HEARING AID SELECTION
USING
SPEECH INTELLIGIBILITY INDEX

A DOCTORAL THESIS

Submitted to the University of Mysore,
for the award of degree of
Doctor of Philosophy (Ph.D) in Speech & Hearing.

By

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Under the Guidance of

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CERTIFICATE

This is to certify that the thesis entitled, **Hearing Aid Selection Using Speech Intelligibility Index,** submitted by Ms. P. Manjula, for the degree of the Doctor of Philosophy in Speech and Hearing, to the University of Mysore, was carried out at the All India Institute of Speech & Hearing, Mysore, under my guidance.

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DECLARATION

I declare that this thesis entitled, **Hearing Aid Selection Using Speech Intelligibility Index,** which is submitted herewith for the award of the Doctor of Philosophy in the field of Speech & Hearing to the University of Mysore, Mysore, is the result of the work, carried out by me at the All India Institute of Speech & Hearing, Mysore, under the guidance of Dr. Asha Yathiraj, Professor of Audiology, All India Institute of Speech & Hearing, Mysore. I further declare that the results of this work have not been submitted for any degree.

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Acknowledgements

At the outset, I would like to sincerely thank my mentor Dr. Asha Yathiraj, Professor of Audiology, All India Institute of Speech & Hearing, Mysore, for her invaluable guidance. She has always been there to help me when I needed her advice and encouragement the most. Thank you very much Madam.

I would like to express my gratitude to Dr. Vijayalakshmi Basavaraj, Director, All India Institute of Speech & Hearing, Mysore, for permitting me to carry out this study.

I thank Dr. Rajalakshmi, Reader and Head of the Audiology Department, All India Institute of Speech & Hearing, Mysore, for allowing me to use the department facilities to carry out the research.

I am gratefully indebted to my friend Dr. Vanaja, C.S., Professor of Audiology, BVB Instiute, Pune, for her constant help, encouragement and moral support in each and every stage of the work.

I would like to thank the Staff Dept. of Electronics for calibrating the equipment when needed. I am thankful to Ms. Chudamani, B.R, Junior Technical Officer, All India Institute of Speech & Hearing, Mysore, for extending the technical support.

I wish to thank Ms. Ramadevi, for her help in converting the speech test material into IPA.

I am thankful to Ms. Vasanthalakshmi, Dr. Lancy D'Souza and Dr. Venkatesan who helped me out in statistical analyses.

My thanks are due to Mr. Vijay Kumar Name, Ms. Vijayalakshmi, C.S., Mr. Ajith Kumar.U., Mr. Sandeep.M. and Mr. Santhosh.M. for the timely help rendered.

The flexible attitude towards my study on the part of all my department colleagues is warmly acknowledged.

I am thankful to all my subjects without whose co-operation this work would not have been possible.

I wish to thank my friends, VMABHLSSR, for their encouragement.

Thanks are also due to Mr. Shivappa and his team.

I am greatly indebted to my parents, though not with me physically, for their blessings and encouragement in every step of my life. I appreciate the encouragement and support given by my sisters and brothers-in-law.

I would like to acknowledge the support of Chikki and parents-in-law.

I am thankful to my husband Mr. Vijayakumar, for the support and help throughout this research.

Last but not the least, my special thanks to my son **DEAR VRUSHANK,** for his co-operation and for allowing me to spend my time in doing this work.

Warm thanks are also due to all those who have directly or indirectly helped me to make this thesis a reality.

Maatru devo bhava
Pitru devo bhava
Acharya devo bhava

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS USED IN THE STUDY

1. SRS: The Speech Recognition Scores for phonemically balanced words which ranged from 0 to 25.
2. SII: The Speech Intelligibility Index, which was the product of band audibility and band importance function. The SII ranged from 0 to 1.
3. SIIw: The SII computed with band importance functions for words.
4. Sllas: The SII computed with band importance functions for average speech.
5. SIIW_{SLD} : The basic SIIw with a correction factor for speech level distortion (SLD) was abbreviated to SIIW_{SLD} . The SLD accounted for the distortion that occurs due to high presentation levels of greater than 73 dBSPL. The SLD factor accounts for the deterioration in speech recognition performance at high sound pressure levels (Ching, Dillon, Katsch & Byrne, 1998).
6. $\mathrm{SIIw}_{SLD, HLD}$: A correction factor for hearing loss desensitization (HLD), incorporated to SIIW_{SLD} . The HLD factor accounted for the reduced ability of the cochlea to extract useful information from increased audibility once the hearing loss crosses 70 dB HL (Ching, Dillon, Katsch & Byrne, 1998).

LIST OF APPENDICES

INTRODUCTION

Hearing plays a vital role in communication through speech. It is a fundamental requirement for most of the activities of life and a pre-requisite for a fully effective participation in our world of communication. The major problem in individuals with a hearing impairment is that they face problems in communication as they cannot detect the auditory signals well. The audibility of sounds is affected in them and restoring audibility is the single most critical factor in providing effective amplification (Ching, Dillon, Katsch & Byrne, 2001). This in turn would result in effective communication. There has been no debate, since the 1800s, that hearing aids do make sounds audible to individuals with a hearing impairment. However, there has been considerable concern regarding the method to be used while selecting hearing aids (Alpiner, 1974).

The goal of hearing aid selection includes selecting hearing aids that make speech audible, comfortable and good in quality as far as possible (Palmer, Lindley & Mormer, 2000). Skinner (1988) also had opined that for a successful fitting, a hearing aid should provide the necessary amplification to maximize speech recognition, provide good sound quality and provide amplification that is comfortable. The hearing aid selection procedures try to fit hearing aids in the residual dynamic range of an individual with hearing impairment. This goal of hearing aid fitting is a key factor in various procedures that have been developed over the years.

Broadly two approaches have been used to select hearing aids for individuals with a hearing impairment. They are the comparative approaches and prescriptive approaches. In the comparative approach, the focus is on auditory experience, such as speech recognition ability (Carhart, 1946), intelligibility judgments (Zerlin, 1962) or quality judgements (Jeffers, 1960), with different hearing aids. Prescriptive approaches on the other hand focus on the auditory potential and specify the required electroacoustic characteristics based on the audiometric findings. These procedures are different for linear and non-linear hearing aids. A few of these prescriptive procedures for linear hearing aids include the Prescription Of Gain and Output (POGO) by McCandless, and Lyregaard (1983); National Acoustics Laboratory - Revised (NAL-R) by Byrne, and Dillon (1986); POGO II by Schwartz, Lyregaard, and Lundh (1988); and NAL-R for profound hearing loss (NAL-RP) by Byrne, Parkinson, and Newall (1990). A few procedures used for selection of non-linear hearing aids are FIG6, which is a procedure based on Figure 6 in a publication by Killion, and Fikret-Pasa (1993), Desired Sensation Level -input/output (DSL $i/_0$) by Cornelisse, Seewald, and Jamieson (1995); and NAL - Non-Linear-1 (NAL-NL1) by Dillon (1999). Thus, several procedures have been developed to select appropriate hearing aids that can solve one of the most ubiquitous problems faced by individuals with a hearing impairment, which is the reduced ability to understand speech.

In some of the hearing aid selection approaches, audibility within the speech spectrum has been used as a guiding principle for setting the gain requirements of the hearing aid (Sandlin, 1990). A procedure for hearing aid selection based on audibility within the speech spectrum, that has gained prominence in the last two decades, is the articulation index (AI). It has been found by Ching, Dillon, and Byrne (1998) that in the AI technique, speech recognition increased in direct proportion to speech audibility, which was calculated from the hearing thresholds of the listener and the long-term average speech spectra reaching the ear of the listener. This method ensured good speech perception (Pavlovic, 1989). As the AI is directly correlated to speech recognition, a higher value of AI has been noted to enable the audiologist to predict higher speech recognition scores, while adjusting the gain of a hearing aid (Zelnick, 1991).

Prior to AI being used for hearing aid selection, it had been used successfully to predict speech recognition performance of normal hearing listeners under a variety of listening conditions such as filtering, noise, distortion and low levels of speech (Pavlovic, Studebaker & Sherbecoe, 1986). In individuals with a hearing impairment too, the AI has gained acceptance as a method for estimating the audibility of speech, from the long-term average speech spectrum (Dubno & Dirks, 1993). From such studies, it is evident that audibility is an important component for auditory performance.

The AI has been modified and given other terms such as importance weighted audibility index -1 WAI (Studebaker & Marincovich, 1989) or speech intelligibility index - SII (ANSI - S3.5, 1997) or audibility index (Sherbecoe & Studebaker, 2003). These modifications were based on the studies that were carried out to improve the predictive ability of the AI in individuals with a hearing impairment (Ching, Dillon, Katsch & Byrne, 2001; Pavlovic, 1993; Studebaker & Sherbecoe, 1993). In the modified version of ANSI S3.5 (1997), the term speech intelligibility index (SII) was used instead of AI. In this procedure, correction factors such as speech level distortion (SLD) and hearing loss desensitization (HLD) have been included in the original AI function, in order to improve the prediction of speech recognition from the AI.

The AI has been thought of as a single number descriptor of several electroacoustic characteristics of a hearing aid. It has been found to go beyond the other electroacoustic measures as it takes into consideration what is audible to the listener and the importance of a particular portion of the signal in speech recognition (Studebaker & Marincovich, 1989). There has been a revived interest in the use of AI for hearing aid selection since the early 1990s, as simplified and computerized procedures have been developed (Zelnick, 1991).

According to Pavlovic (1989), the AI or SII enables an audiologist to decide how the gain of the hearing aid should be changed to increase speech intelligibility. This is because the AI gives an indication on an audiogram regarding the effect of a given hearing aid and the threshold on the speech spectrum.

Articulation index procedures have been proposed to help differentiate the effect of electroacoustic characteristics of different hearing aids. Dugal, Braida, and Durlach (1980), Fletcher (1952) and Pavlovic (1989) have reported that the SII can be used to specify the frequency-gain characteristics of a hearing aid to optimize the filter setting. They have further opined that the SII can be used to determine the boundaries of each filter setting in a multi-channel hearing aid. Further, Souza, and Turner (1999) have reported that increasing the amount of audible speech information played the same role in recognition for compression-amplified as well as for linearly amplified speech. This suggested that for the conditions tested, compression did not introduce any detrimental changes in the speech signal to offset the benefits of improved audibility.

The SII has been reported, by Zelnick (1992), to provide the audiologist with a clear visual indication of an unaided or aided audiogram, in relation to the speech spectrum. In addition, it has been found to help the audiologist decide how the gain of a hearing aid should be changed to further increase the speech recognition ability. It has also been used to demonstrate the reasons for selecting a particular amplification device. Further, it has been used to explain to clients the reasons for poor performance with amplification (Zelnick, 1992). This would substantiate the information that is provided while counselling an individual regarding the expectation from a hearing aid.

An additional advantage of the SII is that the hearing evaluation and hearing aid selection for an individual can be done in a single sitting, using a single instrument. Hence, there would be no need for an additional equipment, for hearing aid fitting, other than that used for sound field audiometry. However, in addition to an audiometer with sound field test facilities, a computer would be required to compute the SII. Recent audiometers utilize software incorporated in computers in which case no additional instruments would be required. Also, the time taken and the cost would be much lesser when compared to a procedure where hearing evaluation and hearing aid selection are done using more than one instrument, such as an audiometer for hearing evaluation and an equipment for measuring insertion gain during hearing aid selection.

A disadvantage cited by Zelnick (1991) regarding the use of AI was that it estimated the overall speech recognition score but did not indicate the type of error that were made by an individual. In other words, it did not indicate whether the errors were due to a perceptual problem in the place of articulation or manner of articulation of speech. He noted that individuals with the same articulation index showed different types of errors in recognition of speech which could be in voicing, manner of articulation or place of articulation.

Berkowitz, and Hochberg (1971), Mathews, Lee, Mills, and Scheem (1990) and McCartney, Maurer, and Sorenson (1976) correlated the hearing handicap scale with audiological measures such as pure tone average and speech recognition scores, both in quiet and in noise. It has been documented in these studies that the perceived hearing handicap correlated better with the pure tone average than with speech recognition scores, for most components of the hearing handicap scale. Further, the inability to comprehend speech correlated more with the high frequency average rather than the pure tone average (Barrenas & Holgers, 2000). Hence, an SII procedure for selecting hearing aids would also reflect the extent of hearing handicap that an individual with hearing impairment faces, as the SII is calculated based on the pure tone thresholds, with more weightage for high frequencies.

Thus, it can be noted that the SII has several advantages and utility. It has been found to be useful in prediction of speech recognition scores and in selection of an appropriate hearing aid. Further, it can be a time- and cost- effective procedure; a tool that can be useful during counselling and; can be used as an indicator of the perceived hearing handicap.

Need for the Study

The SII has been considered as one of the efficient techniques for selection of hearing aids. Though there are several procedures for hearing aid selection, the demerits of each of these procedures prevent them from being used effectively as a technique for hearing aid selection. There are several reasons as to why there is a need to use an SII. These are discussed below.

Need for Non-Speech Based Tests for Hearing Aid Selection

India being a multi-lingual country, audiologists frequently have to test individuals in languages that are not familiar to them. It has been noted that perception of non-native languages is poorer than that of a native language (Takata & Nabelek, 1990). This problem of inadequate knowledge about the production may be partly overcome with the use of recorded material. However, while scoring the verbal response of the individual, the audiologist would again face difficulty, leading to erroneous perception and thus incorrect prescription of a hearing aid.

The SII procedure, being a non-speech procedure, is highly useful while testing individuals speaking different languages across the country. It has been observed by Ramakrishna et al. (1962) that several of the Indian languages have common sounds. In India, where there are twenty-two officially recognized languages and 1652 mother tongues spoken (Mathew, 2007), it would be an unachievable task to develop a standardized speech test in each of the languages or mother tongues. Hence, the use of SII for hearing aid selection would prove to be more appropriate.

