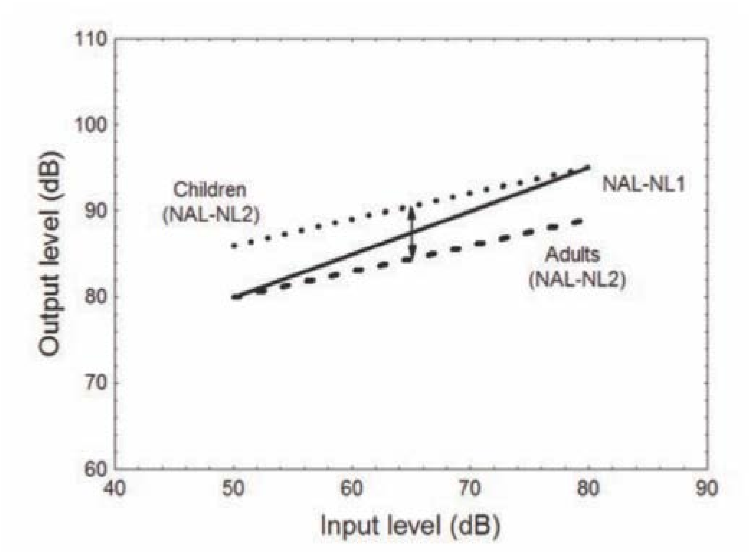

Fig 2.1: Adapted from Keidser et al. (2011). A schematic overview of the changes to the overall output level prescribed by NAL-NL2 relative to NAL-NL1 across different input levels for children (dotted line) and adults (broken line).

From the figure 2.1, Keidser et al. (2011) suggested that adults with mild and moderate hearing loss preferred less overall gain (3 dB on average) than advised by NAL-NL1 for a 65 dB SPL input. According to the same data set, hearing aid users with mild or moderate hearing loss preferred a higher gain reduction for higher input levels (80 dB SPL) but a smaller gain reduction for lower input levels (50 dB SPL) in at least one study (Karolina Smeds et al., 2006), implying that the adults preferred a slightly higher compression ratio than prescribed by NAL-NL1. Overall, NAL NL2 prescribes relatively more gain across low and high frequencies and less gain across mid frequencies than NAL-NL1 (Keidser et al., 2011).

2.1.3. Desired sensation level Version 5 (DSLv5)

The DSL approach is frequently used to fit hearing aids for newborns, toddlers, and adults whose devices feature multichannel compression, expansion, and multimemory technologies. The DSL version 5.0 (Scollie et al., 2005) iteration extends the DSL version to take into account differences between adult and child listening preferences and requirements, avoiding loudness discomfort, and choosing a frequency response and compression characteristics that appropriately match technology to the user's needs. The DSLv5 recommends as hearing loss increases compression threshold also gets higher. This calculates across frequencies, according to the number of channels in the hearing aid which can be grouped.

According to the study by Ching et al. (2015) on fitting hearing aids to kids with moderately severe to profound hearing loss revealed that the overall gain prescribed by the NAL-NL1 and DSL v5 was significantly different, with effects on anticipated speech intelligibility and loudness. The computed SII values are consistent with observed gains in children's speech perception in quiet environments with DSL v5 relative to NAL-NL1 and show that improved audibility at low input levels (higher gain than that recommended by NAL-NL1) is advantageous (Ching et al., 2015).

2.1.4. Company fit.

Company fit also known as Manufacturer’s initial fit, is a comprehensive approach that involves an “approximation” of the hearing aid gain and output based on various data such as acclimatization, age of the patient, venting and tubing characteristics (Abrams et al., 2012). There is no validation that the hearing aid response (with company fit) meets the prescription with the initial-fit method; rather, it is assumed that the prescribed response will be close to the underlying prescription used in the initial-fit approach of the manufacturer.

There are research evidences that have also demonstrated the efficacy of company fit formula with that of the probe-microphone measurements and have found that the outcomes of both the measures are similar (Gottermeier & De Filippo, 2018).There are different generic company fits available, few are Adaptive Phonak Digital Bimodal Fitting Formula (APDB) for Phonak, General DSE for Oticon, Audiogram+ for Resound, e- stat for Starkey and Audiogram+ for Danavox.

According to the Vroegop et al. (2019), for frequencies of 2 kHz and above, the suggested gain of the two fitting formulas, NAL NL 2 & Adaptive Phonak digital bimodal (APDB) fitting formula varied. In contrast, the APDB formula applies a reduced frequency bandwidth of the gain if the slope of the hearing loss is greater than 35 dB per octave, the high-frequency hearing loss exceeds 85 dB HL, or if the hearing loss is greater than 110 dB HL. This is what was expected because NAL-NL2 provides gain for the entire frequency range (Vroegop et al., 2019).

2.2 Objective measures: The use of perceptual measures to quantify speech output from the patient, might not always be feasible in difficult to test population such as children and those with communication disorders. In such cases, manufactures claim about the output from hearing aids are not directly inferable. The use of the objective measures for measuring hearing aid processed speech output can have practical implications in hearing aid prescription and measuring its benefits in hearing impaired individuals.

2.2.1. Perceptual Assessment of Speech Quality (PESQ, Hashmi, 2021)

The most frequent objective acoustic measure for assessing speech quality is the perceptual assessment of speech quality (PESQ, Hashmi, 2021). PESQ scores range from 0 to 4.64, with higher scores denoting higher quality. The PESQ scores were found to have a strong relationship with the listening tests (Palomar et al., 2008) and subjective quality assessments (Hu & Loizou, 2008). In a variety of situations, including background noise, the PESQ score accurately predicts subjective quality. Furthermore, the PESQ has a 93.5 percent correlation with a subjective listening test, the greatest of any objective measure (Narne et al., 2021). Hu & Loizou (2007) provided the MATLAB code for PESQ.

2.2.2. Waveform Amplitude Distribution Analysis-Signal to Noise Ratio. (WADA-SNR).

This objective acoustic measure of WADA-SNR was developed by Kim & Stern (2008). WADA-SNR knowledge can be used to determine whether the implementation of a noise reduction approach results in appropriate changes in the SNR. According to Kim & Stern (2008), the WADA-SNR method of SNR estimate is less biased and changeable in terms of noise kind. The SNR approaches are also said to have high forecasting ability.

Ellis' MATLAB code can be used to calculate the WADA-SNR (2011). To calculate the WADA-SNR, the target signal, which is the processed phrase is fed into the MATLAB, function along with the sample frequency (10,000 Hz). Because speech is a time-varying signal, the speech signal's SNR varies from frame to frame (Krishnamoorthy, 2011). As a result, the author reported that a better objective acoustic measure of speech quality exists in the literature, which measures the SNR for short frames and averages the results.

2.2.3. Envelope Difference Index (EDI)

Another acoustic measure is the Envelope Difference Index (EDI), which quantifies the temporal envelope contrast between the two sound streams (Fortune et al., 1994). This approach produces a precise difference between the two signal envelopes. The EDI value ranges from 0 to 1, with '0' referring to entirely comparable signal envelopes. An EDI value of '1' denotes envelopes that are fully different. According to Jensen & Taal (Jensen & Taal, 2016), a higher EDI reduces sentence recognition. Furthermore, according to Fortune et al (1994) activating the noise reduction feature in hearing aids may result in a higher speech transmission index due to a larger temporal envelope. As a result, prior research has emphasized the use of the EDI measure to evaluate noise reduction measures. EDI on the other hand, is yet to be researched for evaluation of impact of different manufacturers and prescriptive formulae on hearing aid processed speech. A non-standardized MATLAB code given by (Fortune et al., 1994) can be used to obtain the EDI.

2.2.4. Extended Short-Term Objective Intelligibility (ESTOI)

The Extended Short-Term Objective Intelligibility (ESTOI) index is an objective metric for predicting speech intelligibility (Jensen & Taal, 2016). The 'd' value, which is an intelligibility index, is returned. The 'd' number goes from 0 to 1, with '0' indicating the least intelligibility and '1' indicating the most intelligibility. Jensen & Taal (2016) gave the MATLAB code for calculating ESTOI. The reference sentence and target processed sentence, as well as the sampling frequency (10,000 Hz), are also necessary in order to estimate the ESTOI.

2.2.5. Long Term Average Speech Spectrum (LTASS).

The long-term average speech spectrum (LTASS) is one of the important factors that determine the acoustic characteristics of speech. The LTASS represents speech energy across the frequency in decibel (dB). Narne et al. (2021) reported that intelligibility scores measured by clear speech which is a method to speak as clear as possible were higher than the scores measured by normal speech for people with hearing loss. According to the result of acoustical analysis, the characteristics of the LTASS was different between two speaking styles. Specifically, increased mid-frequency speech energy was apparent in the clear speech compared to the normal speech. Thus, the LTASS can be an important factor to compare acoustic features between different speaking styles (Lee & Jin, 2017). LTASS and dynamic range (DR) are language-dependent functions that are used to fit hearing aids, calculate the Speech Intelligibility Index and automatically recognize speech. In India, hearing aids are currently fitted using the LTASS and DR functions for English (Narne et al., 2021).

2.2.6. Speech Intelligibility Index (SII).

The Speech Intelligibility Index or SII, is a measure ranging between 0.0 and 1.0, with values closer to 1.0 being highly correlated with the intelligibility of speech (Hornsby, 2004). SII can be used to predict speech recognition scores by means of an empirically derived transfer function. These transfer functions are based on the specific speech materials being used during testing (Hornsby, 2004).The speech intelligibility index (SII) is also a tool for determining speech intelligibility in the presence of additive stationary noise or bandwidth compression (Kates & Arehart, 2005). There are several studies which extends the SII idea for assessing intelligibility to incorporate broadband peak-clipping and center-clipping distortion, with the coherence between the input and output signals being utilised to estimate the noise and distortion effects (Kates & Arehart, 2014).