It has been reported that the SII is based on the root mean square (RMS) spectrum of the language and that the RMS spectra of different languages differ. Byrne (1977) and have noted this difference for American English and Australian English. However, in a later study by Byrne et al. (1994), who compared the RMS speech spectra of thirteen different languages, it has been reported that the RMS speech spectra were similar for all the languages although there were minor differences. Further, they have proposed a "universal" long-term average speech spectrum (LTASS) that would be applicable across languages for the purpose of hearing aid selection. It has also been noted in a study, by Mili, Sairam, Vani, Manjula, and Yathiraj (2004), which compared the LTASS of three Indian languages, Kannada, Hindi and Malayalam, that though there were slight differences in the low frequencies, there was no significant difference between the three languages in the mid-frequencies and high-frequencies. Based on this, it may be expected that the LTASS for Indian languages also may not differ significantly. Thus, the efficacy of an SII, that makes use of the universal LTASS, developed by Byrne et al. (1994) needs to be investigated for the purpose of prediction of speech recognition and hearing aid selection.

SII to Replace Speech Recognition Tests

The most striking problem facing individuals with a hearing impairment is reduced ability to understand speech. In order to quantify the hearing aid benefit, it is necessary to determine the extent to which the hearing instrument facilitates speech understanding. It needs to be investigated if the SII could be used in place of a speech recognition test for selection of a hearing aid. Hence, there is a need to study the efficacy of SII to predict speech recognition so that selection of hearing aids could be based on this non-speech based procedure. For this purpose there is a need to derive equations relating the SII and SRS in order to predict speech recognition scores. If this is established, hearing aid selection could be carried out based on a non-speech procedure, instead of using speech recognition scores. Speech material for different Indian languages need not be utilized if SII could be used in hearing aid selection instead of speech recognition scores. Therefore, there is a need to compare the aided speech recognition performance and the SII scores.

SII in Different Types, Degrees and Configurations of Hearing Impairment

It had been established that speech recognition abilities vary depending on the type, degree and configuration of hearing loss. Normally good speech recognition scores are obtained in individuals with a conductive hearing impairment when compared to those with a sensorineural hearing impairment (Newby & Popelka, 1992). However, speech recognition scores vary depending on the degree of hearing impairment (Bilger & Wang, 1976). Rankovic (1991) has also reported that subjects with sloping hearing losses demonstrate non-monotonic relationship between the AI and the SRS, due to poor performance. Further, it has been reported by Ching, Dillon, Katsch, and Byrne (2001) that maximizing audibility may not always maximize the ability to understand speech. They reported that more audibility may in fact lead to no improvement or reduced improvement in higher degrees and sloping configurations of hearing impairment. Hence, it needs to be studied if the SII also reflects such a pattern in different types, degrees and configurations of hearing loss. This would throw light as to whether the SII can be used effectively in determining the perceptual differences across different type, degree and configuration of hearing loss.

SII to Judge Quality and Intelligibility of Speech

Sound quality is often used by hearing aid wearers in making decisions regarding continued use of their hearing aids. Thus, although optimizing speech intelligibility is a very important aspect of hearing aid fitting, it has been reported that other dimensions such as sound quality should also be considered (Magnusson, Karlsson, Ringdahl & Israelsson, 2001). In addition to the speech recognition scores, hearing aids can also be selected by evaluating the judgements on quality (Jeffers, 1960) and intelligibility (Zerlin, 1962) of the speech processed through the hearing aid. The subjective nature of sound quality makes it more difficult to use a structured measure of hearing aid outcome (Narendran & Humes, 2003). There is a need to evaluate the relationship between overall quality judgement and speech intelligibility. The correlation of these two parameters on SII also requires to be studied. Individuals who judge a hearing aid to have a good quality are more likely to use it. By evaluating the relationship between the quality and intelligibility, it can be established whether the SII can predict this aspect as well.

Thus, it can be observed that there are several reasons as to why an SII requires to be used. If SII is found to be useful, it would be of considerable utility, especially while prescribing hearing aids.

Objectives of the Study

The main aims of the present study are to study the effectiveness of using an SII for prediction of speech recognition scores and for hearing aid selection. In order to do this the following objectives will be developed/ investigated:

1. Development of software programs for:
    - 1.1. Computation of SII to predict speech recognition scores, using the band importance function for CID W-22 words (SIIw). Three SIIw programs will be developed. These include -
        - 1.1.1. A software program for computing the basic SIIw,
        - 1.1.2. A software program for computing the SIIw with a correction factor for speech level distortion ($SIIw_{SLD}$) and
        - 1.1.3. A software program for computing the SIIw with a correction factors for speech level distortion (SLD) and hearing loss desensitization ($SIIW_{SLD,HLD}$)
    - 1.2. Computation of SII for selection of hearing aids, using the band importance function for average speech (Silas).
2. Investigate the utility of SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ in predicting SRS by
    - 2.1. Comparing the SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$with SRS,
    - 2.2. Determining if SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ can predict SRS and
    - 2.3. Determining whether there is any significant difference between the measured SRS and the SRS predicted by SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$,

if the SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$ can predict SRS.

3. Investigate the efficacy of Silas in hearing aid selection to determine
    - 3.1. A criterion to decide about the hearing aid candidacy, based on Silas,
    - 3.2. The relationship between unaided and aided SRS with Silas,
    - 3.3. The relationship between the Silas and the quality judgments of hearing aids and
    - 3.4. The effect of the following aspects of hearing impairment in hearing aid selection using Silas:
        - 3.4.1. Different types of hearing impairment (conductive and sensorineural),
        - 3.4.2. Different degrees of hearing impairment (mild, moderate and moderately-severe) and
        - 3.4.3. Different audiogram configurations of sensorineural hearing impairment (gradual and steep slope).
    - 3.5. Effectiveness of Silas in selection of hearing aids across different degrees of hearing loss and configurations of audiograms.

The above objectives will be investigated, taking into consideration, the information available in literature. An overview of the relevant literature is given in the following chapter.

REVIEW OF LITERATURE

An important component of an aural rehabilitation program is the successful and consistent use of hearing aids by individuals with a hearing impairment. This is dependent on competent hearing evaluation and selection of hearing aids. Use of appropriate amplification would ensure that the individuals with a hearing impairment make maximum use of their residual hearing, enabling them to communicate effectively.

The primary reason most people wear hearing aids is to hear and understand speech (Skinner, 1988). Thus, the goals of hearing aid selection should be to make the speech audible, comfortable and good in quality as far as possible (Palmer, Lindley & Mormer, 2000). These goals should dictate how the hearing aids are selected and assessed.

Over the years, various procedures have been put forth to select appropriate amplification devices. The hearing aid selection procedures can be classified based upon their assessment approach. The hearing aid selection is usually done using a comparative and/or prescriptive procedure. In the *comparative procedure,* hearing aid selection is done by comparing the performance of an individual with two or more hearing aids based on the performance on speech tests. A few of the comparative procedures include the Carhart's procedure (Carhart, 1946), the quality judgment procedure (Jeffers, 1960) and the intelligibility judgement procedure (Zerlin, 1962). In the *prescriptive procedures,* the hearing aid selection is done by determining the gain, frequency response, saturation sound pressure level and other electroacoustic parameters required for a client with a hearing impairment, based on their audiometric data. These procedures try to fit the hearing aids in the residual dynamic range of the individuals with hearing impairment.

The use of articulation index (AI), a procedure based on audibility, has steadily gained importance in the recent past. The AI has been put to use in the prediction of speech recognition as well as in hearing aid selection. A reason as to why the AI or SII was seldom used in the past for hearing aid selection was that the procedure for calculating AI was complicated. Simplified procedures for this computation are now available (Berger & Gans, 1993). In addition, computer-based programs are designed, not requiring the tester having to carry out complicated calculations manually. These computer programs can calculate both unaided and aided SII.

The review of literature on SII, its relation to speech based tests and their use in hearing aid selection is discussed under the following headings:

1. Articulation index (AI) or speech intelligibility index (SII) - a brief historical perspective.
2. Primary parameters in the derivation of AI or SII
    - 2.1. Audibility function
        - 2.1.1. Hearing thresholds
        - 2.1.2. Long-term average speech spectrum
        - 2.1.3. Speech dynamic range
    - 2.2. Frequency band importance functions
3. Procedures for computation of AI or SII
    - 3.1. Basic procedure for computation of AI
    - 3.2. Modifications of the basic AI procedure

4. Prediction of speech recognition from AI or SII
5. AI or SII in different types, degrees and configuration of hearing impairment
6. Hearing aid selection
    6.1. Hearing aid selection and speech tests
    6.2. Hearing aid selection and quality judgments
    6.3. Hearing aid selection and SII
    6.4. Hearing aid effectiveness and SII
    6.5. Counselling and SII.

1. Articulation Index (AI) or Speech Intelligibility Index (SII)

- A Brief Historical Perspective

The AI was developed more than fifty years ago as an acoustical index that could be used to predict the speech recognition ability in individuals with normal hearing listening to speech under a variety of conditions (Fletcher & Galt, 1950; French & Steinberg, 1947). According to French, and Steinberg (1947) the AI was expressed and calculated as the sum of contributions of a number contiguous frequency bands which are necessary for speech recognition. All the modifications of AI that were published later used the procedure given by French, and Steinberg as a basis. Using this procedure and that put forth by Kryter (1962), the American National Standards Institute published a standard document on the calculation of AI (re: ANSI S3.5 - 1969).

The AI has been used successfully to predict speech recognition performance of listeners with normal hearing under a variety of conditions of filtering, noise distortion and low speech levels (Pavlovic, Studebaker & Sherbecoe, 1986). Thus, the AI quantifies the relationship between audibility and speech recognition in individuals with normal hearing. Further, the AI has gained acceptance as a method for estimating the audibility of speech in subjects with a hearing impairment (Dubno & Dirks, 1993). As it has been noted that there are factors other than audibility affecting the AI; various correction factors have been incorporated to the original AI calculation. This is done in order to improve the prediction of the speech recognition from the AI, in individuals with normal hearing (Fletcher, 1952) and with hearing impairment (Ching, Dillon & Byrne, 1998; Sherbecoe & Studebaker, 2003). When some of these correction factors were incorporated, the term speech intelligibility index (SII) was preferred rather than AI (re: ANSI S3.5 -1997).

2. Primary Parameters in Derivation of AI or SII

In the original AI developed by French, and Steinberg (1947), the AI was expressed and calculated as the sum of contributions of twenty contiguous frequency bands which were necessary for speech recognition. The AI was obtained based on the audibility of speech within specific frequency bands, with each band weighted by the importance of the information carried by it. That is, the AI was a product of band audibility and band importance or weightage. The *band audibility* was equal to the proportion of the speech signal, within the band, that was above the hearing threshold level, or interference level (noise), whichever was higher. The *band importance* or *weightage* was a number that was related to the importance of the speech frequency band to speech intelligibility. Higher frequency bands were weighted more heavily than the lower frequency bands, because they contributed much more to speech intelligibility than the low frequency vowels.

While the original purpose of the AI method was to provide good predictions of speech intelligibility under various conditions of filtering, noise and low speech level (French & Steinberg, 1947; Kryter, 1962; Pavlovic & Studebaker, 1984); audiologists now use the AI technique to determine the amount of speech that would be intelligible on account of the presence of a hearing problem (Ching, Dillon & Byrne, 1998; Kamm, Dirks & Bell, 1985; Ludvigsen, 1987; Pavlovic, Studebaker & Sherbecoe, 1986).

The basic formula for AI calculation, as described by French, and Steinberg (1947), was $AI = \Sigma\ Ai\ Ii$, i.e., AI was the sum of the product resulting from multiplying the audibility function in each band, A,, which ranged from 0 to 30 dB referred to the amount of speech energy that was above the listener's threshold or any competing noise, and, the band importance function in each band, Ii, ranged from 0.0 to 1.0. Thus, the first parameter in the calculation of AI was the *audibility function* and the second parameter was the *frequency band importance function*. The calculation of AI was carried out in each individual band (i band), and then, summed up. In the subsequent modifications of the AI the number of bands used varied from 4 to 21 (Amlani, Punch & Ching, 2002).

Several different methods exist for computing an AI. These various methods do not differ conceptually but differ in terms of the individual weights, and the number of narrow bands. Some of these methods fix the bandwidth and vary the individual weights (Pavlovic, 1991) while others fix the weights and vary the individual band widths (Black, 1959; French & Steinberg, 1947).

As reported by French, and Steinberg (1947) and many other investigators (Berger, 1990; Amlani, Punch & Ching, 2002) the value of AI ranged from 0.0 to 1.0. Pavlovic (1994) reported that the maximal value of AI (1.0) signified that all speech information was reaching the listener, while its minimal value (0.0) signified that no speech information was available to the listener. An AI value of 0.5 likewise suggested that half of the speech information was reaching the listener. He further opined that for an individual with a hearing impairment, an AI of 1.0 does not mean that the auditory system with the hearing aid was functioning normally. Even with an AI of 1.0 these individuals may still have substantial difficulties processing the speech information. However, for most individuals with a hearing impairment, an aided AI of 1.0 indicated that the hearing aid was optimally matched to the hearing impaired system for maximizing speech intelligibility.

2.1 Audibility Function

As mentioned earlier, according to French, and Steinberg (1947) the AI was obtained based on the audibility of speech within specific frequency bands, with each band weighted by the importance of the information carried by it. The band audibility was equal to the proportion of the speech signal within the band that was above the hearing threshold level. Thus, the audibility was determined by the *hearing thresholds, long-term average speech spectrum* and *speech dynamic range.* Several other factors affect audibility, such as, the speaker characteristics, room characteristics, language being spoken, distance from the speaker to the measuring device and the measurement process itself.

2.1.1 Hearing Thresholds

As implied by Pavlovic (1987), for the purpose of AI calculation, audibility in quiet was obtained by subtracting a listener's hearing threshold from the speech maxima of the long-term average speech spectrum. When the entire dynamic range of speech was above the listener's hearing threshold, the band made maximal contribution to audibility, i.e., 1.0. The contribution of a given frequency band was 0.0 when the speech dynamic range was below the listener's hearing threshold. The AI, therefore, was the sum of the weighted audibility across all the frequency bands.

2.1.2. Long-Term Average Speech Spectrum (LTASS)

Consideration of the speech spectrum appears to be assuming increasing prominence in the literature pertaining to the hearing aid design, selection and evaluation (Byrne, 1977). Further, Byrne noted that in any hearing aid selection, there appeared to be rather widespread agreement that, for any given hearing threshold level or most comfortable loudness level, less gain be provided at the frequencies below 1 kHz than at higher frequencies because the low frequency part of the speech spectrum contained greater energy. This is also because excessive low frequency amplification would result in the low frequency region of the speech signal being delivered at a level where it would tend to mask the lower energy, higher frequency, parts of the speech signal and that it would tend to produce a sensation of loudness which would induce the hearing aid wearer to use a volume setting which would be too low for optimum reception of the higher frequencies.

The level and shape of the long-term average speech spectra in a hearing aid selection procedure affects the absolute amount of gain prescribed at each frequency (Cox & Moore, 1988). The idealized speech spectrum was assumed to be presented in quiet, with normal vocal effort, and at a distance of one meter from the talker (Pavlovic, 1987). The average level of such an idealized speech was assumed to be 65 dB SPL in ANSI S3.5 - 1969 standard and 63 dB SPL in ANSI S3.5 - 1997 standard.

There are various long-term average speech spectra used by different investigators for computation of the AI. Two types of multi-talker speech spectra, the *simultaneous* spectrum and the *sequential* spectrum, have been employed for the purpose of hearing aid prescription procedures. The simultaneous spectrum is obtained by measuring the long-term average speech spectrum of a recording of several talkers speaking together. Pascoe (1978) and Cox (1983) have employed this type of spectrum in hearing aid prescription. In contrast, a sequential spectrum is obtained by measuring the long-term root mean square (RMS) spectrum for each of the several individual talkers and arithmetically averaging the obtained levels across talkers. Byrne, and Tonisson (1976) have used this type of spectrum for prescribing hearing aids.

For the purpose of hearing aid selection, a sequential type of spectrum seems to be more appropriate because the sequential spectrum accurately represents the average levels in the speech of the individual talkers. With simultaneous spectrum, the vocal effort of all the speakers would not be the same, despite training being given. This again would lead to some voices being heard louder than others. While this problem can be overcome by normalizing the speech sample of each individual in the sequential spectrum, this would not be possible in the simultaneous spectrum. This has led the sequential spectrum being more popular.

For uniformity of design and testing of hearing and hearing aids, several commonly accepted composite speech spectra have been established. A few of the widely referenced standard speech spectra are those developed by Byrne (1977); Pearsons, Bennett, and Fidell (1977); and Cox, and Moore (1988). Each of these studies varied in the procedure and/or language used for deriving the long-term average speech spectra. The spectra developed by Byrne (1977) was generated using fifteen male and fifteen female talkers; Pearsons, Bennett, and Fidell (1977) derived the spectra using males and females with normal vocal effort, with an unknown number of talkers; Cox, and Moore (1988) used thirty male and thirty female talkers to generate the average long-term 1/3-octave band speech spectra; and the spectrum in the study by Burnett (1991) was derived by measuring a two-minute sample of speech from five male and five female talkers, normalizing the speech spectrum for each talker to remove amplitude variations, then averaging all the speech samples together.

On perusal of the spectra obtained in the above studies, it is observed that normal speech contained more energy in the low frequencies than in the high frequencies. Although there were similarities in the spectral curves, especially in the low frequencies, there were differences in the middle and higher frequencies.

It was reasoned by Agnew (1999) that the possible reasons for the variations in LTASS were due to differences in language or dialect, differences due to measurement of different populations of talkers, differences due to differences in measurement procedures, differences due to different speech samples being analyzed and differences due to different overall levels of vocal effort. According to Pavlovic (1989), other factors that may influence the speech spectrum under everyday circumstances are the level of background noise. The speech level roughly increases by 0.46 dB for each decibel increase in noise, once the background noise exceeds 50 dB A. Another complicating factor, as reported by Pavlovic (1989), was that the increase in speech level varied across frequency. The speech level may increase either because an individual with hearing impairment may assume a more favourable position than described for average speech spectrum or the talker may increase the speech level knowing that the listener has a hearing impairment. It is very difficult to estimate how these factors will combine to affect a given individual with hearing impairment.

As reported by Kiukaanniemi, and Mattila (1980), some languages have significantly more vowels than others. The spoken Japanese and English for example, contain 52% and 38% vowels respectively. Thus, Japanese listeners with a high frequency hearing loss can utilize the remnants of their hearing better than can English speaking listeners with a corresponding hearing loss.

There are equivocal findings with respect to the long-term average speech spectra of different languages. It has been reported in literature that the average spectra of different languages differ. Byrne (1977); and Pearsons, Bennett, and Fidell (1977) have noted this difference for American English and Australian English. However, McCullough, Tu, and Lew (1993) compared LTASS of English and Mandarin languages and reported no significant difference. The outcome of the investigation by Cox, and Moore (1988) revealed that different dialects of English had similar long-term speech spectra. In a later study by Byrne et al. (1994), after having compared the average speech spectra of thirteen different languages, it was reported that the average speech spectra were similar for all the languages although there were minor differences. Further, they recommended that a "universal" LTASS be used across languages for the purpose of hearing aid selection.

It has been observed by Ramakrishna et al. (1962) that several of the Indian languages have common speech sounds, and, that their frequency of occurrence in the language is comparable too. Based on this, it may be expected that the LTASS for Indian languages too may not differ significantly from that reported by Byrne et al. (1994).

A study by Anitha, and Manjula (2005) to investigate the effect of multi-talker babble of three different Indian languages, that is Kannada, Hindi and Malayalam, on the speech recognition scores in Kannada. They found that there was no significant difference among the masking effect of multi-talker babble, of different languages studied, on the speech recognition scores. It could be construed from this that the acoustic composition of the three languages is similar and hence resulted in masking of the speech in a similar manner.

Mili, Sairam, Vani, Manjula, and Yathiraj (2004) carried out a study on the comparison of LTASS of three Indian languages, Kannada, Hindi and Malayalam. It was reported in their study that though there were slight differences in the low frequencies, there was no significant difference between the three languages in the mid-frequencies and in the high-frequencies. When the LTASS in their study was compared with that of Cox, and Moore (1988) and Byrne et al. (1994), it was found that there was a difference in energy concentration in lower frequencies (up to about 500 Hz.) and the differences towards mid-frequencies and high-frequencies were minimal.

The studies carried out in India reveal that the difference in the LTASS of different languages is not much, and that they have a similar masking effect. Further, these LTASS were not very different from the common or universal LTASS reported by Byrne et al. (1994). Hence, it can be concluded, that it would be appropriate to use the common or universal LTASS, which represents 13 different languages, for the purpose of calculation of SII to select the hearing aids.

2.1.3. Speech Dynamic Range

Depending on the particular speech sound that is produced, the speech energy varies over time along its long-term average value (Popelka & Mason, 1987). French, and Steinberg (1947) used the range of speech energy that varied between +12 dB and -18 dB. The resultant 30 dB dynamic range was termed as the speech dynamic range or perceptual dynamic range (Boothroyd, 1990). A speech dynamic range of 30 dB indicates that the overall average speech level minimally required for speech recognition of weak consonants was 30 dB higher than that required minimally for recognition of strong vowels.

According to Humes, Dirks, Bell, Ahlstrom, and Kincaid (1986) from the average value of the speech signal 12 dB was added to indicate the upper limit of the dynamic range. This 12 dB represented the peak level of the speech signal. The level of speech "peaks" determined the upper limit of this dynamic range. The peaks of the speech signal carry important information. The lower limit of the speech spectrum was determined by subtracting 18 dB from the average value. This represented the speech minima. Thus, the dynamic range of the long-term average speech spectra that was effective in maximizing speech intelligibility is 30 dB with linear intensity weighting (Dunn & White, 1940).

The objective of using SII in hearing aid selection was to amplify the long-term average speech spectrum (LTASS) or the root mean square (RMS) speech spectrum to a level 15 to 18 dB above the threshold at each frequency. According to the AI theory, this would allow an audibility of a 30 dB range of amplitude fluctuations in speech, in the entire frequency range (Kryter, 1962).

Several of the AI or SII procedures have used 30 dB to represent the dynamic range of speech. Some of these include the procedures developed by Popelka, and Mason (1987) and Pavlovic (1991). Pavlovic (1991) has used a 25 dB in one of the simple procedures in the calculation of AI. However, in some procedures for calculation of AI, such as the recent ANSI standard, ANSI S3.5 - 1997, this division of the range has been modified to + 15 to - 15 dB, relative to the LTASS. While this division is convenient to use, the original + 12 and - 18 dB continues to be used more widely.

2.2. Frequency Band Importance Functions

It is commonly accepted that certain frequencies are more important for speech intelligibility than others. The relationship between frequency and intelligibility can be defined by a mathematical expression called frequency band importance or weightage function. The frequency band importance functions characterize the importance of different frequency bands for speech recognition (Byrne, 1977; Pavlovic, 1994).

Initially French, and Steinberg (1947) defined the importance function by dividing the frequency spectrum into 20 bands ranging in frequency from 250 to 7500 Hz, such that each band contributed equally to speech intelligibility. Each band had a weightage of 0.05. Black (1959) also utilized a procedure where in the bandwidth varied while the weithage per band was kept constant. In other methods, such as that developed by Pavlovic (1991), the bandwidth was fixed and the weightage per band varied. The AI procedure given by Kryter (1962) also used 20 bands of varying widths and equal weights (i.e., 0.05) for each band. It also included an alternative method that divided the speech spectrum, into 15 equal l/3rd octave bands and varied the weights accordingly. The important amplitude fluctuations of speech covered a 30 dB range over the entire frequency range. Thus, the weight for any individual band was equally distributed over this 30 dB range, with 1 dB resolution.

Inferences about the overall importance function have sometimes been based on the single frequency that divides the speech spectrum into two equally intelligible halves. This measure of central tendency was referred to as the cross-over frequency. Thus, the cross-over frequency was the mid-point of the importance function. Although the cross-over frequency cannot be used to infer about the shape of an importance function, it was useful to compare different test materials along the frequency scale (Studebaker, Pavlovic & Sherbecoe, 1987). The cross-over frequency tends to decrease as the as the redundancy of the speech material increases. The cross-over frequency also tends to decrease as the presentation level is reduced or as the signal-to-noise ratio becomes less favourable.

Studebaker, Pavlovic, and Sherbecoe (1987) reviewed the cross-over frequencies for different types of speech material. The cross-over frequency varied from a low of 725 Hz for synthetic speech intelligibility test (Speaks, 1967) up to 1930 Hz for non-sense syllables (French & Stienberg, 1947). The cross-over frequency for connected discourse test was 1189 Hz (Studebaker, Pavlovic & Sherbecoe, 1987) and that for diagnostic rhyme test varied from 425 for the nasality feature up to 2521 Hz for the sibilance feature sub-test (Duggirala, Studebaker, Pavlovic & Sherbecoe, 1988).

The relative importance of individual frequency bands may differ as a function of the degree of the redundancy available in the speech message itself (Studebaker, Pavlovic & Sherbecoe, 1987; Studebaker & Sherbecoe, 1991). This was inferred from the fact that speech recognition improved with an increase in redundancy (Pavlovic, 1987). Evidence from reports by Studebaker, Pavlovic, and Sherbecoe (1987) suggested that the importance function was influenced by the phonemic composition and the format of the test material. The contribution of low-frequency cues to intelligibility may be greater in the presence of context, i.e., the frequency importance function appeared to differ in highly contextual conditions when compared to non-sense syllables.

The frequency importance functions for various types of speech material have been developed. They have been developed for non-sense syllables (French & Stienberg, 1947; Kryter, 1962), average speech (Pavlovic, 1987), continuous discourse (Studebaker, Pavlovic & Sherbecoe, 1987), closed-set rhyme words (Duggirala, Studebaker, Pavlovic & Sherbecoe, 1988), isolated monosyllabic words (Studebaker & Sherbecoe, 1991), CID W-22 test (Studebaker & Sherbecoe, 1991), words in low- and high- context sentences (Bell, Dirks & Trine, 1992), monosyllables of Speech Intelligibility in Noise (Bell, Dirks

& Trine, 1992) and NU-6 test (Studebaker & Sherbecoe, 1993) and connected speech (Sherbecoe & Studebaker, 2002).

Band importance function plays an important role when AI or SII is used to predict speech recognition abilities in individuals with a hearing loss. Pavlovic (1987) observed that the speech recognition improved with an increase in redundancy and this was accounted for by using different transfer functions for different speech material. For the prediction of SRS, the band importance function that is used in the calculation of AI should correspond to the speech material that is used for obtaining the speech recognition score. However, there is yet another view which says that any changes in the number of syllables would not affect the importance function (Studebaker & Sherbecoe, 1993). This approach was incorporated in ANSI S3.5 -1969 standard.

According to Pavlovic (1994), the decision of whether to use the importance function for average speech, or the importance function for a specific speech material depends on the particular application. The use of inappropriate importance function may be one of the reasons why poorer predictions of performance are sometimes made in case of individuals with a hearing impairment.

Further, in the opinion of Pavlovic (1994), if the user was interested in predicting the average performance of an individual across different communication situations, then the band importance function for average speech should be selected. In this case the calculated AI cannot be converted to any corresponding speech intelligibility score. It may be interpreted as a proportion of the total speech information available to the listener. It is recommended to use the band importance function of average speech while predicting hearing aid performance in everyday life. Pavlovic (1991) used the importance function of average speech while deriving the A_1 Ao, A_s and A_d articulation index models, which were used in hearing aid selection.