The aided speech intelligibility measure outperformed the pure tone average (PTA) as a predictor of word and nonword repetition and receptive vocabulary. Aided SII remained a strong predictor of nonword repetition and receptive vocabulary after controlling for PTA. Assisted SII, unlike PTA, integrates hearing aid amplification characteristics and speech-frequency weightings, and hence may provide a more accurate evaluation of a child's access to and ability to learn from auditory information in real-world situations (Stiles et al., 2012). The SII could successfully be used to predict speech recognition scores for both adults and children, when the impacts of age and hearing loss were factored into the building of a transfer function (Scollie et al., 2005).

2.2.7. Hearing Aid Speech Perception Index (HASPI).

The Hearing-Aid Speech Perception Index (HASPI) is a metric for predicting monaural speech intelligibility (Kates & Arehart, 2014a). HASPI requires a reference signal (aided hearing aid processed output signal); it compares a degraded signal's time-frequency envelope and temporal fine structure (TFS) to the unprocessed reference (unaided input signal). HASPI is based on an auditory peripheral model that takes hearing loss into account (Kates & Arehart, 2014b). The index compares the auditory model's envelope and temporal fine structure outputs for a reference signal to the model's outputs for the signal under test (Kates & Arehart, 2014a). The reference signal's auditory model is configured for normal hearing, while the test signal's model includes peripheral hearing loss. The new index is compared to indices that measure the envelope correlation between the reference and test signals, as well as indices that measure the coherence between the reference and test signals. HASPI has been found to provide accurate intelligibility predictions for a wide range of signal degradations, including speech that has been degraded by noise and speech that has been deteriorated by other factors (Kates & Arehart, 2014b).

In HASPI , there are two modifications, first alteration is to change the speech features that are used to predict intelligibility, and the second is to alter the modelling process that is used to link the speech characteristics to the listener data (Kates & Arehart, 2021). In the first modification, combination of a lowpass envelope filter and the TFS computation is replaced by an envelope modulation filter bank, the speech intelligibility has been successfully predicted using this envelope modulation filter banks (Dau et al., 1997). The main procedure is to run the signal through an auditory filter bank, extract the envelopes in each auditory band, and then run the envelopes through a bank of modulation filters for each band (Jørgensen & Dau, 2011). Cross-frequency analysis can provide a benefit, they found that adding data across aural frequency bands increased the performance of the intelligibility models they investigated (Chabot-Leclerc et al., 2014). In second modification, it is replacing the parametric model used in version 1 with a neural network (Kates & Arehart, 2021). Interactions between envelope amplitude modulation components occur in the auditory pathway, a neural network allows for such interactions in creating the intelligibility prediction even if their exact nature is unknown a priori (Carney, 2018).

2.2.8. Hearing Aid Speech Quality Index (HASQI).

The Hearing-Aid Speech Quality Index (HASQI) is based on an auditory peripheral model that takes hearing loss into account (Falk et al., 2015). Changes in the signal envelope, temporal fine structure, and spectrum produced by hearing aid or audio system processing are measured using the auditory model outputs. The quality prediction is created by taking the product of two terms: a nonlinear term sensitive to noise and nonlinear distortion and a linear term sensitive to long-term spectral changes (Kates & Arehart, 2014b).

The nonlinear term includes envelope and temporal fine structure observations, and it has been found to produce more accurate predictions than nonlinear terms based solely on envelope or temporal fine structure measurements. The new HASQI improves accuracy for a variety of degraded signal conditions, such as frequency compression, noise suppression, speech replaced with the output of a noise vocoder, acoustic feedback and feedback cancellation and speech combined with modulated noise, when compared to the previous version of HASQI (Kates & Arehart, 2014b) to test HASQI's robustness as a quality measure by evaluating its performance in predicting subjective quality ratings on a large novel (i.e., not used in the model design) speech corpus under various distortion situations (Kressner et al., 2013). Specifically, in terms of correlation and prediction error, HASQI and its retrained version are comparable to the best-performing metrics.

According to the studies, the HASQI version 2 model was employed. The middle ear, an auditory filter bank, dynamic-range compression mediated by the outer hair cells in the cochlea, two-tone suppression (where a tone at one frequency can reduce the cochlear output for a tone at a different frequency), and the onset enhancement inherent in the inner hair-cell neural firing behaviors are all part of the auditory model. With increased hearing loss, the model incorporates a broadening of the auditory filters, a reduction in the amount of dynamic-range compression, a decrease in two-tone suppression, and a shift in the auditory threshold (Falk et al., 2015).

Therefore, from the above studies we can clearly infer that most of the times, individual with hearing impairment are facing difficulties in speech understanding i.e, intelligibility and quality. It is also been proven that only perceptual measure wont be sufficient to check the speech intelligibility and quality. Therefore, the use of objective measure to find the quality measure of speech is very important. Hence, the present study aim to see the effect of different prescriptive formulae on hearing aid processed speech using objective assessment methods and also aimed to understand the language-based differences in hearing aid processed speech across different companies and prescriptive formulae.

CHAPTER 3

METHODS

3.1. Study design*:* True experimental design.

3.2. Materials: The 8-channel digital behind the ear (BTE) hearing aids from 5 different hearing aid companies were selected. The company and the specific models which were used for the study are as follow:

- Company 1- Oticon, Xceed 3 UP BTE.
- Company 2- Phonak, Noida M30 SP BTE.
- Company 3- Resound, Enya 377 BTE
- Company 4- Starkey, Livio 1000 BTE.
- Company 5- Danavox, Klar 398 SP BTE.

The electroacoustic characteristics of each hearing aid i.e. Output sound pressure level (OSPL 90), Full on gain (FOG 50), Total harmonic distortion (THD) and frequency response was similar for all the hearing aids, which was tested prior to their inclusion.

All these were the hearing aids were connected through NOAH link wireless interface to the personal computer, loaded with the programming softwares. The fitting rationales used for programming were company specific software such as Genie 2 for Oticon hearing aids, Phonak Target for Phonak hearing aids Resound smart fit for Resound hearing aid, Starkey Inspire for Starkey and for Danavox hearing aid the programming software, it is be more. All the hearing aid was programmed for moderate flat hearing loss (thresholds plotted in 1/3rd octaves from 125 Hz to 8000 Hz) for 4 different prescriptive formula such as Company first fit, NAL-NL 1, NAL-NL 2, and DSLv5.

3.3. Procedure: the study was conducted in three phases.

3.3.1. Phase I: Unaided recordings

The international speech test stimuli (ISTS) and 10 kannada sentences (Geetha et al., 2021) were routed to the loudspeaker (Genlec 8020B, Finland), kept at 0 degree azimuth at a distance of 1 meter, as shown in Figure 3.1.

Fig 3.1. The setup for calibration, unaided and aided recordings. KEMAR was kept at 0-degree azimuth at a distance of 1 meter from the loudspeakers.

The presentation software was Abode Audition 3.0. (Adobe Systems, San Jose, CA), with stimuli presented at 65 dB SPL calibrated using sound level meter (SLM, Bruel and Kjaer 2270, Naerem, Denmark), as shown in Figure 3.2.

Fig 3.2. Presentation of the stimulus through Adobe audition 3.0 (Adobe Systems, San Jose, CA).

The SLM was connected to a Manikin (Knowles Electronics Mannequin for Acoustics Research, KEMAR, GRAS Sound and Vibrations, type 45 BA, Denmark). The stimuli was picked by the microphone (model 4187) placed on the manikin right ear. The output from the microphone was recorded using sound level meter. The schematic representation of test set up is shown in Figure 3.3.

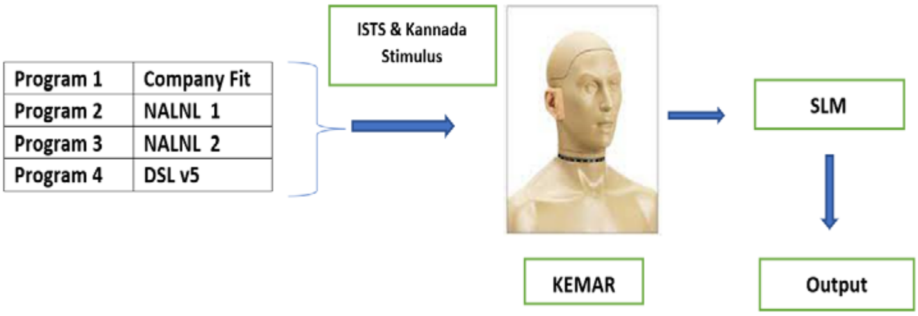

Figure 3.3. Schematic representation of the test setup for the unaided recording.

3.3.2. Phase II: Programming hearing aid and recording of processed speech.

The digital BTE hearing aids which fit the inclusion criteria was chosen from each of the five companies (as specified in section 3.2). These hearing aids were programmed for moderate flat sensorineural hearing loss. The hearing aids were connected through a NOAH link wireless connection to the Personal Computer (PC) with the company-specific software for programming the hearing aid, as shown in Figure 3.4.

Fig 3.4. The digital hearing aid was connected through a NOAH link wireless to the Personal Computer (PC) with the software for programming the hearing aid.

After the hearing thresholds were fed into the software (NOAH-3.0), the digital hearing aid was programmed based on the prescriptive procedure i,e Company first fit, NAL NL 1, NAL NL 2, DSL v5, as shown in Fig 3.5. All the additional features such as noise reduction, feedback suppression, directionality etc. was switched off. Each hearing aid was programmed to 4 prescriptive formula and they were stored under the following:

- Hearing aid configured to Companies first fit was stored as Program 1
- Hearing aid configured to NAL NL 1 was stored as Program 2
- Hearing aid configured to NAL NL 2 was stored as Program 3
- Hearing aid configured to DSL i/o was stored as Program 4.

Fig 3.5. Programming the hearing aid by selecting the specific prescriptive formula. In the fig, the company specific fit for Starkey hearing aid using e-STAT software is show.

The hearing aid belonging to company 1 (i.e., Oticon), was placed on KEMAR, as shown in Figure 3.6, with the program 1 (i.e. Company fit) on. The ISTS and Kannada sentences were presented using abode Audition 3.0, similar to the procedure described in section 3.3.1. The output of hearing aid processed speech was obtained for this setting, using SLM connected to KEMAR microphone. Similarly, hearing aid processed speech for all the other 3 programs were also obtained. The same procedure was repeated for all the 4 company hearing aids. For each hearing aid company, its specific fitting formula and other conventional fitting rationale (NAL-NL 1, NAL-NL 2, DSL v5) were used.