Thus, the research has well documented that the band importance function depends on the type of speech material for which intelligibility needs to be predicted. If the audiologist is interested in predicting the average performance of an individual across different communication situations, then the band importance function for average speech should be selected. However, when importance function for average speech is utilized for computation of AI, the calculated AI is not converted to any corresponding speech intelligibility score (Pavlovic, 1994).

3. Procedures for Computation of SII

Several different procedures for computing an articulation index exist. The different methods reported in literature are modifications of the initial AI procedure developed by French, and Steinberg (1947). Though several modifications of AI have been put forth by experts, the primary application in Audiology remains the same. They all aim at predicting speech recognition as well as selecting hearing aids. While some of the modifications were made to simplify the calculation (Pavlovic, 1991) others were done to improve the prediction of speech recognition scores using AI (Ching, Dillon, Katsch & Byrne, 2001; Pavlovic, 1993; Studebaker & Sherbecoe, 1993). Almost every researcher who has recently used the method as a tool for predicting speech intelligibility has changed it to a greater or lesser degree. Though they are different methods for computing the AI, they do not differ conceptually. The fact that different researchers use different modifications renders comparison of the results obtained in various studies virtually impossible (Pavlovic, 1987).

As the AI has been modified over the years, the terminology has also changed from time-to-time. In the ANSI S3.5 - 1997, the term speech intelligibility index (SII) has been used instead of AI. In this procedure, computation of the SII incorporates correction factors such as the speech level distortion (SLD) and hearing loss desensitization (HLD). The following section describes the original and the modified procedures.

3.1. The Basic Procedure for AI Calculation

The basic model and calculation method of AI was reported by French, and Steinberg in 1947. According to these investigators, the AI was based on the algebraic sum of the product of the band audibility function (obtained from the proportion of speech and hearing loss in the frequency bands; noise levels are substituted for threshold when it exceeds the thresholds) and band importance function (which characterizes the importance of different frequency bands to speech intelligibility). Twenty frequency bands were considered here.

The basic formula for calculation of AI was, $AI = \Sigma\ Ai\ Ii$, where AI was the algebraic sum of contributions Ai and Ii While Ai was the proportion of the speech dynamic range in the i^{th} frequency band that was above the listener's hearing threshold, Ii characterized the importance of the i^{th} frequency band to speech intelligibility. This basic formula has been modified by several experts, over the years.

3.2. Modifications of the Basic AI Procedure

There have been several attempts at simplifying the calculation of the AI for clinical use. Despite the similarities in their concept, each procedure differed with regard to the parameters such as the amount of frequency importance and number of bands used.

As a means to validate the AI, Kryter (1962) published a series of studies on calculation of AI that resulted in ANSI S3.5 - 1969 standard. The ANSI S3.5 - 1969, uses 21 bands, in l/3rd octave interval, and the short-term RMS level of speech was determined relative to the threshold or ambient noise, which ever was greater. These sensation levels were multiplied by the importance function that specified the relative importance of each frequency region to the speech spectra. The resulting values were summed across frequencies to produce the AI.

Pavlovic (1988), who developed the precursor to the simplified methods for AI calculation, reported five variations of calculating the AI. These included Ao(4) method, A_s method, $A_0(6)$ method, Ad method and A1 method, ranging from extremely simple to more complex methods suitable for computer applications.

Later a count-the-dot method was devised by Mueller, and Killion (1990) and Pavlovic (1991). The count-the-dot method was originally described by Cavanaugh, Farrel, Hirtle, and Walters (1962). These methods employed a series of dots placed on a conventional audiogram, which represent the average speech spectrum. The density of dots was related to the importance of that particular frequency for understanding speech. Counting the number of dots, out of a maximum of either 33 or 100, that fell below the unaided or aided threshold curve, and, dividing this number by 100 gave the AI.

The above methods have incorporated modifications to improve or simplify the AI or SII. In addition, a series of researchers have made modifications or included additional calculations in order to make it more applicable for prediction of speech performance in individuals with a hearing impairment. These modifications included incorporation of speech level distortion (SLD) and hearing loss desensitization (HLD).

Incorporation of Speech Level Distortion and Hearing Loss Desensitization to the Basic AI Procedure

Investigators have opined that modifications or corrections in the basic AI were warranted if accuracy in prediction of speech performance was required (Ching, Dillon & Byrne, 1998; Ching, Dillon, Katsch & Byrne 2001; Hogan & Turner, 1998; Ludvigsen, 1987; Pavlovic & Studebaker, 1984; Pavlovic, Studebaker & Sherbecoe, 1986). To investigate this aspect, Pavlovic, and Studebaker (1984) incorporated the presumed increase in critical bandwidth estimated from the measured critical ratio into the basic AI procedure. Speech identification was tested in three listeners with normal hearing in thirteen conditions that differed in filtering, level of noise and level of signal (i.e., 3 conditions of low pass speech filtering, 2 conditions of high pass speech filtering, 2 conditions of low speech signal level, 3 conditions of high frequency noise masking, 2 conditions of speech type broad band noise - BBN masking, and 1 condition of undistorted and unmasked speech). The modified AI scheme suggested by these researchers was found to be accurate not only for the average listener but also for each listener.

Pavlovic, Studebaker, and Sherbecoe (1986) incorporated corrections in the SII to account for the deterioration in speech processing, seen in sensorineural hearing loss at supra-threshold levels. In their study, data from four subjects with normal hearing and four subjects with hearing impairment were used to relate the loss in hearing sensitivity to the deterioration in speech processing in quiet and in noise. The new procedure only required hearing threshold measurements and consisted of two modifications of the earlier AI procedure given by Pavlovic, and Studebaker (1984). In the modification, the speech and noise spectrum densities integrated over bandwidths, which when expressed in decibels, were larger than the critical bandwidths by 10% of the hearing loss. This was in contrast to the unmodified procedure where integration was performed over critical bandwidths. The contribution of each frequency to the AI was the product of its contribution in the unmodified AI procedure and a "speech desensitization factor". The desensitization factor was specified as a function of the hearing loss.

The predictive accuracies of both the unmodified and the modified calculation procedures were assessed by comparing the expected and observed speech recognition scores of four subjects with sensorineural hearing impairment under various conditions of speech filtering and noise masking. The modified procedure appeared to be accurate for general applications. In contrast, the unmodified procedure appeared accurate only for applications where results obtained under various conditions on a single listener were compared to each other. The data of Pavlovic, Studebaker, and Sherbecoe (1986) showed that corrections for deterioration in supra-threshold speech processing were not necessary when results obtained with various hearing aids were compared with each other for a single subject.

Ludvigsen (1987) evaluated the word recognition ability of four normal hearing and thirteen listeners with cochlear hearing impairment. Filtered and unfiltered speech in quiet and in noise was presented monaurally through headphones. The noise varied over listening situations with regard to spectrum level and temporal envelopes. The articulation index was calculated to predict the results. Two calculation methods were used; both based on the ANSI S3.5 - 1969, twenty-band method. Method-I was similar to the ANSI method. Method-II included a level dependent and hearing loss dependent calculation of masking of stationary and on-off gated noise signals and self-masking of speech. He found that Method-II provided the best prediction capability, supporting the notion that modifications or corrections in the basic AI are warranted if accuracy in prediction of speech performance is required.

Hogan, and Turner (1998) have also reported a decrease in performance with increasing audibility in the high frequencies for individuals with moderate or severe sloping hearing losses. In their study they investigated the benefit of providing the individuals with a hearing impairment with audible high frequency speech information. Five individuals with normal hearing and nine individuals with high frequency hearing impairment identified non-sense syllables that were low pass filtered at a number of cut-off frequencies. As a means of quantifying audibility for each condition, AI was calculated for each condition for each listener. Most listeners with hearing impairment demonstrated an improvement in speech recognition as additional audible high frequency information was provided. In some cases, for listeners with more severe impairment, increasing the audibility in high frequency speech information resulted in no further improvement in speech recognition, or even decrease in speech recognition.

Based on the above finding, a new measure on how well an individual with hearing impairment used information within specific frequency bands called 'efficiency' was devised. In this measure, the benefit of providing a given increase in speech audibility in a listener with hearing impairment was compared with the benefit observed in listeners with normal hearing for the same increase in speech audibility. Efficiencies were calculated using the old AI and the new Al method, which took into account the effects of high speech presentation levels. There was a clear pattern in the results suggesting that as the degree of the hearing loss at a given frequency increased beyond 55 dB HL, the efficacy of providing additional audibility to that frequency region was diminished, especially when this degree of hearing loss was present at frequencies of 4000 Hz and above. A comparison of analyses from 'old' and 'new' AI procedures suggested that some, but not all, of the deficiencies of speech recognition in these listeners were due to high presentation levels. Presentation level varied from 40 to 60 dB SPL for normal-hearing and 65 to 105 dB SPL for those with a hearing impairment. Extending the amplification bandwidth beyond 3500 Hz led to lower speech scores than when a restricted bandwidth was used for two listeners with severe sloping hearing loss. These findings agreed with those reported by Murray, and Byrne (1986) who found that a narrower amplification bandwidth was adjudged to be more intelligible and pleasant than a wider bandwidth by two listeners with severe high frequency hearing losses. Thus, factors other than audibility and level distortion affected the ability of listeners with hearing impairment to understand speech.

Ching, Dillon, and Byrne (1998) explicitly investigated how the contribution of audibility to intelligibility varied for different degrees of hearing losses. They conducted two experiments to examine the relationship between audibility and speech recognition in forty individuals with sensorineural hearing impairment ranging from mild to profound degrees. Speech scores measured using filtered sentences were compared to predictions based on the SII. At high sensation levels, the SII over predicted performance. For many listeners, the SII under predicted performance at low sensation levels. The SII incorporating the level distortion factor did not adequately explain speech recognition in many listeners with a hearing impairment. The data suggested that for individuals with severe or profound hearing losses at high frequencies, amplification should only achieve a low sensation or zero sensation level at this region, contrary to the implications of the unmodified SII.

From studies by Ching et al. (1998) and Hogan, and Turner (1998) it can be construed that the deterioration of effectiveness of audibility was greater at high frequencies than at low frequencies. These findings suggest that instead of maximizing the audibility or the signal level above threshold, amplification should aim to "maximize effective audibility" or the contribution of audibility to speech intelligibility.

Ching, Dillon, Katsch, and Byrne (2001) have also reported that it is not true that maximizing audibility will always maximize the ability to understand speech. They reported that it is "effective audibility" rather than physical audibility that is important. "Effective audibility" may be regarded as audibility modified by the effects of hearing loss desensitization (HLD) combined with a factor that has been called level distortion factor (LDF) or speech level distortion (SLD) by Studebaker, Sherbecoe, McDaniel, and Gray (1997). Thus, for adjusting the gain of a hearing aid for a given listening level, less gain is provided at frequencies where the hearing is most impaired to allow more gain at frequencies where audibility is most useful. The level distortion factor in the correction is based on the observation that the speech recognition performance of normally hearing people deteriorates at high sound pressure levels. This allows for reduced contribution of audibility to speech intelligibility, from a maximum of one, when the overall sound pressure level exceeds 73 dB SPL (ANSI S3.5 - 1997). These factors summarize all forms of distortion associated with hearing loss, probably related at least partly to reduced temporal and/or frequency resolution. Thus, it is clear that substituting 'audibility' by 'effective audibility' improves the ability of SII to predict speech performance. According to Ching et al. (2001), effective audibility can be calculated using the formula mentioned below.

$$\text{SII (SLD, HLD)} = \Sigma \text{ Effective Audibility}_i, \text{ X } I_i,$$

where *Effective Audibility i = Desensitized Audibility, X Li*

where Li is the level distortion factor (LDF) or speech level distortion (SLD) for each frequency band i. They expressed hearing loss desensitization (HLD) in terms of desensitized audibility, which is related to the sensation level of speech maxima by a double inverse function:

$$\textit{Desensitized Audibility}_i = \frac{m_i}{[1 + (30 / SLi)^{pi}]^{1/pi}}$$

The parameter *mi,* was the maximum value of desensitized audibility. The value of *SL,* was determined by calculating the difference between the maximum level of the signal and the hearing threshold level at the i^{th} frequency band. For large values *of pi* and when *mi* = 1, effective audibility was equal to the band audibility function. The rate at which effective audibility changed with audibility at low sensation levels was equal to 01,730. The parameter/?/ controlled the curvature of the function that related sensation level to effective audibility.

The way in which mi varied with hearing threshold was expressed by a logit function, which had a minimum value of 0.0 and a maximum value of 1.0. The function was expressed by,

$$m_i = \frac{e^{v1,i - v2,i \ X \ Hi}}{1 + e^{v1,i - v2,i \ X \ Hi}}$$

where *mi* for each frequency band *i* was determined by two parameters v and *Hi.* The v parameters were related to frequency and *Hi* was related to the hearing threshold level at the centre frequency of band *i.*

Accordin g to Ching et al. (2001), this procedure generally resulted in less mean square errors than other procedures for all degrees of hearing losses and for low frequency and high frequency loss. Thus, it can be construed that while computing SII, correction factors need to be incorporated to account for perceptual changes that occur due to a hearing loss. Some of these factors are SLD and HLD.

AI for noisy situations

Hou, and Thornton (1994) reported a method for integrating the articulation index (AI) across listening conditions such as in quiet and in noise. The model considered hearing threshold, masking of noise, self-masking of speech, high level cochlear distortion, and the peak-clipping effects of a hearing aid, while calculating the AI. The integrated AI (IAI) across a range of listening conditions was used as a criterion for evaluating a specific hearing aid response characteristic and calculating an optimal frequency-gain characteristic that maximized the IAI. The frequency-gain characteristics and IAIs derived from an optimal IAI (OIAI), POGO and NAL prescriptions were compared for two of the listening situations, a quiet setting and a setting with a signal-to-noise ratio of -3 dB, in individuals with a high-frequency hearing loss. The results highlighted that in quiet, the OIAI prescription was not significantly different from the well-established prescriptive procedures such as the POGO and the NAL. However, for the noise condition, the optimal IAI model was a better predictor of speech intelligibility. The frequency response and gain of a hearing aid that produced the greatest integrated articulation index (IAI) was considered to be the optimal prescription. Hence, while selecting hearing aids for use in noisy condition it would be appropriate to utilize the IAI method.

AI for Hearing Aids with Compression

Souza, and Turner (1997) evaluated the predictability of aided audibility index (AAI) with linear and compressed hearing aid conditions. They found that for both linear and compressed conditions, observed performance was poorer than that predicted by AAI solely on the basis of audibility. These differences were greater in compressed condition, suggesting that factors other than audibility may play a relatively greater role in recognition of compressed speech.

In another study, Souza, and Turner (1999) compared the relationship between increasing audibility and recognition of compression amplified vs. linearly amplified speech. They also explored the adequacy of the aided articulation index (AAI) in describing performance with wide dynamic range compression (WDRC) amplified speech. Recognition of non-sense syllables that had been digitally processed with linear or WDRC amplification was evaluated at three input levels relative to the listeners hearing thresholds. At low and moderate input levels, the AAI values and corresponding recognition scores were higher for the compression amplified than for the linearly amplified speech. At high input levels, the AAIs and speech recognition scores were essentially the same for both types of amplification. There was no significant difference between the functions for linearly amplified and compression amplified speech. In other words, a given increase in audibility resulted in the same increase in recognition for both types of amplification, at high input levels. They concluded that increasing the amount of audible speech information played the same role in recognition for compression amplified as well as for linearly amplified speech. This suggested that for the conditions tested, compression did not introduce detrimental changes to the speech signal that offset the benefits of improved audibility at high input levels.

Souza, and Bishop (2000) carried out an investigation to see if the increases in audibility with Dynamic Range Compression amplification improved speech recognition to a comparable degree for listeners with different degrees of hearing loss. They found that increasing the amount of audibility (and there by the aided audibility index) of speech information with WDRC had similar effects on consonant recognition for listeners with different degrees of hearing loss. The subjects had either a mild to moderate or severe degree of hearing loss. Results for sentence recognition showed a greater benefit of WDRC amplification for listeners with mild to moderate than for listeners with severe hearing loss. This difference in sentence recognition for listeners with different degrees of hearing loss was attributed to processing effects or to differences in available acoustic information for longer segments of WDRC amplified speech.

Souza, and Turner (1999) used the aided audibility index, AAI, which was developed by Stelmachowicz, Lewis, Kalberer, and Creutz (1994) to quantify audibility of both linear amplification and WDRC amplification. They used different formulae for linear amplification and WDRC amplification.

The AAI formula for linearly amplified speech was as follows:

$$\sum_{i=l}^{g} [\, Ii\,(\mathrm{LTASS} + 15 - \mathrm{Threshold})] \,/\, 30 \,,$$

where, LTASS was the long-term average speech spectrum level; Threshold was the listener's hearing threshold at a particular frequency; and Ij was the band importance value for non-sense syllable at frequency i (Pavlovic, 1989).

The AAI formula for WDRC-amplified speech was as follows:

$$\sum_{i=1}^{8} I_i \; [\; (LTASS+15 \,/\, MCR - Threshold_i \;] \;) \,/\, (30 \,/\, MCR)$$

where LTASS was the long-term average speech spectrum level; Threshold i was the listener's hearing threshold at frequency i; Ii was the band importance value at frequency *i* for nonsense syllables (Pavlovic, 1989); and MCR was the modified compression ratio. It was found that the higher the compression ratio, the more the speech peaks were reduced. Souza, and Turner (1999) found that for those with mild to moderate hearing loss, a given increase in audibility improved recognition to the same extent for WDRC-amplified speech as for a linearly-amplified speech.

Woods, Van Tasell, Ricket, and Trine (2006) have studied how the speech audibility and the Cambridge method for loudness equalization (CAMEQ) provided by compression, changed with the number of channels. They found that for individuals with mild and moderate degrees of hearing loss, one to five channels were sufficient to yield predicted speech performance. Further, they found that three to nine channels were necessary for the same level of predicted performance for those with a severe degree of hearing loss.

Thus, for individuals who require hearing aids with output limiting, appropriate changes in the computation of AI is warranted. Incorporation of appropriate corrections will improve the utility of AI in selection of hearing aids with output limiting.

AI to account for Age Effects

According to Cox, Alexander, and Gilmore (1987), the use of AI with correction to predict speech performance in children with hearing impairment seems more suitable. These corrections were applicable to children below 12 years of age, as it was reported that normal hearing children as young as 12 year old do not perform significantly different from adults when tested in comparable conditions.

Stelmachowicz, Hoover, Lewis, Kortekaas, and Pittman (2000) reported that there were systematic changes in a child's ability to use audible acoustic speech information as a function of age. They collected the data from 15 children with normal hearing in each of the four age groups (5, 6, 8, and 10 years), 23 children with hearing impairment under 12 years of age, and 20 adults with normal hearing. Performance intensity (PI) functions were obtained for semantically correct and semantically anomalous sentences. For each participant AI was computed. The results suggested that the young children required a higher AI to achieve performance equivalent to that of adults. That is, for a given level of audibility, the performance of older children and adults far exceeded that of younger children. Improvement in performance with addition of semantic context was observed for children and adults with normal hearing. Since the cochlea is essentially developed at birth, it is unlikely that physiological differences in the peripheral auditory system between the children and adults can account for these findings. The children lacked sufficient experience with the phonetic representation of language to perform well at low presentation levels. As the children gained more experience with their native language, loss. They also reported that the AI was less successful in predicting speech recognition in adverse listening situations.

According to Ching et al. (2001), among the procedures used for hearing aid selection, some prescribe more gain in frequencies where the hearing loss is severe because the aim is to restore loudness and ensure audibility. However, some other techniques include a hearing loss desensitization factor because it is believed that the individuals with hearing impairment have reduced ability to extract useful information from speech at frequencies where the hearing loss is severe. Thus, there is a need to investigate the role of degree and type of hearing impairment in predicting the aided benefit.

5.3. SII and Sloping Hearing Loss

Pavlovic (1984) noted that the deficit in supra-threshold speech processing varies with frequency. In the frequency regions where the hearing sensitivity is poorer, the deficit is larger. Hence, variables affecting the SII include abnormal upward spread of masking, auditory frequency selectivity characteristics or deterioration in temporal processing abilities.

Rankovic (1991) demonstrated non-monotonicity due to poor performance in clients with sloping hearing loss. Earlier, Skinner (1980, 1988) too had reported that in individuals with sloping hearing loss, emphasis of high frequencies degraded the speech intelligibility by upsetting the "balance" of the speech spectrum.

From the studies on different types of hearing loss it is seen that inclusion of correction factors in the calculation of AI is necessary. This was considered necessary to compensate for distortions that occurred due to the presence of a hearing loss. The correction factor that is to be used depends on the type of hearing loss.

5.2. SII and Different Degrees of Hearing Loss

According to Green (1978), there is a relationship between a pure tone average and speech understanding. This enables an audiologist to have an idea on the degree of disability present as well as appreciate the magnitude of rehabilitation needs. Earlier, Goodman (1965) gave a guideline on the relations between hearing threshold level and the probable handicap and needs. From that table, it can be implied that individuals with mild or greater than mild degrees of hearing loss will require a hearing aid.

Speech recognition scores (SRS) also vary depending on the degree of hearing loss (Bilger & Wang, 1976). Pavlovic (1984) reported good predictions of speech recognition under various conditions (of filtering and S/N ratios) and concluded that good predictions were possible for subjects with normal hearing and subjects with less hearing impairment, but not for those with greater impairment. He found that the subjects with hearing impairment tended to exhibit a disproportionate loss in speech discrimination than that predicted on the basis of the AI procedure. This discrepancy appeared to increase with the magnitude of hearing loss.

Tawfik, Sadek, and Wael (1999) found that the degree of hearing loss had a more prominent effect on the speech recognition abilities than the relative duration of hearing

Hou, and Thornton (1994) have included a correction for conductive hearing loss while calculating the speech level distortion (SLD). In their equation for SLD, air-bone gap is included because level distortion is believed to be mainly a cochlear phenomenon. The SLD was equal to $1 - (L_i - A_i - U_i - 10)/160$. Here, L_j is the equivalent speech spectrum level, A_i is the air-bone gap, and U_{ij} is the standard speech level for normal vocal effort.

Halpin, Thornton, and Hasso (1994) have reported that the calculation of AI does not account for additional cochlear or retrocochlear processing losses, nor is it sensitive to the possibility of low-frequency thresholds, which are actually the product of the asymmetric spread of excitation in the cochlea. The standard AI calculation can be used to model the condition in which the organ of Corti is intact in the apex. Removing the contributions of the low frequency area from the AI calculation can make the alternate model, in which the organ of Corti is assumed to be destroyed. In such a case, the maximum performance is based on the high-frequency areas alone and is usually lower than 100%. This calculated maximum does not increase with intensity beyond that level at which all the thresholds in the surviving region have been exceeded by the lower boundary of the speech dynamic range in that frequency band. These two calculations provided two different hypothetical results, in terms of word recognition scores, against which the actual performance of the patient could be tested. If the organ of Corti survives in the apex, it will serve to increase the bandwidth, and hence the performance for speech intelligibility as the speech levels rise to exceed the elevated thresholds (Van Tasell & Turner, 1984). If not, these thresholds will cause the standard AI to predict a performance-intensity function that exceeds what is possible with no apical function.

Ricketts, Henry, Hornsby, and Benjamin (2005) investigated the application of frequency importance functions on the directivity index of microphones. This was done to predict the benefit of directional microphone in noise conditions. This directivity index (DI) is an electroacoustic measure that provides a single number index, as a function of frequency. It expresses the difference, in dB, between the microphone's responses to sound arriving from a single direction with its response to a diffused sound field. The investigators called this DI as articulation index weighted directivity index (AI-DI). They found that the performance and calculated SII values were in good agreement across noise conditions. This implied that the directivity index (DI) provided a reasonable frequency-specific estimate of the signal-to-noise ratio changes in the test environment. Their results supported the use of articulation index weighted directivity index (AI-DI) for prediction of directional benefit from hearing aids.

From the above studies it can be construed that when the SII is to be used to predict speech identification scores, a transfer function should be utilized. The transfer function would vary depending on the speech material used for obtaining SRS that is intended to be predicted. Further, in order to improve the prediction of SRS from the SII, incorporation of correction factors for high level of presentation of speech and degree of hearing loss seem to be reasonable.

5. SII in Different Types, Degrees and Configurations of Hearing Impairment

Research has brought to light that speech performance varies in individuals with different types, degrees and configurations of hearing loss (Goetzinger, 1978). Likewise, research has usually indicated that the prediction of speech performance from AI or SII also varies with the type, degree and configuration of hearing loss. Brandy (2002) has cautioned the audiologists about giving a range of expected SRS for individuals with conductive, sensorineural or central hearing loss with any degree of certainty. Research and clinical experience have demonstrated a wide range of scores within each of these groups (Penrod, 1994). It is usually safe to say that, generally, word- and sentence-recognition score are least affected in individuals with a conductive hearing loss and most affected in individuals with a neural hearing loss. Both the sensory (cochlear) and neural (retrocochlear) loss groups of patients produce very wide score ranges, hence, extreme variability in scores (Johnson, 1968; Penrod, 1994). Further, according to Penrod (1994) there is no way to equate a particular SRS with a given level of social functioning. Thus, there seems to be a lack of consensus regarding this matter.

5.I. SII and Different Types of Hearing Loss

Generally, good speech recognition scores are obtained in individuals with a conductive hearing impairment when compared to sensorineural hearing impairment (Goetzinger, 1978). Kringlebotn (1999) has opined that a sensorineural hearing loss gives rise to an additional loss in speech recognition due to reduced frequency resolution and temporal resolution. This supra-threshold deficit is corrected for, if the SII contribution in each frequency band is multiplied with a hearing threshold level dependent "desensitization factor".

these abilities improved and performance became more adult-like. In general, adult-like performance in their study reached by ten years of age.

The studies have not reported of a correction being required for older children and adults. Hence, the SII method does not require any such correction in this population. However, findings of studies on the geriatric population report that age-related corrections are warranted in this age group. Magnusson (1995) and Studebaker et al. (1997) have reported that the formulae that correct the SII for age-related changes in speech recognition cannot be attributed solely to reduced audibility. Magnusson suggested that correction for age was applicable only when the listener's age exceeded 83 years. In contrast, the correction by Studebaker et al. (1997) was appropriate for listeners ranging in age from 20 to 90 years. Their correction calculated an adjustment factor (K) from the subject's age in years (y). The entire SII was multiplied by this factor. The correction factor for age given by them was:

$K = a + b(y) + c(y)^2$,

where, $a = 0.8788097200$, $b = 0.0068361149$ and $c = 0.0000786034$.

In the opinion of Gates, and Popelka (1992) the difference between the Al and the recognition score of a subject provides a reliable index of suspicion that may reduce the diagnostic dilemma of neural involvement. They have suggested using pure tone thresholds and a single speech recognition score to screen for neural lesions. Sherbecoe, and Studebaker (2003) reported that the predictions of speech performance decreased with age, when the subject's age increased beyond 70 years despite the application of an SII correction for age. They found that the decrease in speech performance was not due to speech audibility, high-frequency hearing loss, hearing loss desensitization, or the method used to combine external and internal noise sources. Perhaps the performance deficits increased due to masking, with increasing hearing loss and age.