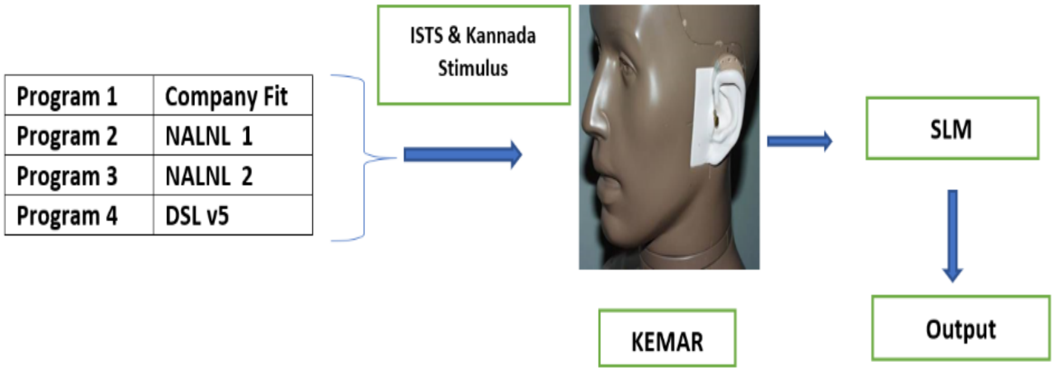

Figure 3.6. Schematic representation of the test setup for the aided recordings.

3.3.3. Phase III: Objective analysis of the aided and unaided speech

The recorded speech material from the SLM (Bruel and Kjaer 2270, Naerem, Denmark) was taken and fine-tuned like peak clipping, Noise reduction and removal of the initial/final silent parts. Later the recorded speech material was analysed using MATLAB codes to obtain spectral composition of the signal i.e., LTASS at 1/3rd octave frequencies from 12 Hz to 8000 Hz), as shown in Figure 3.7. From the analysed LTASS, low frequency LTASS (average of frequencies from 12 – 1000 Hz), mid frequency LTASS (average of 1250 – 3000 Hz) and high- frequency LTASS (average of 3100 – 8000 Hz) were computed.

Speech Intelligibility Index (SII, HASPI) and speech quality (HASQI v2) values were also analysed using MATLAB codes given by Kates & Arehart, (2021) and tabulated across companies and prescriptive formulas. The objectively analyzed data (LTASS, SII, HASPI v2, HASQI v2) were derived by providing input (unaided recordings) and corresponding outputs (aided recordings) to a total of 20 recordings (5 companies * 4 prescriptive formulae* 1 sentence stimuli) for ISTS and 200 recordings (5 companies * 4 prescriptive formulae* 10 sentences) for Kannada sentences.

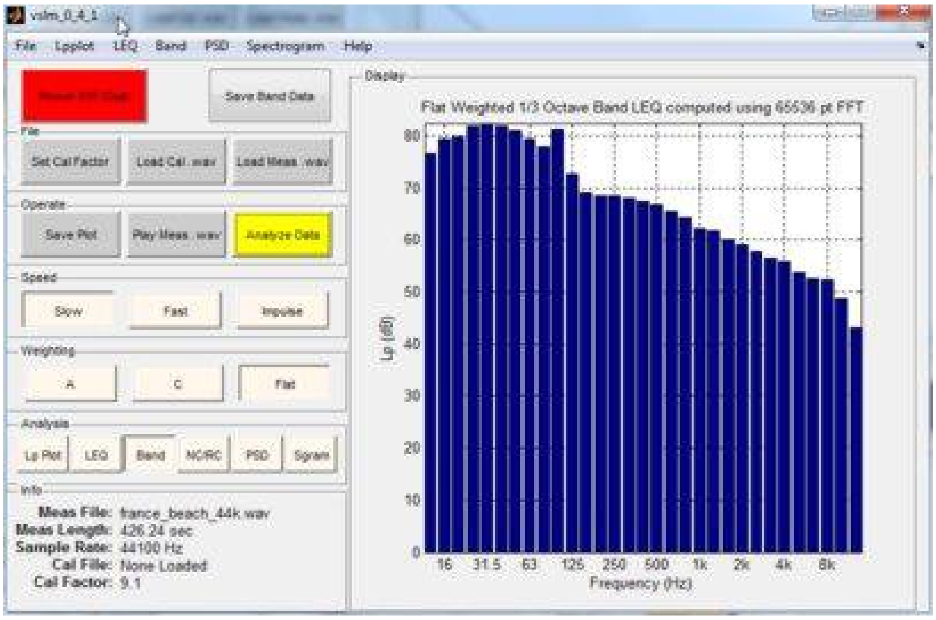

Fig 3.7. Measuring LTASS using the MATLAB code.

3.4. Statistical analyses.

The data was subjected to statistical analysis using the IBM Statistical package for social science SPSS software version 25.0 (IBM Corp., Armonk, NY, USA). Shaprio Wilks test was carried out initially to check whether the collected data follow a normal distribution. The descriptive statistics of mean and the standard deviation was reported for all the companies and across formulas. The parametric test was done i.e., One way ANOVA was carried out with independent variables (Companies & formulae) and dependent variables (Objective measures- HASPI, HASQI, SII, LTASS). Wherever the significance was seen the partial Eta square (η_p^2) was reported. When the main effects were observed Bonferroni pairwise comparisons between related pairs was done. In addition, one sample t test was done to compare between Kannada and ISTS sentences for all the objective measures, wherever the significance differences were seen Cohen's d values were reported.

Chapter 4

RESULTS

The present study aimed to compare the intelligibility and quality of hearing aid processed speech across companies and prescriptive formulae through objective measures. The objective measures used in the analyses include Hearing Aid Speech Perception Index (HASPI), Hearing Aid Speech Quality Index (HASQI), Speech Intelligibility Index (SII) and Long Term Average Speech Spectrum (LTASS).

The Shapiro wilk's test of normality revealed that data followed normal distribution ($p>0.05$). The results of the parametric tests will be discussed in the following headings:

4.1. Comparison of objective measures of speech intelligibility and quality across companies within each formula.

4.2. Comparison of objective measures of speech intelligibility and quality across formulae within each company.

In each section, the results of descriptive statistics (Mean and standard deviation) followed inferential statistics (Analysis of Variance, ANOVA and post-hoc Bonferroni, wherever indicated) are discussed. Further, the comparisons of the intelligibility of Kannada vs International Speech Test Stimuli (ISTS) sentences using one-sample t-test are also reported.

4.1. Comparison of Objective Measures of Speech Intelligibility and Quality Across Companies Within Each Formula:

The differences in speech intelligibility (HASPI, SII), speech quality (HASQI), and spectral information (LTASS) across the companies (Oticon, Phonak, Resound, Starkey & Danavox) are elaborated in this section. The comparisons across companies was carried out for each prescriptive formula separately.

4.1.1. Hearing Aid Speech Perception Index (HASPI) and Hearing Aid Speech Quality Index (HASQI):

The objective metrics HASPI and HASQI yielded similar values (HASPI = HASQI) for Kannada and ISTS sentences for all the formulae, hence only one value is used for analyses. The mean (± one standard deviation) of HASPI & HASQI across companies is given for each formula separately as shown in Figure 4.1, suggestive of similarity in the HASPI & HASQI values. The similarity in the descriptive statistics for HASPI & HASQI were also verified statistically using ANOVA, as indicated in Table 4.1.

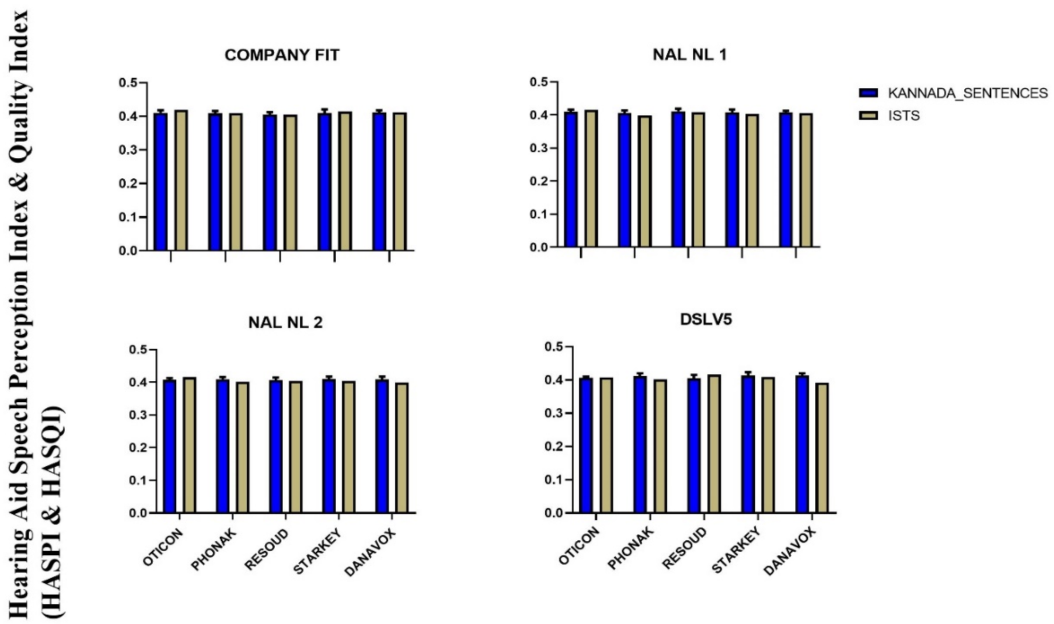

Figure 4.1: Comparison of mean HASPI/ HASQI across companies within each formula. The error bar represents ± one standard deviation.