From these studies, it can be acknowledged that there is a need to incorporate correction factors for age, for children less than 12 years of age, and for elderly individuals beyond 70 years of age. The kind of correction to be applied would differ for these two age groups. However, such corrections have not been indicated for adults.

SII and Audio-Visual (AV) Cues

Visual cues help the listeners to understand speech when audibility is degraded by noise, hearing loss or other factors. Sherbecoe, and Studebaker (2003) noted that there were two methods to predict speech intelligibility when the visual cues were used. One method was to base the predictions on SII functions that were derived from speech tests in which the listener was able to view the talker's face. The other method was to calculate the SII in the usual way and apply a correction for visual cues, as was done in ANSI standards S3.5-1969, and S3.5-1997. ANSI S3.5-1969 used a graph to transform the AI values into AV AI values. The ANSI S3.5-1997 used simple linear equations; these equations were based on more data using more number of subjects and hence provided more precise results. The equations used were, $A \leq 0.2$, $AAV = 0.10 + 1.5 (A)$ and $A \geq 0.2$, $A_{AV} = 0.25 + 0.75 (A)$, where A and AAV referred to the auditory and audio-visual AI values.

Using this correction in their investigation, Sherbecoe, and Studebaker (2003) reported that for individuals with normal hearing, the ANSI formulae significantly overcorrected the AI in most cases. The investigators opined that new correction factors be incorporated to the SII to improve the speech recognition predictability in individuals with normal hearing as well as hearing impairment.

AI and neural involvement

Bondy, Bruce, Becker, and Haykin (2004) have put forth the concept of neural articulation index (NAI) that estimates the speech intelligibility from the instantaneous neural spike rate over time, produced when a signal is processed by an auditory neural model. According to them, while AI or SII can take into account threshold shifts in an individual with hearing impairment, neither of them can account for sensorineural, supra-threshold degradations. The spiking over time of an auditory nerve fibre for an undistorted speech signal (control condition) is compared to the neural spiking over time for the same signal after undergoing some distortion (test condition). The difference in the estimated instantaneous discharge rate for the two cases is used to calculate a neural equivalent to the transmission index (TI, which is a function of the signal to noise ratio), the neural distortion (ND), for each frequency band. From this, the NAI was calculated with a weighted average of NDs at different best frequencies (BFs).

There are thus several modifications of the original AI in order to improve its clinical utility. The more complicated the technique is the more accurate it is. From the reports of the studies in literature, it can be inferred that correction factors such as SLD, HLD are required while computing AI for the individuals with a hearing impairment.

Further, correction factor for age is required when the listener is very young or very old. Corrections are also required when a subject is evaluated in an AV mode.

4. Prediction of Speech Performance from SII

As an alternative to speech tests, objective methods have been used for evaluating the speech performance. There has been an increased interest in quantitative prediction of speech recognition (Dirks, Bell, Rossman & Kincaid, 1986; Dugal, Braida & Durlach, 1980; Pavlovic, 1984; Pavlovic & Studebaker, 1984; Studebaker, Pavlovic & Sherbecoe, 1987). The two prediction methods that have received considerable attention are the Articulation Index (AI) or Speech Intelligibility Index (SII) and the Speech Transmission Index (STI). The calculated index can be transferred to expected speech recognition scores by using an appropriate transfer function.

A transfer function is required for converting the AI to speech scores. Several transfer functions have been presented to date for different speech test material. Some of the speech material for which transfer functions have been developed for are CID W-22 (Studebaker & Sherbecoe, 1991), Auditec NU-6 (Studebaker, Sherbecoe & Gilmore, 1993), Dantale monosyllabic words (Keidser, 1994) and Hagerman's sentences (Magnusson, 1996a). Magnuson, in 1996a, made a comparison of the transfer functions. He reported that the transfer function (TF) of Hagerman's sentences was very steep and similar to that of familiar English sentences. Also, the TF of Swedish PB word was very similar to that of English PB words.

Transfer functions relating the AI to speech performance were different depending on the type of contextual speech material. The AI transfer functions for high probability items rose steeply, much as for sentence materials, while the function for low probability items rose more slowly, as for monosyllabic words. Different transfer functions were also reported for tests conducted in quiet or white noise rather than in a babble background (Dirks, Bell, Rossman & Kincaid, 1986). Dillon (1993) noted that speech gain (i.e., effectiveness of hearing aid assessed by the difference between the aided and unaided scores) measured with monosyllabic words, correlated highly with those measured with the continuous discourse test, provided similar presentation levels were used.

Studebaker, and Sherbecoe (1991) reported frequency-importance and transfer functions for the Technisonic Studios' recordings of the CID W-22 word test. These functions were used to calculate AI values or to predict scores on the W-22 test. The functions were derived from the word recognition scores of eight normal-hearing listeners who were tested under 308 conditions of filtering and masking. The importance function for the W-22 test had a broader frequency range and a different shape than the importance function used in the, standard on the AI, ANSI S3.5 - 1969. The transfer function was similar in slope to the ANSI transfer function for 256 PB-words, but was shifted to the right of that function by 0.05.

Fletcher, and Gait (1950) demonstrated that the relationship between the AI and phoneme recognition could be described by a power function $S = 1 - 10^{-AP/Q}$, where S was the is the proportion of words correct or speech recognition score; A was the articulation index; P was a proficiency factor ranging from 0 to 1 related to efficiency of the talker/listener pair; and Q a fitting constant. They described the proficiency factor as the measure of how experienced the listener was in listening to the talker, and incorporated the skill of the listener in decoding a message. Studebaker, and Pavlovic (1984) reported that 'P' had a value of 'one' for listeners of their own dialect with normal hearing and when the listener's experience and skill was equal to that of average listener with normal-hearing used for deriving the transfer function. For the average individuals with hearing impairment, who are normal in other aspects, the proficiency factor was one.

The AI has been reported to be an acoustical index that is monotonically related to speech recognition performance (Fletcher & Galt, 1950; Fletcher & Steinberg, 1947). The monotonic relation of SII with speech recognition performance was found to hold good not only for individuals with a normal hearing but also for individuals with a hearing impairment (Aniansson, 1974; Kamm, Dirks & Bell, 1985; Pavlovic, 1984; Pavlovic & Studebaker, 1984; Rankovic, 1998) and for individuals with hearing impairment who wore hearing aids (Magnusson, Karlsson & Leijon, 2001).

Studebaker, and Marincovich (1989) used AI to compare speech recognition for hearing aid processed speech. The results demonstrated excellent agreement between the predicted and observed performance. This revealed that the audibility of speech accounted for a very large proportion of variance in performance. Thus, audibility appeared to be the single most important factor in predicting recognition scores. It has also been noted by Pavlovic (1989) that speech recognition increased in direct proportion to the speech spectrum audibility. This was calculated from the long-term average spectra of speech and the hearing threshold of the listener. The maximal value of the SII was 1.0 and its minimal value was 0.0. It was reported that for an individual with a hearing impairment, an AI of 1.0 did not mean that the auditory system with the hearing aid was functioning normally. Even an AI of 1.0, for most hearing aid users, indicated that the hearing aid was optimally matched to the hearing impaired system for maximizing the speech intelligibility.

Over the years, several efforts have been put to improve the predictive ability of the AI for individuals with a hearing impairment (Ching et al. 2001; Pavlovic, 1993; Studebaker & Sherbecoe, 1993). Pavlovic, Studebaker, and Sherbecoe (1986); based on the findings by Kamm, Dirks, and Bell (1985); and Pavlovic (1984), concluded that there was a need to modify the AI scheme so that it also accounted for supra-threshold impairment in speech processing. However, the unmodified and modified procedures for AI gave the same results for normal hearing individuals. Also, the unmodified procedure was accurate for the relative comparison of various listening conditions in case of a single listener (Pavlovic, Studebaker & Sherbecoe, 1986). Further, this inference may not hold good for some subjects such as very young (Stelmachowicz et al., 2000) or old subjects (Gates, Feeney & Higdon, 2003).

Dillon (1993) observed that as the hearing loss increased, the presence of distortions such as reduced frequency and temporal resolution makes it less likely that audible energy will continue to be equally useful. In order to account for cochlear dysfunction, such as impaired frequency and temporal resolution, Pavlovic, Studebaker, and Sherbecoe (1986) introduced a hearing loss dependent desensitization function. This function decreased linearly from 1 to 0 as the hearing thresholds increased from 15 to 94 dBHL.

In ANSI S3.5 - 1997, where the term speech intelligibility index (SII) had been used instead of AI, the procedure to compute the index specified inclusion of corrections in the original AI. The corrections for hearing loss desensitization and speech level distortion were included to improve its prediction of speech performance. These corrections were necessary if the goal was to predict the speech performance of an individual with hearing impairment.

According to Ching, Dillon, and Byrne (1998), the monotonic relationship between the speech recognition and SII may not be true for individuals with severe hearing loss. They examined the relationship between audibility and speech recognition for individuals with sensorineural hearing losses ranging from mild to profound degrees. They too noted that the monotonic relationship between the speech recognition scores and SII were not present for individuals with a severe hearing loss. They reported that the corrections for hearing loss desensitization and speech level distortion were essential for accurate prediction of speech recognition scores in individuals with a hearing impairment.

Although the concept of desensitized audibility allowed better estimation of speech intelligibility for any combination of hearing loss, input level and frequency-gain response, the results were applicable only to the average person with the degree of loss for which the calculation was performed. Some individuals performed considerably better, and some considerably worse than the average. Thus, incorporation of appropriate correction factors in the computation of AI or SII would improve its applicability (Ching etal.,2001).

It has been suggested by Byrne, in 1992, that the AI might not be applicable to steeply sloping high-frequency hearing loss. To verify this, Turner, and Cummings (1999) investigated whether there were limitations on the benefit of providing audible speech information to listeners with high-frequency hearing loss. In a group often listeners with various degrees of high-frequency hearing loss, speech recognition was tested across a wide range of presentation levels. For each of these listeners with a hearing loss, recognition performance reached an asymptote of less than 100%. When the spectrum of the speech for this asymptotic performance level was compared with the listener's pure-tone thresholds, it was seen that providing audible speech to high-frequency regions > 3000 Hz), where hearing loss exceeded 55 dB HL, tended to produce little or no improvement in recognition scores. In contrast, providing audible speech to lower frequency regions for a listener with a flat, severe-to-profound hearing loss did show improvement with increasing speech audibility, despite the listener's thresholds being greater than 55 dB HL.

Souza, and Bishop (2000) studied whether increases in audibility with non-linear instrument improved speech recognition to a comparable degree for listeners with sloping sensorineural as compared to a group having a flat sensorineural loss. Consonant recognition was examined as a function of audibility with wide dynamic range compression amplification and with linear amplification. For linearly amplified speech, listeners with flat and sloping loss showed similar improvements in recognition given the same increases in audibility. Results for non-linearly amplified speech revealed that the listeners with a flat loss showed a greater rate of improvement as audibility increased than the listeners with a sloping loss. This difference was largely attributed to superior performance by listeners with a sloping loss for low-audibility speech in comparison to equivalent group performance for high-audibility speech.

From the above studies it can be construed that the articulation index may overestimate the performance in subjects with a sloping hearing loss. By providing audible speech to high-frequency regions > 3000 Hz), where hearing loss exceeded 55 dB HL, tended to produce little or no improvement in recognition scores. Thus, while selecting amplification requirement for individuals with sloping hearing loss, this aspect needs to be considered. Effective audibility instead of just audibility seems to be appropriate for such individuals.

5.4. SII and Dead Regions in Cochlea

The method of evaluating potential benefit of hearing aids with SII needs to be treated with caution. Individuals with hearing loss differ in their ability to make use of amplified speech information in various frequencies and that these differences may be due to the presence or absence of cochlear dead regions (Hornsby & Ricketts, 2003). For individuals without cochlear dead regions, the SII may provide a valid indication of the audibility and intelligibility of speech. However, for those with dead regions, the SII may lead to an overestimation and thus reduce the potential benefit from amplification because the AI does not account for the presence of dead regions. This may partly account for the finding that people with severe to profound hearing loss or those with dead regions in cochlea often show poorer speech intelligibility than that predicted from the articulation index (Vickers, Moore & Baer, 2001). Rankovic (2002), however, found that audiogram differences accounted for the observed performance differences; and that it was not necessary to invoke dead regions to explain the speech test results. Vestergaard (2003) also reported that large variability was observed with regard to the ability of audibility to predict recognition scores for subjects with and without dead regions.

Thus, it can be inferred that there is a differential effect of different aspects, of hearing impairment, such as type, degree and configuration, on the SII and thus on speech intelligibility. Further studies are required to strengthen these reports. The subjects with hearing impairment tended to exhibit a disproportionate loss in speech discrimination than that predicted on the basis of the AI procedure. This discrepancy appeared to increase with magnitude of hearing loss. In sloping hearing loss, non-monotonicity due to poor performance in the best AI condition was noted.

6. Hearing Aid Selection

Selecting appropriate amplification devices with appropriate characteristics has long been a challenge for audiologists. Significant advances in technology have made this selection process even more difficult by increasing the variety of parameter settings under the control of the audiologist and placing further demand upon the ability to evaluate and determine the appropriateness of these settings (Dempsey, 1994). Several methods have been employed to select hearing aids. In the following section use of speech and SII for hearing aid selection are discussed.

6.1. Hearing Aid Selection and Speech Tests

The ability to understand speech is considered as the most important measurable aspect of human auditory function. Communication through speech is a pre-requisite for fully effective participation in the society (Penrod, 1994). Individuals with hearing loss obtain hearing aids principally to improve their understanding of speech in everyday listening situations. Therefore a major goal in hearing aid selection is to choose an instrument that will result in the greatest possible improvement in speech comprehension. To this end, the results of tests assessing speech recognition with each of several hearing aids often determine which instrument is ultimately recommended (Cox, Alexander & Gilmore, 1987).

A number of tests employing speech stimuli have been utilized in hearing aid evaluations. For example, aided and unaided speech reception thresholds (SRT) have often been compared to arrive at the speech gain. In addition to the SRTs, speech recognition scores (SRS) have been widely used for hearing aid selection (Skinner, 1988).

A classical approach for hearing aid selection using speech material is the Carhart's approach (Carhart, 1946). In this approach, the hearing aids were compared based on the sound-field speech presentations. The hearing aid that provided the best SRT, best word recognition score in quiet, in noise, and the widest dynamic range, was the one that was selected. Variations of this procedure were often used, though the final decisions regarding hearing aid recommendation was similar to the original approach. In these procedures, the instrument that provided the most appropriate gain, the best word recognition score, and the most acceptable sound quality to the subject was the one that was selected. A problem inherent in this approach, as well as the modified versions that ensued, was that a single instrument did not meet all the above criteria. Another problem of this approach was the method of pre-selection of hearing aids. Through other current techniques, hearing aids are selected that have very similar electroacoustic performance. This explains, at least partially, why this approach often yielded results with little or no discernable differences in the aided performance across instruments. Despite these inherent problems in speech based procedures, the use of SRS continues to be a popular and useful technique.

Advocates of SRS testing suggest that several steps need to be taken to increase the validity and reliability of the scores. These steps would include using a full length word list for obtaining scores in quiet and in noise, using tape recorded stimuli, and having subjects provide written responses when possible (Ross, 1978). For the SRS testing, the speech stimuli are usually presented at levels ranging between 40 and 50 dB HL to approximate normal conversation level of speech (Hodgson, 1981).

The speech tests not only help in selection of hearing aids but also in selection of candidates who require hearing aids. Though the relationship between word recognition scores and social adequacy is not well defined a general idea about the perceptual difficulties can be obtained (Goetzinger, 1978). According to Goetzinger (1978) a general guide for evaluating SRS ability is that a person with 90 to 100 % word recognition would have no problem in social adequacy, 75 to 90 % will have slight difficulty; 60 to 75% will have moderate difficulty; 50 to 60 % will have poor recognition and thus difficulty in following conversation and those with < 50 % will have very poor recognition and difficulty following running speech.

Speech recognition procedures, in hearing aid selection, continue to be used in research studies as a useful tool (Mueller, 2001). This technique is useful as long as standard test material is utilized. However, in countries like India, a multitude of languages are spoken and standard speech test materials are not always available. In such times, the use of non-speech techniques is advocated.

6.2. Hearing Aid Selection andSII

A procedure for hearing aid selection, based on audibility within the speech spectrum that has gained prominence in the last two decades, is the use of articulation index (AI). In some of the hearing aid selection approaches, the audibility within the speech spectrum is used as a guiding principle for setting the gain requirements of the hearing aid (Sandlin, 1990). The speech recognition increases in direct proportion to the speech audibility or AI, which can be calculated from the hearing thresholds of the listener and the long-term average speech spectra reaching the listener's ear. This will ensure good speech perception (Pavlovic, 1989).

Marincovich and Studebaker (1985) determined the relationship between the articulation index and the measured speech intelligibility across hearing aids. They also determined the extent of variance, created by the quality of the signal, affecting the speech intelligibility. Three graduate students with normal hearing participated in the study. Recognition of recorded non-sense syllables through six hearing aids in the presence of low level all pass noise, high level low pass noise and high level high pass noise was obtained. It was seen that the relationship between predicted and observed speech recognition scores was very high in all noise conditions, except in high level low pass noise. Repeated measured ANOVA revealed that all the differences between the hearing aids and noise conditions was accounted for by the AI. A small percent of the variance not accounted for by the AI was related to the amount of harmonic distortion.

Berger (1992) compared three hearing aid prescriptive procedures, POGO, Berger method and NAL-R method with AI. Ten hearing loss patterns were used to investigate this. Small AI differences were found between POGO and the Berger method for most of the hearing loss patterns. In contrast, NAL-R produced substantially lower AIs. In a study carried out in India by Chadha (1998), similar results were reported.

The utility of SII in hearing aid selection has also been evaluated by Studebaker, and Marincovich (1989). They tested three individuals with normal hearing with non-sense syllables processed through six linear over-the-ear hearing aids, under various noise masking conditions. The masking conditions included testing in the presence of spectrally shaped noises, i.e., high pass, low pass and low level all pass. The subjects were also tested in a quiet situation. The procedure given by French and Steinberg (1947) was used to compute the AI. Results indicated that importance weighted audibility accounted for a very large proportion of the variance in hearing aid performance. In addition, the speech recognition scores predicted on the basis of AI agreed very well with the average scores obtained, in all the conditions.

The above studies indicate that AI or SII could predict speech intelligibility performance of an individual. This implies that AI or SII can be used for hearing aid selection. The SII has been used both for selecting candidacy as well as shaping the frequency-gain of the hearing aid. However, in most of these studies, either the subjects had normal hearing or the hearing loss was simulated using noise or no subjects were used. Hence, the findings cannot be generalized to subjects with a hearing impairment. This is because the physiology of hearing is different in the two subject groups. Besides using AI or SII for hearing aid selection, it has also been found to be useful to determine whether a client is a candidate for hearing aids or not.

Bergenstoff (1990) noted that for determining whether the person requires hearing rehabilitation is often based on the pure tone average. The disadvantage of this is that the frequencies that are important for speech understanding are not represented adequately. Therefore, the use of the AI for selecting a candidate for hearing aid seems to be more appropriate. This approach incorporates weightage for speech unlike procedures based only on pure tone average.

The AI has been noted to be useful in the selection of candidates for hearing aids. The criterion used to decide whether or not to recommend hearing aids for individuals with hearing loss are sometimes nebulous and debatable. Simplifying this clinical decision without compromising the end result, without increasing the time to collect the clinical data, and without increasing the costs to the patient are all common professional goals. The articulation index (AI) is an uncomplicated procedure that can facilitate the hearing aid purchase decision for both audiologists and their clients.

Skinner (1988) opined that an AI value of less than 0.8 could be taken as a criterion for hearing aid recommendations, provided this information is in agreement with the results of other audiological tests. Moog and Geers (1990) have devised four speech perception categories and have found rough correlations between these and the AI scores of the patients. They are:

Category 1: No pattern perception (AI score of 0.0 to 0.20)
Category 2: Pattern perception (AI score of 0.21 to 0.49)
Category 3: Some word identification (AI score of 0.50 to 0.69)
Category 4: Consistent word identification (AI score of 0.70 to 1.0)

They observed that children in categories 3 and 4 were capable of attaining a good level of speech recognition with the help of their auditory prosthesis. These categories are useful in predicting the hearing aid benefit and thus this can also serve as an indicator for cochlear implant candidacy.

Roth, Lankford, Meinke, and Long (2001) evaluated the use of AI for making hearing aid recommendations for clients with a hearing impairment. In their study, data was collected retrospectively from the Audiology files of 100 sequential patients, ranging in age from 40 to 92 years, with a mean age of 71 years. The patients had a bilateral, sloping symmetrical sensorineural hearing loss not greater than 40 dB between ears at any one frequency. Pavlovic's Ao (6) calculation method was used to obtain AI. The articulation indices for all subjects who purchased hearing aids ranged from 0.0 to 0.62, with the mean being of 0.28. Of the 100 subjects, 96 percent purchased hearing aids when their articulation index was 0.50 or less. The remaining 4 percent of subjects who acquired hearing aids had articulation indices ranging from 0.51 to 0.62. Thus, they recommended that an AI of 0.50 or less be used as a predictor of the need for amplification.

Hornsby (2004) has also opined that one of the most obvious uses of AI is in determining the candidacy for hearing aid. He further reported that individuals with very high unaided AIs are unlikely to show large aided benefit, at least for conversational speech. As it is difficult to say how "high" an unaided AI is "high enough", he opined that self-assessment questionnaires could help to identify borderline candidates who required hearing aids. Kamlesh (1998) and Sweetow (1989) reported that speech-in-noise testing can be conducted to help determine candidacy for border-line patients.

From these studies it is evident that there is no one AI value that has been agreed up on to decide whether a client is a candidate for a hearing aid or not. The listening needs of the clients could help the audiologist whether a higher or a lower AI value should be used.

Another application of AI or SII, is that it can be used to objectively select optimal frequency-gain of a hearing aid (Berger, 1992). A hearing aid with the best AI or SII should be the one to be selected. Further, AI or SII when represented graphically will provide information as to how the gain of the hearing aid should be changed to further increase the speech recognition ability. Thus, it helps the audiologist to decide how the gain of the hearing aid should be changed further to increase the speech recognition.

Magnusson, Karlsson, and Leijon (2001) investigated the applicability of the modified SII in hearing aid fitting. They tested 29 elderly individuals with mild to moderate hearing loss, who were using monoaurally fitted linear hearing aids. The SRS were obtained for PB words in the presence of noise. Performance on connected speech was also evaluated in the presence of noise. The subjects were tested without and with their hearing aids, set at three different frequency responses. The SRS was predicted in each condition based on the modified SII which included a correction factor for sensorineural hearing loss. It was found that for each condition, the measured SRS was well predicted by the SII. It can be deduced from this study, that prediction of speech recognition is possible by using an AI that incorporates a correction factor for hearing loss. However, it cannot be confirmed that without using this correction, speech recognition can be predicted. Similar findings on predicting speech recognition was reported earlier by Magnusson (1996b).

SII has also been used for counselling purposes. A graphical representation of the SII would provide the audiologist with a clear visual indication, on an audiogram, the aided and unaided performance, in relation to the speech spectrum. This SII illustrates the variation in performance with different hearing aids and thus helps in hearing aid selection. Thus, it can also be used to demonstrate the reasons for selecting a particular amplification device. Hearing aid fitting is never complete without counselling the users on the usefulness of a hearing aid. These illustrations help to demonstrate to the client why he/she continues to experience problems in understanding speech even though he/she is fitted with a hearing aid (Pavlovic, 1989; Zelnick, 1992). This substantiates the information that will be provided while counselling an individual regarding the expectation from a hearing aid. Thus, the AI is a useful counselling and selling tool too.

6.3. Hearing Aid Selection and Quality Judgements

The primary goal of a hearing aid is to make sounds audible so that speech is intelligible and the perceived sound quality is acceptable. Although the focus of most hearing aid fitting procedures had been to achieve optimal intelligibility, incorporation of subjective judgments of sound quality is also gaining prominence as a necessary and integral part of such evaluations (Eisenberg, Dirks, Takayanagi & Martinez, 1998).

The subjective nature of sound quality makes it more difficult to use a structured measure of hearing aid outcome (Narendran & Humes, 2003). There is a need to evaluate the relationship between overall quality judgement and speech intelligibility. The correlation of these two parameters on SII also requires to be studied. Individuals who judge a hearing aid to have a good quality are more likely to use it.

Thus, in addition to the speech recognition scores, hearing aids can also be selected by evaluating the judgments on intelligibility (Zerlin, 1962) and the judgments on quality (Jeffers, 1960) of the speech processed through the hearing aid. Gabrielsson, Schenkman, and Hagerman (1988) suggested that the gain-frequency response that provides optimal speech understanding might not always be preferred by listeners in terms of optimal sound quality. Pavlovic (1989) too pointed out that there is no evidence that the aid that provides maximum intelligibility will also be the best aid for the patient using other criteria, i.e., in terms of providing maximum acceptability. However, in his opinion, speech intelligibility or its predictor should be used in hearing aid selection together with other important indices such as user satisfaction. Such indices include qualitative judgments, client's reaction and above all the audiologist's clinical expertise.

Hence, there is a need to evaluate the correlation between overall quality and intelligibility with the SII. Individuals who judge a hearing aid to have a good quality are more likely to use it. By evaluating the correlation between the overall quality and intelligibility, it can be established whether the SII can predict this aspect too.

6.4. Hearing Aid Effectiveness and SII

Effectiveness reflects the benefit the typical patient receives in a community setting for treatment under ordinary conditions. Souza, Yueh, Sarubbi, and Loovis (2000) studied the relationship between audibility and hearing aid effectiveness. As most clinical tests focus on how much a particular hearing aid improves speech audibility under controlled conditions, it is unclear how these measures relate to hearing aid effectiveness. In the study, AI was used as the measure of audibility along with two hearing specific surveys and self-reported ratings of global satisfaction. Results indicated that there were no systematic relationships between measurements of improved audibility and a client's ratings of communication ability. Improved audibility was not related to the overall satisfaction with the amplification characteristics of the hearing aid. However, improved audibility was related to hearing aid use adherence, with patients who achieved better audibility reporting that they used their hearing aids more frequently.

There are several studies (Berkowitz & Hochberg, 1971; Mathews, Lee, Mills & Scheem, 1990; McCartney, Maurer & Sorenson, 1976; Vanaja, 2000), which correlate the hearing handicap scale with the audiological measures such as pure tone average and speech recognition scores, both in quiet and in noise. It has been documented from these studies that the perceived hearing handicap correlated better with the pure tone average than with speech recognition scores, for most components of the handicap scale. Further, the inability to comprehend speech correlated more with the high frequency than the mid-frequency pure tone average (Barrenas & Holgers, 2000). Hence, an SII procedure, for selecting hearing aids would also reflect the extent of hearing handicap that an individual

Table 3.1

The LTASS in dB SPL, sound field SPL to HL conversions and the LTASS in dB HL

Freq. (*Hz*)	*Combined LTASS* (*dB SPL*) (*Byrne et ah, 1994*) **A**	*Sound field SPL to HL conversions* (*Morgan et al, 1979*) B	*LTASS* (*dB HL*) *A-B*
250	60.3	20.2	40.1
500	62.1	7.8	54.3
750	56.8	4.2	52.6
1000	53.7	3.7	50
1500	52	2.6	49.4
2000	48.7	3.8	44.9
3000	46.8	-2.9	49.7
4000	45.6	-4.4	50
6000	44.3	3.5	40.8

For the purpose of the study, two separate *band importance functions* were used. In order to predict the speech recognition scores (SRS), the band importance of CID W-22 PB word lists (Studebaker & Sherbecoe, 1991) was utilized. This was utilized as the stimuli closely resembled the speech material used in the present study, i.e., phonetically balanced words in Kannada language. The band importance function of the average speech (Pavlovic, 1994) was used for selecting hearing aids as it reflected everyday speech. Pavlovic (1994) recommended that the band importance function of average speech be used for hearing aid selection.

with hearing impairment faces, as the SII is calculated based on the hearing thresholds and band importance functions.