Table 4.1. *Results of ANOVA for the main effect of Companies on HASPI & HASQI for each formula for Kannada sentences.*

Formulae	**Main effect of company** $F(4,45) =, p =$	η_p^2
Company Fit	0.97, 0.42	0.08
NAL NL 1	0.75, 0.57	0.06
NAL NL 2	0.31, 0.87	0.02
DSL v5	2.30, 0.07	0.17

The results of one sample t test is shown in Table 4.2, reflective of statistically similar HASPI/HASQI values for Kannada and ISTS sentences across companies (company fit, NAL NL 1, NAL NL 2 & DSL v5) in each formulas.

Table 4.2. *Results of one sample t test comparing the HASPI/ HASQI values of Kannada and ISTS sentences across companies within each formula.*

Formulae	Companies	$t(9)$=	p value	(Cohens d)
Company fit	Oticon	-1.21	0.41	1.23
	Phonak	-2.01	0.52	1.58
	Resound	-1.72	0.42	2.12
	Starkey	-1.97	0.49	0.02
	Danavox	0.97	0.36	0.31
NAL NL 1	Oticon	-1.90	0.45	1.61
	Phonak	-2.11	0.56	1.90
	Resound	0.61	0.41	1.44
	Starkey	-1.49	0.46	1.42
	Danavox	-1.48	0.52	2.36
NAL NL 2	Oticon	-1.50	0.42	2.37
	Phonak	-2.14	0.51	1.53
	Resound	-1.30	0.45	1.68
	Starkey	-1.19	0.43	1.32
	Danavox	-1.13	0.46	1.30
DSL v5	Oticon	-1.91	0.51	2.08
	Phonak	-2.09	0.53	0.98
	Resound	0.66	0.42	1.47
	Starkey	-1.09	0.44	0.66
	Danavox	1.07	0.51	0.97

4.1.2. Speech Intelligibility Index (SII):

The mean (center line on error bar) & the one standard deviation (error bar) of SII across companies in each formula is shown in figure 4.2, indicative of higher mean SII values for ISTS compared to Kannada sentences, for all the companies within each prescriptive formula. Also, mean SII was consistently higher in Danavox company compared to other companies, for all the prescriptive formulae.

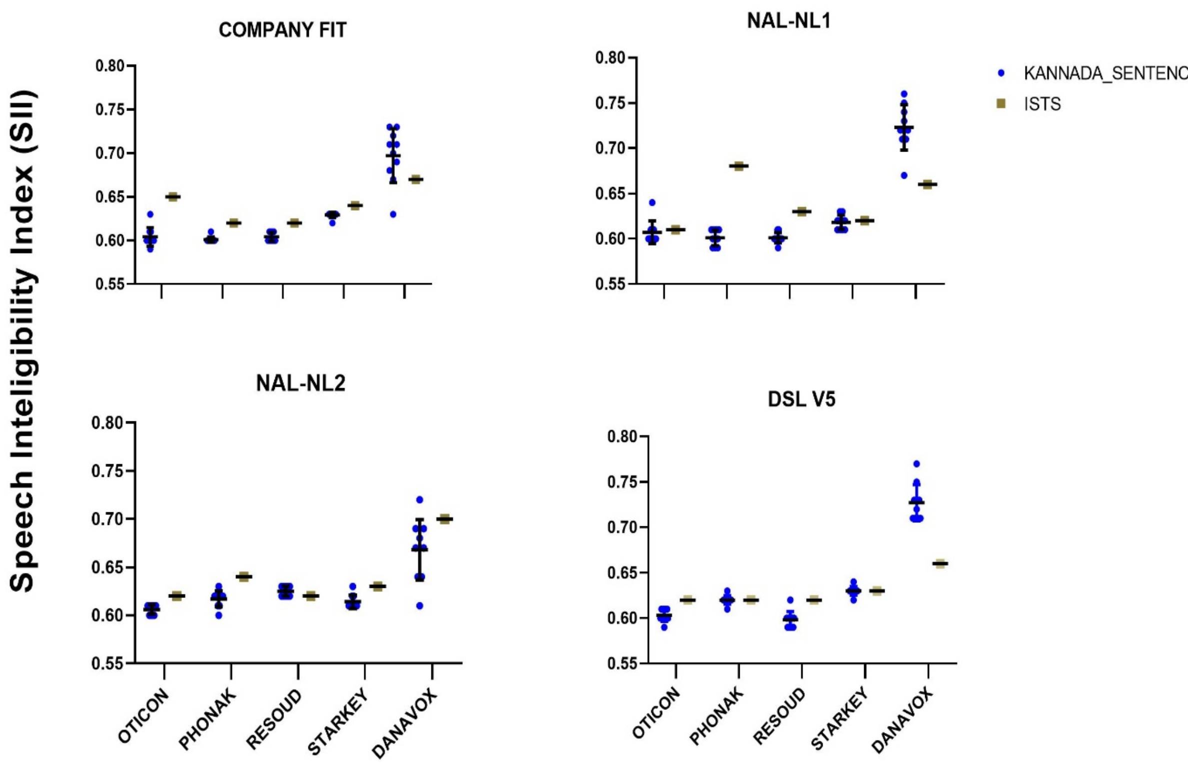

Figure 4.2: Comparison of SII values across companies within each formula.

The main effect of companies within each formula was also verified statistically using ANOVA test, confirming the main effect of companies as shown in the Table 4.3. The results of post-Hoc Bonferroni test showed that SII of Danavox hearing aids was significantly higher (p<0.001) than the other companies for 3/4 formulae (Company fit, NAL-NL1 & NAL-NL2), as depicted in Table 4.4. However, for the DSL v5, the Danavox hearing aids showed significantly higher SII (p<0.05) compared to all other companies except Phonak, whose SII was similar to Danavok (p>0.05).

Table 4.3. *Results of ANOVA for the main effect of Companies on SII for each formula for Kannada sentences.*

Formulae	**Main effect of company** $F(4,45) =, p =$	**Effect size** η_p^2
Company Fit	74.16, <0.001	0.86
NAL NL 1	43.95, <0.001	0.79
NAL NL 2	26.10, <0.001	0.69
DSL v5	36.54, <0.001	0.76

Table 4.4. *Results of Bonferroni test for pairwise comparisons of SII values between companies for each formula for Kannada sentences.*

Formulas		Oticon	Phonak	Resound	Starkey	Danavox
Company Fit	Oticon		1	1	0.05	<0.001
	Phonak	1		1	0.01	<0.001
	Resound	1	1		0.05	<0.001
	Starkey	0.05	0.01	0.05		<0.001
	Danavox	<0.001	<0.001	<0.001	<0.001	
NAL NL 1	Oticon		1	1	1	<0.001
	Phonak	1		1	0.18	<0.001
	Resound	1	1		0.36	<0.001
	Starkey	1	0.97	0.29		<0.001
	Danavox	<0.001	<0.001	<0.001	<0.001	
NAL NL 2	Oticon		1	0.75	1	<0.001
	Phonak	1		1	1	<0.001
	Resound	0.73	1		1	<0.001
	Starkey	1	1	1		<0.001
	Danavox	<0.001	<0.001	<0.001	<0.001	
DSL v5	Oticon		<0.001	1	<0.001	<0.001
	Phonak	<0.001		<0.001	0.24	1
	Resound	1	<0.001		<0.001	<0.001
	Starkey	<0.001	0.23	<0.001		0.24
	Danavox	<0.001	1	<0.001	0.22	

The results of one sample t-test comparing the differences between Kannada sentences and ISTS is shown in Table 4.5, indicative of higher SII values for ISTS compared to Kannada for all the companies, except Danavox programmed for Company fit, NAL-NL1 AND NAL-NL2.

Table 4.5. *Results of t test comparing the SII values of Kannada and ISTS sentences across companies within each formula*

Formulas	Companies	*t*(9)=	*p* value	Effect size Cohens d
Company fit	Oticon	-13.53	<0.001	-4.28
	Phonak	-19.0	<0.001	-6.01
	Resound	-9.79	<0.001	-3.1
	Starkey	-11.0	<0.001	-3.48
	Danavox	2.76	0.22	0.87
NALL NL 1	Oticon	-10.86	<0.001	-3.44
	Phonak	-6.86	<0.001	-2.17
	Resound	-13.41	<0.001	-4.24
	Starkey	-8.82	<0.001	-2.79
	Danavox	2.63	0.27	0.83
NAL NL 2	Oticon	-26.94	<0.001	-8.52
	Phonak	-1.15	0.27	-0.36
	Resound	3.01	0.02	0.95
	Starkey	-11.75	<0.001	-3.72
	Danavox	-0.21	0.44	-0.16
DSL v5	Oticon	-22.02	<0.001	-6.96
	Phonak	-1.12	0.11	0.74
	Resound	-7.57	<0.001	-2.39
	Starkey	-6.70	<0.001	-2.12
	Danavox	9.02	<0.001	2.85

4.1.3. Long term average speech spectrum (LTASS)

The mean & the standard deviation of LTASS revealed differences for low, mid- and high- frequency Long Term Average Speech Spectrum across companies in each formula, as shown in Figure 4.3 and confirmed statistically on ANOVA test (Table 4.6).

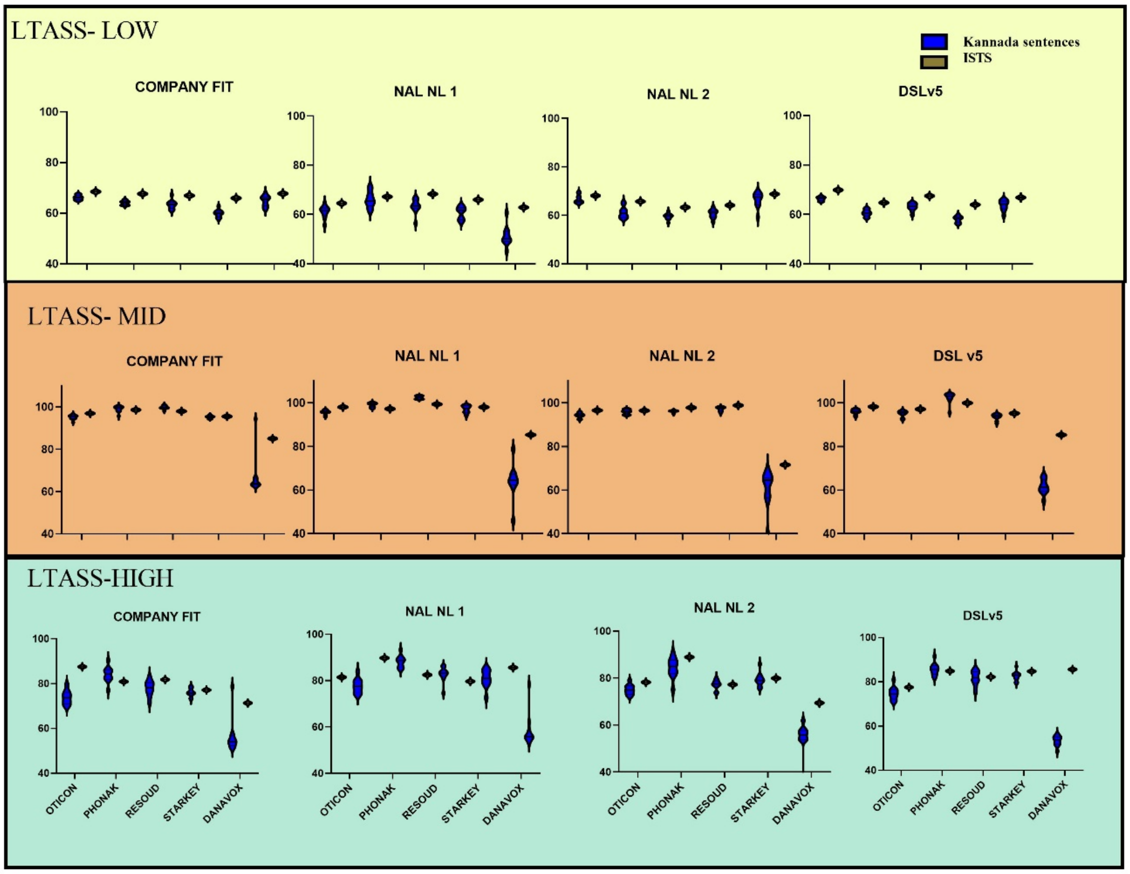

Figure 4.3. Comparison of low- frequency Long Term Average Speech Spectrum (average of frequencies from 12 – 1000 Hz in 1/3rd octaves), mid frequency Long Term Average Speech Spectrum (average of 1250 – 3000 Hz in 1/3rd octaves) and high- frequency Long Term Average Speech Spectrum (average of 3100 – 8000 Hz) across companies within each formula. The color shades correspond to each of the frequencies mentioned.

Table 4.6. *Results of ANOVA for the main effect of Companies on LTASS for each formula for Kannada sentences.*

	LTASS-Low		**LTASS-Mid**		**LTASS-High**	
Formulae	F(4,45)=, *p*=	η_p^2	F(4,45)= , *p*=	η_p^2	F(4,45)=, *p*=	η_p^2
Company Fit	23.82, <0.001	0.67	95.27, <0.001	0.89	51.17, <0.001	0.82
NAL NL 1	27.71, <0.001	0.71	61.97, <0.001	0.84	63.88, <0.001	0.85
NAL NL 2	36.92, <0.001	0.76	84.97, <0.001	0.93	67.29, <0.001	0.86
DSL v5	28.52, <0.001	0.68	78.55, <0.001	0.87	42.16, <0.001	0.79

As seen in table 4.6, there is a significant main effect of Companies in low, mid and high frequencies LTASS in each formula. The results of Bonferroni showed that the low-frequency LTASS of Danavox company was significantly higher (*p*<0.001) than

Starkey company, while the low-frequency LTASS of the former company was comparable to other companies tested ($p>0.05$). On the other hand, the low-frequency LTASS of the latter company (Starkey) was significantly lower than ($p<0.001$) all the other companies. For the mid- and high-LTASS, Danavox company consistently had significantly higher ($p<0.001$) values compared to the other companies tested, as shown in Table 4.7.

The one sample t test showed statistically significant differences between the Kannada sentences and International Speech Test Stimuli (ISTS) across the prescriptive formulae, more in the mid-frequencies compared to the high- and low-frequency as shown in the Table.4.8. For the low-frequency LTASS, ISTS sentences had significantly higher LTASS values than Kannada sentences in all companies for 3 out of 4 prescriptive formulae (Company fit, NAL-NL1, & NAL-NL2) except Starkey, in which the low-frequency LTASS between Kannada and ISTS were comparable. For the DSL-v5, in the low-frequency LTASS language based differences were only seen for Phonak company. For the high frequency-LTASS evident language differences were seen for all companies only in NAL-NL1 formula.

Table 4.7. *Results of Bonferroni test for pairwise comparisons of Low, Mid & High frequency LTASS values between companies for Kannada sentences*

		LTASS-LOW					**LTASS-MID**					**LTASS-HIGH**				
		Oticon	Phonak	Resound	Starkey	Danavox	Oticon	Phonak	Resound	Starkey	Danavox	Oticon	Phonak	Resound	Starkey	Danavox
Company fit	Oticon		0.05	0.01	<0.001	0.58		0.57	0.23	1	<0.001		<0.001	0.52	1	<0.001
	Phonak	0.05		1	<0.001	1	0.58		1	0.67	<0.001	<0.001		0.04	0.01	<0.001
	Resound	0.02	1		<0.001	0.39	0.23	1		0.28	<0.001	0.52	0.04		1	<0.001
	Starkey	<0.001	<0.001	<0.001		<0.001	1	0.66	0.27		<0.001	1	0.01	1		<0.001
	Danavox	0.58	1	0.39	<0.001		<0.001	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	
NAL-NL1	Oticon		0.001	1	1	<0.001		1	0.13	1	<0.001		<0.001	0.12	1	<0.001
	Phonak	0.001		0.08	<0.001	<0.001	1		1	1	<0.001	<0.001		0.12	0.01	<0.001
	Resound	1	0.08		1	<0.001	0.14	1		0.50	<0.001	0.12	0.13		1	<0.001
	Starkey	1	<0.001	1		<0.001	1	1	0.51		<0.001	1	0.01	1		<0.001
	Danavox	<0.001	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	
NAL NL2	Oticon		<0.001	<0.001	<0.001	1		1	1	1	<0.001		<0.001	1	0.39	<0.001
	Phonak	<0.001		0.47	1	<.001	1		1	1	<0.001	<0.001		0.01	0.18	<0.001
	Resound	<0.001	0.47		1	<.001	1	1		1	<0.001	1	0.01		1	<0.001
	Starkey	<0.001	1	1		<.001	1	1	1		<0.001	0.39	0.18	1		<0.001
	Danavox	1	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	
DSL v5	Oticon		<0.001	<0.001	<0.001	1		<0.001	1	1	<0.001		1	1	1	<0.001
	Phonak	<0.001		0.86	1	<0.001	<0.001		<0.001	<0.001	1	1		0.60	0.07	<0.001
	Resound	<0.001	0.87		1	<0.001	1	<0.001		1	<0.001	1	0.60		1	<0.001
	Starkey	<0.001	1	1		<0.001	1	<0.001	1		<0.001	1	0.07	1		<0.001
	Danavox	1	<0.001	<0.001	<0.001		<0.001	1	<0.001	<0.001		<0.001	<0.001	<0.001	<0.001	

Table.4.8. *Results of one sample t test comparing the low, mid & high frequencies LTASS values of Kannada and ISTS sentences across Companies within each formula.*

		LOW- LTASS			MID - LTASS			HIGH - LTASS		
	Companies	*t*(9)=	*p v*alue	cohens d	*t*(9)=	*p* value	cohens d	*t*(9)=	*p v*alue	cohens d
Company fit	Oticon	5.54	<0.001	1.75	28.88	<0.001	9.13	-13.59	<0.001	-4.29
	Phonak	18.7	<0.001	5.92	0.86	0.42	0.27	2.77	0.02	0.87
	Resound	7.8	<0.001	2.48	6.69	<0.001	2.11	1.88	0.09	0.59
	Starkey	-0.08	0.94	0.03	22.52	<0.001	7.12	1.49	0.17	0.47
	Danavox	6.13	<0.001	1.93	-4.52	0.001	-1.43	-5.8	<0.001	-1.83
NAL NL 1	Oticon	-4.28	0.002	-1.35	32.69	<0.001	10.34	-9.69	<0.001	-3.06
	Phonak	5.74	<0.001	1.81	1.26	0.24	0.39	8.91	<0.001	2.81
	Resound	4.66	0.001	1.47	19.92	<0.001	6.3	6.07	<0.001	1.92
	Starkey	0.87	0.41	0.27	12.59	<0.001	3.98	4.64	0.001	1.46
	Danavox	-6.85	<0.001	-2.16	-3.62	0.01	-1.15	-5.44	<0.001	-1.72
NAL NL 2	Oticon	4.02	0.01	1.27	26.28	<0.001	8.31	-18.65	<0.001	-5.9
	Phonak	3.4	0.01	1.07	-7.72	<0.001	-2.44	2.45	0.04	0.78
	Resound	1.35	0.21	0.42	-10.28	<0.001	-3.25	2.05	0.07	0.65
	Starkey	1.21	0.26	0.38	20.78	<0.001	6.57	4.57	0.001	1.44
	Danavox	5.7	<0.001	1.8	-7.61	<0.001	-2.4	-6.78	<0.001	-2.14
DSL v5	Oticon	-1.89	0.09	-0.6	25.21	<0.001	7.31	-8.61	<0.001	-2.72
	Phonak	4.94	<0.001	1.56	-6.62	<0.001	-2.12	-0.06	0.96	-0.02
	Resound	-0.44	0.67	-0.14	-9.28	<0.001	-3.1	1.42	0.19	0.45
	Starkey	1.03	0.33	0.33	19.58	<0.001	5.86	-0.19	0.85	-0.06
	Danavox	2.04	0.07	0.65	-6.14	<0.001	4.82	-5.45	<0.001	-1.72

4.2. Comparison of Objective Measures of Speech Intelligibility and Quality Across formulae Within Each company:

The differences in speech intelligibility (HASPI, SII), speech quality (HASQI), and spectral information (LTASS) across the formulae (Company fit, NAL NL 1, NAL NL 2, DSL v5) within each company are elaborated in this section..

4.2.1. Hearing Aid Speech Perception Index (HASPI) and Hearing Aid Speech Quality Index (HASQI):

The objective metrics HASPI and HASQI yielded similar values for Kannada and ISTS sentences for all the prescriptive formulae across companies. The mean (± one standard deviation) of HASPI & HASQI across formulae is given for each company separately as shown in Table 4.9, suggestive of similarity in the HASPI & HASQI values across formulas in each company. The results of ANOVA showed no main effect (*p*> 0.05) of the formulae on the HASPI & HASQI scores in each companies, as indicated in Table 4.9.

Table 4.9. *Comparison of mean and one SD of HASPI & HASQI across formulae within each company for Kannada sentences. The ANOVA results are shown in the right-most column.*

	Mean (SD)				*Main effect of Formulae*	
	Company Fit	*NAL NL 1*	*NAL NL 2*	*DSL v5*	*F(3,36) =, p =*	η_p^2
Oticon	0.41,(0.08)	0.40,(0.07)	0.41,(0.05)	0.40,(0.07)	0.88, 0.46	0.07
Phonak	0.40,(0.07)	0.41,(0.07)	0.41,(0.07)	0.42,(0.08)	0.83, 0.49	0.06
Resound	0.41,(0.06)	0.41,(0.07)	0.40,(0.08)	0.41,(0.10)	1.34, 0.28	0.1
Starkey	0.41,(0.09)	0.41,(0.08)	0.41,(0.07)	0.41,(0.10)	0.54, 0.66	0.04
Danavox	0.41,(0.06)	0.41,(0.05)	0.40,(0.09)	0.41,(0.07)	0.99, 0.40	0.07

The differences between the Kannada sentences and ISTS using one sample t test is shown in the following Table 4.10, The results of one sample t-test is shown in Table

4.10 reflective of similar HASPI and HASQI values (p>0.05) for Kannada sentences compared to ISTS for all the formulae within each company.

Table 4.10. *Comparison of mean and one SD of HASPI & HASQI values of Kannada and ISTS sentences across formulae within each company. Results of one sample t test for the comparing the HASPI & HASQI values of Kannada and ISTS sentences along with p value.*

Companies	Formulae	(Mean ± one SD)			
		Kannada	ISTS	t(9)=	p value
Oticon	Company fit	0.41,(0.77)	0.41	-1.76	0.11
	NAL NL 1	0.40,(0.66)	0.41	-1.44	0.42
	NAL NL 2	0.40,(0.54)	0.40	-2.71	0.54
	DSL v5	0.40,(0.63)	0.41	-2.02	0.61
Phonak	Company fit	0.40,(0.70)	0.40	-1.01	0.12
	NAL NL 1	0.40,(0.71)	0.39	-2.53	0.44
	NAL NL 2	0.40,(0.70)	0.40	-2.99	0.39
	DSL v5	0.41,(0.83)	0.41	-1.13	0.41
Resound	Company fit	0.40,(0.67)	0.40	-1.67	0.21
	NAL NL 1	0.41,(0.73)	0.40	-1.67	0.41
	NAL NL 2	0.40,(0.79)	0.40	-2.01	0.52
	DSL v5	0.40,(0.81)	0.41	-1.89	0.44
Starkey	Company fit	0.40,(0.81)	0.41	-1.00	0.29
	NAL NL 1	0.40,(0.85)	0.40	-2.86	0.43
	NAL NL 2	0.40,(0.77)	0.40	-2.24	0.55
	DSL v5	0.41,(0.89)	0.41	-1.42	0.42
Danavox	Company fit	0.40,(0.63)	0.41	1.90	0.14
	NAL NL 1	0.40,(0.58)	0.40	1.94	0.43
	NAL NL 2	0.40,(0.88)	0.39	2.85	0.50
	DSL v5	0.41,(0.65)	0.39	-1.62	0.48

4.2.2. Speech Intelligibility Index (SII):

The mean & the one standard deviation of SII across formulae in each company is shown in Table 4.11, indicative that company fit had significantly higher SII values for Kannada sentences, compared to other prescriptive formulae in all companies except Danovox. The main effect of prescriptive formulae on SII value was verified statistically using ANOVA test, as shown in right hand column of the table. 4.11. The main effect of prescriptive formulae on SII was seen for all companies except Oticon.

Table 4.11. *Comparison of mean and one SD of SII values across formulae within each company for Kannada sentences. The ANOVA results are shown in the right-most column.*

	(Mean ± one SD)				*Main effect of Formulae*	
	Company Fit	NAL NL 1	NAL NL 2	DSL v5	*F*(3,36)= , *p* =	η_p^2
Oticon	0.48,(0.32)	0.41,(0.35)	0.39, (0.24)	0.43,(0.31)	0.39,0.76	0.03
Phonak	0.55,(0.39)	0.48,(0.31)	0.37,(0.26)	0.39,(0.29)	23.45, <0.001	0.66
Resound	0.68,(0.27)	0.41,(0.34)	0.42,(0.37)	0.40,(0.29)	38.29, <0.001	0.76
Starkey	0.51,(0.32)	0.37,(0.29)	0.37,(0.02)	0.48,(0.28)	17.74, <0.001	0.59
Danavox	0.42,(0.25)	0.40,(0.28)	0.38,(0.21)	0.39,(0.25)	5.51, 0.01	0.31

The results of post-Hoc Bonferroni test shown in the Table 4.12, showed that NAL-NL 2 is statistically lower from other prescriptive formulae for Oticon and Phonak companies, while for Starkey NAL-NL 2 was statistically lower from company-fit and DSL v5. No statistical difference between any of the formulae (Company fit, NAL-NL1 & NAL-NL2 & DSL V5) was seen in Danavox company.

Table 4.12 *Results of Bonferroni test for pairwise comparisons of SII values across formulae within each company for Kannada sentences*

		Company Fit	NAL NL 1	NAL NL 2	DSL v5
PHONAK	Company fit		1	<0.001	<0.001
	NAL NL 1	1		<0.001	<0.001
	NAL NL 2	<0.001	<0.001		1
	DSL v5	<0.001	<0.001	1	
RESOUND	Company Fit		1	<0.001	0.29
	NAL NL 1	1		<0.001	1
	NAL NL 2	<0.001	<0.001		<0.001
	DSL v5	0.25	1	<0.001	
STARKEY	Company Fit		0.001	<0.001	1
	NAL NL 1	0.001		0.87	<0.001
	NAL NL 2	<0.001	0.86		<0.001
	DSL v5	1	<0.001	<0.001	
DANAVOX	Company Fit		1	0.36	0.31
	NAL NL 1	1		0.64	1
	NAL NL 2	0.35	0.64		0.02
	DSL v5	0.31	1	0.2	

The differences between the Kannada sentences and International Speech Test Stimuli (ISTS) using one sample t test is shown in the table 4.13, which revealed SII of ISTS was greater than Kannada sentences across formulae in all the companies (i,e Oticon, Phonak, Resound, Starkey and Danavox).

Table 4.13. *Results of one sample t - test comparing the SII values of Kannada and ISTS sentences across formulae within each company.*

		(Mean ± one SD)		t-test results		
Companies	Formulae	Kannada	ISTS	*t*(9)=	*p* value	Cohens d
Oticon	Company fit	0.48,(0.32)	0.65	-1.76	0.19	-0.71
	NAL NL 1	0.41,(0.35)	0.61	-8.44	<0.001	-5.83
	NAL NL 2	0.39,(0.24)	0.62	-9.71	<0.001	-4.65
	DSL v5	0.43,(0.31)	0.63	-11.02	<0.001	-6.96
Phonak	Company fit	0.48,(0.39)	0.62	-9.01	<0.001	-2.85
	NAL NL 1	0.48,(0.31)	0.68	-14.53	<0.001	-9.02
	NAL NL 2	0.37,(0.26)	0.64	-4.99	<0.001	-1.58
	DSL v5	0.39,(0.29)	0.62	-11.13	<0.001	-6.36
Resound	Company fit	0.55,(0.27)	0.62	-3.67	<0.001	-1.16
	NAL NL 1	0.41,(0.34)	0.63	-12.67	<0.001	-8.97
	NAL NL 2	0.42,(0.37)	0.62	-3.01	<0.001	-0.95
	DSL v5	0.40,(0.29)	0.63	-13.89	<0.001	-5.66
Starkey	Company fit	0.68,(0.32)	0.64	17.01	<0.001	6.01
	NAL NL 1	0.37,(0.29)	0.62	-24.86	<0.001	-7.86
	NAL NL 2	0.42,(0.37)	0.63	-7.24	<0.001	-2.29
	DSL v5	0.48,(0.28)	0.62	-13.42	<0.001	-4.24
Danavox	Company fit	0.51(0.25)	0.67	8.90	<0.001	2.81
	NAL NL 1	0.40,(0.28)	0.66	1.94	0.08	0.61
	NAL NL 2	0.38,(0.21)	0.73	3.85	0.004	1.22
	DSL v5	0.39,(0.25)	0.66	-11.62	<0.001	-3.67

4.2.3. Long Term Average Speech Spectrum:

The mean & the standard deviation of LTASS across formulae in each company are shown in table 4.14, indicative of differences in LTASS values at low, mid and high frequencies across formulas in each company. These differences were also verified statistically using ANOVA test, as shown in the table 4.15, suggestive of main effect of formulae on 4/5 companies (all except Starkey) in low-frequency LTASS, 2/3 companies (Phonak, Resound) in mid-frequency LTASS and only Resound in high-frequency LTASS. Results of Bonferroni pairwise comparison showed significant differences between the formulae, in all companies except Danovox in mid- and high-frequencies LTASS values. In Danavox significant differences between formulae were confined only to low-frequency LTASS as seen in Table 4.16. In addition, the results of one-sample t-test for comparing LTASS of Kannada and ISTS revealed that there was a significant higher LTASS values for ISTS sentences compared to Kannada sentences.

Table 4.14. *Comparison of mean and one SD (in parentheses) of low- frequency LTASS, mid- frequency LTASS and high- frequency LTASS across formulae within each Company for Kannada sentences.*

		Kannada sentences				ISTS			
		Company fit	NAL NL 1	NAL NL 2	DSL V5	Company fit	NAL NL 1	NAL NL 2	DSL V5
Oticon	Low	66.18, (0.95)	61.03,(2.56)	66.6,(1.69)	67.60,(1.69)	64.52	64.53	69.09	71.89
	Mid	81.10,(1.12)	91.60,(1.04)	90.20,(1.13)	91.70,(1.96)	88.93	94.07	93.03	96.25
	High	73.80,(3.18)	71.70,(3.21)	75.01,(2.12)	71.91,(3.53)	87.55	74.43	78.01	75.55
Phonak	Low	64.16,(.93)	67.83,(5.05)	61.20,(2.38)	61.20,(2.38)	69.66	72.19	65.71	67.77
	Mid	93.90,(1.45)	91.01,(1.03)	89.90,(1.1)	66.09,(9.09)	98.62	93.25	94.48	97.33
	High	84.00,(3.58)	88.10,(2.59)	84.30,(4.38)	80.82,(3.86)	89.91	91.75	87.91	86.87
Resound	Low	63.39,(1.78)	63.30,(2.96)	59.50,(1.30)	59.50,(1.30)	68.97	72.31	62.28	63.49
	Mid	92.70,(0.86)	91.14,(0.71)	93.03,(0.59)	91.14,(1.12)	97.95	96.37	97.83	97.95
	High	77.90,(3.53)	82.90,(3.72)	77.15,(2.06)	76.80, (2.38)	82.82	87.45	88.2	85.27
Starkey	Low	58.89, (1.48)	60.6,(2.53)	60.6,(1.81)	60.60,(1.81)	63.94	66.98	65.51	67.96
	Mid	91.20, (0.67)	93.14,(1.66)	90.16,(1.01)	92.60,(1.04)	94.51	98.05	94.86	95.21
	High	76.03, (1.85)	80.80,(3.86)	79.32,(2.88)	75.01,(2.12)	79.15	84.65	82.88	79.73
Danavox	Low	64.85,(2.12)	51.20,(4.3)	67.07,(1.92)	66.40,(3.14)	68.73	62.87	54.74	69.85
	Mid	67.18,(9.64)	66.1,(10.1)	60.60,(8.45)	64.30,(1.95)	81.03	85.33	71.63	85.33
	High	56.40,(8.07)	58.50,(7.39)	53.90,(8.09)	57.20,(8.17)	71.33	85.61	69.38	85.62

Table 4.15. *Results of LTASS for the main effect of formulae for each Company*

	LTASS-Low		**LTASS- Mid**		**LTASS-High**	
	F(3,36)=, *p* =	η_p^2	F(3,36)=, *p* =	η_p^2	F(3,36)=, *p*=	η_p^2
Oticon	22.8, <0.001	0.66	3.83, 0.02	0.24	3.63, 0.02	0.23
Phonak	10.43, <0.001	0.46	22.75, <0.001	0.66	2.73, 0.06	0.19
Resound	12.82, <0.001	0.52	46.48, <0.001	0.79	9.01, <0.001	0.43
Starkey	0.35, 0.79	0.02	6.72, 0.001	0.36	4.68, 0.01	0.28
Danavox	58.58, <0.001	0.83	1.20, 0.33	0.09	0.81, 0.50	0.06

.

Table 4.16. *Results of test for pairwise comparisons of low-, mid-, high-frequency LTASS values across formulae within each company for Kannada sentences*

		LOW-LTASS				**MID-LTASS**				**HIGH-LTASS**			
		Company Fit	NAL NL1	NAL NL 2	DSL v5	Company Fit	NAL NL 1	NAL N 2	DSL v5	Company Fit	NAL NL 1	NAL NL 2	DSL v5
Oticon	Company Fit		<0.001	1	1		1	0.56	0.57		0.18	1	1
	NAL NL 1	<0.001		<0.001	<0.001	1		0.47	0.46	0.18		0.2	0.2
	NAL NL 2	1	<0.001		1	0.57	0.47		1	1	0.2		1
	DSL v5	1	<0.001	1		0.56	0.48	1		1	0.2	1	
Phonak	Company Fit		0.68	<0.001	<0.001		1	<0.001	<0.001		0.13	1	1
	NAL NL 1	0.68		<0.001	<0.001	1		<0.001	<0.001	0.12		0.17	0.17
	NAL NL 2	0.22	<0.001		1	<0.001	<0.001		1	1	0.17		1
	DSL v5	0.23	<0.001	1		<0.001	<0.001	1		1	0.18	1	
Resound	Company Fit		1	<0.001	<0.001		0.03	<0.001	<0.001		0.01	1	1
	NAL NL 1	1		<0.001	<0.001	0.03		<0.001	<0.001	0.01		<0.001	<0.001
	NAL NL 2	<0.001	<0.001		1	<0.001	<0.001		1	1	<0.001		1
	DSL v5	<0.001	<0.001	1		<0.001	<0.001	1		1	<0.001	1	
Starkey	Company Fit		1	1	1		0.01	0.01	0.01		0.01	0.11	0.1
	NAL NL 1	1		1	1	0.01		1	1	0.01		1	1
	NAL NL 2	1	1		1	0.01	1		1	0.1	1		1
	DSL v5	1	1	1		0.01	1	1		0.11	1	1	
Danavox	Company Fit		<0.001	0.87	1		1	0.93	0.90		1	1	1
	NAL NL 1	<0.001		<0.001	<0.001	1		1	1	1		1	1
	NAL NL 2	0.85	<0.001		1	0.94	1		1	1	1		1
	DSL v5	1	<0.001	1		0.91	1	1		1	1	1	

Table 4.17. *Results one sample t - test comparing the low, mid & high LTASS across of Kannada and ISTS sentences across formulae within each company.*

		LOW -LTASS			MID-LTASS			HIGH-LTASS		
	Formula	*t*(9)=	*p* value	(cohens d)	*t*(9)=	*p* value	(cohens d)	*t*(9)=	*p* value	(cohens d)
Oticon	Company Fit	0.99	0.35	0.31	10.99	<0.001	3.42	-1.69	0.125	-0.52
	NAL NL 1	4.11	0.01	1.3	-4.37	0.01	-1.35	-6.01	<0.001	-1.89
	NAL NL 2	15.27	<0.001	4.84	-2.53	0.03	-0.8	-1.76	0.11	-0.56
	DSL v5	2.35	0.04	0.75	12.56	<0.001	3.9	-6.87	<0.001	-2.17
Phonak	Company Fit	-5.85	<0.001	-1.8	16.87	<0.001	5.3	7.49	<0.001	2.38
	NAL NL 1	6.34	<0.001	1.9	5.74	<0.001	1.84	5.37	<0.001	1.69
	NAL NL 2	3.62	0.01	1.15	2.02	0.073	0.64	5.83	<0.001	1.84
	DSL v5	1.34	0.21	0.43	-7.06	<0.001	-1.77	4.17	0.01	-1.23
Resound	Company Fit	-4.33	0.01	-1.4	31.13	<0.001	9.78	2.11	0.06	0.68
	NAL NL 1	-5.93	<0.001	1.87	23.54	<0.001	7.48	-0.7	0.5	-0.22
	NAL NL 2	2.52	0.03	0.82	4.49	0.01	1.42	1.44	0.18	0.46
	DSL v5	-2.13	0.06	-0.68	16.98	<0.001	5.37	-11.53	<0.001	-3.64
Starkey	Company Fit	-12.99	<0.001	-4.02	18.98	<0.001	5.93	0.82	0.44	0.29
	NAL NL 1	3.56	0.01	1.12	0.034	0.97	-0.59	-2.43	0.04	-0.76
	NAL NL 2	3.78	0.01	1.19	6.12	<0.001	1.94	3.41	0.01	1.07
	DSL v5	-0.31	0.76	-0.09	19.9	<0.001	6.29	-15.75	<0.001	-4.92
Danavox	Company Fit	-2	0.16	-0.48	-7.89	<0.001	-2.5	-7.47	<0.001	-2.35
	NAL NL 1	4.71	0.01	-1.49	-7.53	<0.001	-2.4	-10.79	<0.001	-3.41
	NAL NL 2	15.37	<0.001	4.47	-13.94	<0.001	-4.08	-8.71	<0.001	-2.75
	DSL v5	0.75	0.47	0.24	-40.19	<0.001	-12.7	-10.98	<0.001	-3.47

Chapter 5
DISCUSSION

The objectives of the study were to verify the intelligibility and quality of hearing aid processed speech across companies and prescriptive formulae using objective measures, and to measure language-based differences in these objective measures. The objective measures that were used for the analyses of hearing aid processed speech were Hearing Aid Speech Perception Index (HASPI), Hearing Aid Speech Quality Index (HASQI), Speech Intelligibility Index (SII) and Long Term Average Speech Spectrum (LTASS).

5.1. Comparison of objective measures of speech intelligibility and quality across companies within each formula.

5.1.1. HASPI and HASQI. The ANOVA test results showed no main effect of companies on the HASPI and HASQI (Table 4.1), suggestive that when hearing aids are programmed effectively using any fitting rationale there would not be any qualitative difference or intelligibility differences in the processed output. When the HASPI and HASQI values for Kannada and International Speech Test Stimuli (ISTS) were compared, similarities between languages across companies was noted on one sample t-test (Table 4.2). The reason attributed to this finding can be linked to the construction of ISTS material. ISTS was constructed from speech of 21 female speakers, speaking 6 languages (Holube et al., 2010) and it followed international LTASS (Byrne et al., 1994). Kannada sentences were also spoken by female speaker and constructed taking into account phonemic and phonetic concentration of the language (Geetha et al., 2021). As the vocal apparatus is similar (both languages spoken by female speakers) and the acoustics were well controlled, the HASPI and HASQI revealed no differences between the Kannada and ISTS sentences.

5.1.2. *Speech Intelligibility Index (SII).*

The mean of SII of Kannada sentences is significantly higher in Danavox company compared to other companies (Figure 4.2, Table 4.4), for all the prescriptive formulae. The reason behind this result can be attributed to the hearing aid design in Danavox company. Danavox ear hook's acoustic damper incorporated by the manufacturer gives a reasonably smooth response till 6000 Hz, thus improving the acoustic output resulting in higher SII values, compared to other companies.

When the language based differences were analysed, one sample t-test showed that higher mean SII values for ISTS compared to Kannada sentences, for all the companies in each prescriptive formula. ISTS contains all characteristics of natural speech, voiced and unvoiced fragments that are easily recognised by human listeners as corresponding to natural speech, whose dynamic range resembles natural speech (20 to 30 dB). ISTS displays a variety of phonological structures and fundamental frequency variations that correspond to a number of different languages (Holube et al., 2010)The prescriptive formulae prescribe gain of the hearing aids using the universal LTASS (ULTASS, Byrne et al., 1994), whose characteristics are imbibed in ISTS (Holube et al., 2010). The hearing aids programmed to prescriptive formulae which account for ULTASS and thus indirectly ISTS gives the advantage to the latter, in terms of SII.

5.1.3. *Long term average speech spectrum (LTASS).*

The mean & the standard deviation of LTASS revealed differences for low, mid & high frequency LTASS across companies in each formulae (Figure 4.3), it can be due to differences in the components (microphone, amplifier, receiver frequency characteristics) of hearing aid across companies. Another probable reason could be different signal processing and/or pre-processing schemes (algorithms) employed in different hearing aid companies (Launer et al., 2016). The results of Bonferroni test showed that Danavox company had significantly higher LTASS values (Table 4.5) compared to Starkey company in low frequencies. In addition, Danavox company hearing aids had better LTASS values at mid- and high- frequencies when compared with all other companies in the study (Table 4.5). This could be attributed to better resolution of frequency fourier transform (FFT) signal processing adopted in Danavox company to other companies (Moore, 1995). The better resolution of FFT is important cue for consonant coding relative to its effectiveness for vowel coding (Schweitzer, 1997), which translates as benefits for Danavox hearing aids having better LTASS values at mid- and high- frequencies respectively (which are important for consonant perception).

The results of one-sample t test showed that ISTS sentences had significantly higher LTASS values across companies, specifically at mid-frequencies compared to the high- and low-frequencies (Table 4.8). The reason for this finding can be related to significantly lower LTASS values in mid and high frequency for Kannada language compared to ULTASS (Nisha & Manjula, 2013; Narne et al., 2021), whose LTASS is similar to ISTS (Holube et al., 2010). Kannada, is predominantly vowel specific language which has low frequency energy (Nisha & Manjula, 2013; Narne et al., 2021), while ISTS languages are predominantly consonant specific with more mid and high frequency composition (Holube et al., 2010). Therefore, LTASS of mid- and high frequency were better for ISTS compared to Kannada sentences.

5.2. Comparison of Objective Measures of Speech Intelligibility and Quality Across formulas Within Each company:

5.2.1. HASPI and HASQI.

The ANOVA test results showed no main effect of prescriptive formulae on HASPI & HASQI values for all companies (Table 4.9), indicative of adequate intelligibility (HASPI) and quality (HASQI) in the hearing aid processed output values across formulae in each company. The reason could be traced to the high efficacy of the target gain fitting procedures adopted across fitting formulae (Company fit, NAL NL 1, NAL NL 2, DSL V5) in each company. Fitting rationale are set of rules that determine the gain of hearing aid, calculated according to a verified arithmetic formula,(Metselaar, 2010). For non linear hearing aids, this prescribed gain is dependent on the input level of sound, with more gain for low inputs and less gain for louder input levels. Although inherent variations in the gain prescription for low vs high level inputs are seen across formulae (eg., NAL-NL1 prescribes slightly higher gain for lower input levels and too low gain for higher input levels, whereas NAL NL 2 provide same gain across all the inputs, Keidser et al., 2012), such differences are nullified in the present study as the presentation level was maintained constant at 65 dB SPL. As all the fitting formulae used in current study were established protocols for non-linear hearing aids and presentation level was maintained constant throughout all recording conditions, output of hearing aids programmed to these well-established fitting rationale yielded similar HASPI and HASPI values irrespective of formula used for all companies.

The objective metrics HASPI and HASQI yielded similar values for Kannada and International Speech Test Stimuli (ISTS) sentences across all the formulae (Table 4.10). The reason for this finding can be attributed to similarity in vocal dynamics as both ISTS and Kannada are recorded by female speakers (as highlighted in Section 5.1.1), and considering adequate gain prescribed across the formulae, no difference in the acoustic quality and intelligibility of the HA processed output was found.

5.2.2. LTASS and SII. Results of SII comparison across prescriptive formulae revealed that company fit had significantly higher SII values for Kannada sentences, compared to other three prescriptive formulae (NAL NL 1, NAL NL 2 & DSL V5) in all companies except Danovox (Table 4.11). The superiority of company fit over other rationale in terms of SII can be viewed as incorporation of proprietor specific features in programming /software simulations which are directly reflective of a particular hearing aid being programmed. In other words, proprietary softwares specific to each company provide estimations of real-ear hearing aid responses associated with a fitting algorithm, taking into account the specific characteristics of the hearing aid including pre-processing, signal processing and suitable corrections specific to related to the age of the patient, the earmold or shell type, venting size, and tubing characteristics, entered in the company-specific softwares (K. Smeds & Leijon, 2001). This gives an edge for the manufacturer fitting algorithm to better adapt and match the consumer specific requirements, and its benefits are realised in increased intelligibility as reflected on better SII values. On language specific differences, ISTS had significantly better SII values than Kannada sentences across formulae (Table 4.13), for reasons discussed in section 5.1.2.

For LTASS, the main effect of formulae was seen in 4/5 companies (all except Starkey) in low-frequency LTASS, 2/3 companies (Phonak, Resound) in mid-frequency LTASS and only Resound in high-frequency LTASS (Table 4.14). The differences in LTASS across frequencies indicate the variations in gain provided by different prescriptive formulae across frequency, despite the fact that the hearing aid was programmed for moderate flat hearing loss (Section 3.3.2). On language specific differences, ISTS had significantly higher LTASS values compared to Kannada sentences across formulae (Table 4.17), for reasons discussed in section 5.1.3.

Chapter 6

SUMMARY & CONCLUSIONS

The present study was carried out to compare the hearing aid outcomes of speech intelligibility and quality across companies and across formulae using the objective measures like Hearing Aid Speech Perception Index(HASPI), Hearing Aid Speech Quality Index (HASQI), Speech Intelligibility Index (SII) & Long Term Average Speech Spectrum (LTASS). Additionally, the study evaluated the hearing aid processed speech for Kannada sentences which was compared with the International Speech Test Stimuli (ISTS) sentences. The output from the digital eight channel digital hearing aid programmed to the four fitting formulae Company fit (manufacturer fit), National Acoustics Laboratory Nonlinear version 1 (NAL-NL1), National Acoustics Laboratory Nonlinear version 2 (NAL-NL 2) and Desired Sensation Level version 5.0 (DSL V5), were recoded using sound level meter (SLM) connected to the manikin (KEMAR). The hearing aid belonged to five companies of the Hearing aid were used in the present study (Oticon, Phonak, Resound, Starkey & Danavox).

From the findings of the present study, the following recommendations are made:

- The HASPI and HASQI yielded similar values across all companies and prescriptive formulae. There was no difference in HASPI/HASQI value between Kannada and ISTS sentences. It can hence be concluded that when hearing aid are programmed according to pre-determined standard procedures, speech intelligibility (HASPI) and quality (HASQI) can be adequately achieved, irrespective of the variations in the prescriptive formula, company and/or language inputs.
- The SII across companies in each formula indicate a higher mean SII values for company fit compared to other formulae, while Danovox hearing aids showed

significantly higher SII values relative to the other companies. This finding was consistent for LTASS values too. Based on the above finding, it is recommended that Audiologists can prefer programming hearing aid based on company fit to maximize hearing aid benefits. Similarly, among the companies Danovox can be preferred, although caution should be exercised as this finding is only applicable to the hearing models used in the study.

- The SII and LTASS of ISTS was higher than Kannada sentences, with pronounced differences seen in mid- and high-frequency LTASS for all the prescriptive formulae and companies. This finding adds on to literature (Narne et al., 2021;Nisha & Manjula, 2013) emphasizing the need to establish language specific programming of hearing aids accounting for spectral variations across languages. Such an effort is need of the hour in a multi-linguistic nation like India where bilingualism and multilingulism are commonly encountered.

The future Implications of the study are:

- The comparisons in the present study using objective measures is done on a small sample (10 Kannada sentences, one ISTS sentence) phonated by only female. It is important to validate in larger sample size, using both male and female recordings.
- All the stimuli used were presented at a single level i.e. 65 dB SPL. However, as the gain of the hearing aid fitted using nonlinear fitting procedure varies with input levels, it would be interesting to see the effect of the input levels on hearing aid output using objective measures.
- The study can also be carried out in real ears, to account for individual variations in the pinnal resonance.

- It is also important to find out the effect of prescriptive formulae on the perceptual measures of speech quality and intelligibility. Also, a correlation between the objective measures and subjective measures would provide important clues to make recommendations on the optimal assessment procedures for inferring the prescriptive formulae-based changes in hearing aid outputs.
- This same study can also be carried out, on different degrees, type, configurations and duration of hearing losses, which invariably affect hearing aid acclimatization and gain prescribed by the fitting rationale.
- If a definite trend is observed on the above variables, then it can be safely assumed that the differences are typically seen and this data can be used to develop a new prescriptive formula.

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