6.5. Limitations of AI or SII in Hearing Aid Selection

There are certain limitations in using the AI for assessing hearing aid performance. Skinner (1988) claimed that a limitation of the AI for hearing aid selection is that there is no adjustment in the computation for the balance of the low-frequency with the high-frequency energy of speech spectrum that is so often necessary in order to obtain maximum speech recognition. While the AI estimates the overall speech recognition score, it does not indicate the type of error that is made by the individual with a hearing impairment. In other words, it does not indicate whether the error is due to place or manner of articulation of speech. Individuals with hearing impairment with the same AI may show different type of errors in speech recognition (Zelnick, 1991). This information is required for further rehabilitation of the individual.

In addition, the AI or SII method does not take into consideration the hearing aid distortion, internal noise, or reduced uncomfortable loudness level. Also, while the AI is concerned with quantifying those critical frequencies which will be audible and contribute to speech intelligibility, it does not consider the cochlear or retrocochlear problems of speech processing nor is it sensitive to the possibility of low-frequency hearing (Halpin, Thornton & Hasso, 1994). In clients with auditory dyssynchrony, also, where the problem is primarily temporal based, there could be improvement in the aided AI, but no improvement in the aided speech intelligibility. Temporal resolution plays an important role in speech perception but is not included in the computation of the articulation index.

Revit (2001) reported that the SII varies significantly for different listening situations. Thus, one hearing aid could have a high SII score and good speech intelligibility for one listening situation and the same hearing aid could have a high SII score and yet result in poor speech intelligibility for a different situation. Furthermore, acoustically different hearing aids can have the same SII score.

Despite the above limitations, determining the frequency response characteristic might specify the optimal spectral shape. Based on the individual's audiogram, UCLs, listening environment and task demands, this optimal spectral shape would maximize the SII (Kamm & Dirks, 1982). Fabry, and Schum (1994) have noted that AI accounts for 90% or more of the variance associated with hearing aid performance. As the advantages out performs the limitations, especially in a multi-lingual country like India, SII seems to be a good choice for hearing aid selection.

From the review of literature, it is evident that the SII is a useful procedure to predict speech recognition scores, as well as select hearing aids. However, several modifications of the original AI formula have been suggested to make the procedure effective for different types, degrees and configurations of hearing loss. Thus, there is a need to study the efficacy of SII in the prediction of speech recognition ability and in hearing aid selection.

METHOD

In order to investigate the efficacy of a speech intelligibility index (SII) in prediction of speech recognition scores (SRS) and in hearing aid selection, the study was carried out in three stages. *Stage I* involved development of a software program for computing speech intelligibility index (SIIw) with the band importance function for CID W-22 word lists. In addition, software programs to calculate SIIw with a correction factor for speech level distortion ($SIIw_{SLD}$); SIIw with correction factors for speech level distortion and hearing loss desensitization ($SIIw_{SLD\ HLD}$); and SII with band importance function for average speech (Silas) were developed. In *Stage II,* the software programs to compute the SIIw, $SIIw_{SLD}$and $SIIw_{SLD\ HLD}$ were used to derive regression equations in order to predict the SRS. Also, on a different group of participants, the predicted SRS was compared with the measured SRS to check the utility of the regression equation. In *Stage III,* a cut-off criterion to differentiate the candidates who required hearing aids from those who did not was established. In addition, the efficacy of Silas in hearing aid selection was investigated. The following sections give the details of these three stages.

Stage I: Development of Software Programs for Computing SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ and Silas

A Microsoft Excel 2000 electronic spreadsheet was utilized for developing the software program for computation of the Speech Intelligibility Index (SII). SII was computed using a formula similar to that developed by French and Steinberg (1947), with band importance functions for words (SIIw) as well as for average speech (Silas). The procedure for computer application was derived from the methods adopted by Popelka and Mason (1987) and Pavlovic (1991). Using the basic SIIw, software programs were developed to compute SIIw_{SLD} which accounted for a correction factor for speech level distortion (SLD). Further, a program was developed to compute $\text{SIIw}_{\text{SLD HLD}}$ which accounted for the correction factors, speech level distortion as well as hearing loss desensitization (HLD).

The product of the *band audibility function* and the *band importance function* was used to compute the SIIw and Silas. The audibility function indicated the extent to which different frequencies would be audible to the listener and the band importance function indicated the relative importance of different frequencies for intelligibility. The band audibility function was determined by noting the proportion of the speech signal within a band that was above the hearing threshold level. The audibility was determined by using information regarding the hearing thresholds, long-term average speech spectra and speech dynamic range. This was obtained in decibel (dB) for nine different frequencies. These frequencies bands were 250, 500, 750, 1000, 1500, 2000, 3000, 4000 and 6000 Hz. The *long-term average speech spectrum (LTASS)*, obtained by Byrne et al. (1994), was used in the computation of SII. These values in dB SPL were converted to sound field referenced dB HL values for frequency-modulated tones from 45° Azimuth, using the values given by Morgan, Dirks, and Bower (1979). This was done in order to calculate the SII from sound field hearing thresholds obtained in dB HL. The long-term average speech spectrum values in dB HL, derived in this way, are depicted in Table 3.1. A *speech dynamic range* of 30 dB was utilized which extended from +12 to -18 dB relative to the long-term average speech spectrum.

Thus, the SII software for computation of SII was developed using the hearing thresholds, long-term average speech spectrum, speech dynamic range (i.e., audibility function) and band importance function. The SIIw or Silas values computed varied depending on the hearing thresholds of an individual. Table 3.2 depicts the Microsoft Excel template used for computing the SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ using the band importance function for the CID W-22 PB wordlists. This SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ template was used to predict the speech recognition scores. Table 3.3 depicts the Microsoft Excel template for computing the unaided and aided Silas using band importance function for average speech. This template was used for establishing a criterion for hearing aid candidacy and for hearing aid selection based on SII.

In Table 3.2, each line provided specific information. The lines numbered 1 to 7 represent information on the band audibility; the line numbered 8 indicates the band importance; the line numbered 9 is the product of band audibility and band importance; the line numbered 10 gives the SIIw value; the lines numbered 11 to 19 represent the procedure for incorporating SLD in SIIw, i.e., $SIIw_{SLD}$; and the lines numbered 20 to 25 depict the procedure for incorporating HLD in $SIIw_{SLD}$, i.e., $SIIw_{SLD\ HLD}$. The program to compute SIIw was modified to incorporate the SLD correction factor reported by Ching, Byrne and Dillon (1998) and the HLD correction factor that was derived by Sherbecoe, and Studebaker (2003).

Table 3.2

The Microsoft excel template for computing the SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ \ HLD}$ for predicting speech recognition scores using band importance for CID W-22 PB wordlists

	Frequency (Hz.)								
Parameters	**A** **250**	**B** **500**	C **750**	**D** **1000**	**E** **1500**	**F** **2000**	**G** **3000**	**H** **4000**	**1** **6000**
1. Threshold (dB HL)	***25***	**35**	***40***	***25***	***35***	***25***	***25***	***25***	***25***
2. LTASS	40.1	54.3	52.6	50	49.4	44.9	49.7	50	40.8
3. HSP-R (L2 + 12 dB)	52.1	66.3	64.6	62	61.4	56.9	61.7	62	52.8
4. HSP (Greater of L1 & L3)	52.1	66.3	64.6	62	61.4	56.9	61.7	62	52.8
5. LASP-R (L2-18dB)	22.1	36.3	34.6	32	31.4	26.9	31.7	32	22.8
6. LASP (Greater of L1 and L5)	25	36.3	40	32	35	26.9	31.7	32	25
7. RASP (L4 - L6)	27.1	30	24.6	30	26.4	30	30	30	27.8
8. Band importance	0.1549	0.1307	0.0836	0.1157	0.1349	0.1401	0.1134	0.0648	0.0619
9. SII band (L7 X L8)	4.19779	3.921	2.05656	3.471	3.56136	4.203	3.402	1.944	1.72082
10. Sum across L9) / 30; **SIIw**	**0.949251**								
11. Overall Level	***87.1***								
12. Speech Spectrum level, Ei	***59***	***65.6***	***75.4***	***81***	***72.4***	***74.4***	***67.3***	***57.2***	***27.8***
13. Std. speech spectrum level, Ui	60.3	62.1	56.8	53.7	52	48.7	46.8	45.6	44.3
14. Ei-Ui-10	-11.3	-6.5	8.6	17.3	10.4	15.7	10.5	1.6	-26.5
15. L= (Ei-Ui-10) /160	-0.070625	-0.040625	0.05375	0.108125	0.065	0.098125	0.065625	0.01	-0.165625
16. SLD=1-L	1.070625	1.040625	0.94625	0.891875	0.935	0.901875	0.934375	0.99	1.165625
17. SLD, Only if overall level >73dBSPL	1.070625	1.040625	0.94625	0.891875	0.935	0.901875	0.934375	0.99	1.165625
18. SLD band	4.494258919	4.080290625	1.9460199	3.095698125	3.3298716	3.790580625	3.17874375	1.92456	2.005830813
19. SII/30; SHw_{SLD}	**0.928195145**								

(table continues)

Table 3.2 (Continued)

Parameters	Frequency (Hz.)								
	A **250**	B **500**	**C** **750**	**D** **1000**	**E** **1500**	**F** **2000**	**G** **3000**	**H** **4000**	**1** **6000**
20. X	1.042	1.0345	1.0285	1.0255	1.114	1.159	1.258	1.3075	1.405
21. Y	0.0028	0.0023	0.0019	0.0017	0.0076	0.0106	0.0172	0.0205	0.027
22. Y(T)	0.07	0.0805	0.076	0.0425	0.266	0.265	0.43	0.5125	0.675
23. HLD	0.972	0.954	0.9525	0.983	0.848	0.894	0.828	0.795	0.73
24. SII band	4.368419669	3.892597256	1.853583955	3.043071257	2.823731117	3.388779079	2.631999825	1.5300252	1.464256493
25. SII/30; $SIIW_{SLD}$.HLD	**0.833215462**								

Note. LTASS : Long term average speech spectrum
HSP-R : High speech level in the speech dynamic range
HSP : Greater of the values in hearing threshold and HSP-R
LASP-R: Low speech level in the speech dynamic range
LASP : Greater of the values in hearing threshold and LASP-R
RASP : Range of audible speech dynamic range
L : Line; the number represents the line number.

Likewise in Table 3.3, the lines numbered 1, 3 and 4 to 8 depict information on band audibility; the lines numbered 2 and 9 may be used in the aided Silas calculation; line numbered 10 represents the band importance for average speech at different frequencies; in line 11 the product of band audibility and band importance is computed for each frequency; and line numbered 12 gives the Silas value which is the sum of the products obtained in line numbered 11. In both the tables (Tables 3.2 and 3.3) the values were calculated for a hypothetical client with a mild hearing loss. The graphical representation. Figure 3.1, was used in hearing aid selection and to aid in counselling the clients.

Table 3.3

The Microsoft excel template for computing Silas, for hearing aid selection, using band importance for average speech

	Frequencies (Hz.								
Parameters	A **250**	B **500**	C **750**	**D** **1000**	**E** **1500**	**F** **2000**	**G** **3000**	**H** **4000**	**I** **6000**
1. Threshold (dB HL)	***25***	**35**	***40***	***25***	**35**	***25***	***25***	***25***	***25***
2. UCL	100	100	100	100	105	110	110	115	110
3. LTASS	40.1	54.3	526	50	49.4	44.9	49.7	50	40.8
4. HSP-R (L3+12dB)	52.1	66.3	64.6	62	61.4	56.9	61.7	62	52.8
5. HSP (Greater of L1 & L4)	52.1	66.3	64.6	62	61.4	56.9	61.7	62	52.8
6. U\SP-R (L3- 18 dB)	22.1	36.3	34.6	32	31.4	26.9	31.7	32	22.8
7. LASP (Greater of L1 and L6)	25	36.3	40	32	35	26.9	31.7	32	25
8. RASP (L5 - L7)	27.1	30	24.6	30	26.4	30	30	30	27.8
9. OSPL-90	95	95	95	95	100	105	105	110	105
10. Band importance	0.0617	0.1344	0.1035	0.1235	0.1321	0.1328	0.1285	0.1039	0.0796
11. SII band (L8X L10)	1.67207	4.032	2.5461	3.705	3.48744	3.984	3.855	3.117	2.21288
12. Sum across L11/30; Silas	0.953716333								

Note. LTASS : Long term average speech spectrum
HSP-R : High speech level in the speech dynamic range
HSP : Greater of the values in hearing threshold and HSP-R
LASP-R : Low speech level in the speech dynamic range
LASP : Greater of the values in hearing threshold and LASP-R
RASP : Range of audible speech dynamic range
L : Line; the number represents line number.

To calculate the SII, only the hearing thresholds, measured in sound field at different frequencies for each test ear, were fed in line 1, as shown in the Tables 3.2 and 3.3. While using the template shown in Table 3.2, the unaided or the aided threshold were fed, depending on whether unaided SII or aided SII were to be computed. The SIIw, $\text{SIIw}_{\text{SLD}}$and $\text{SIIw}_{\text{SLD HLD}}$ (Table 3.2) and Silas (Table 3.3) values were automatically computed once the hearing thresholds (Line 1) and the levels of the speech (for SLD correction) were entered.

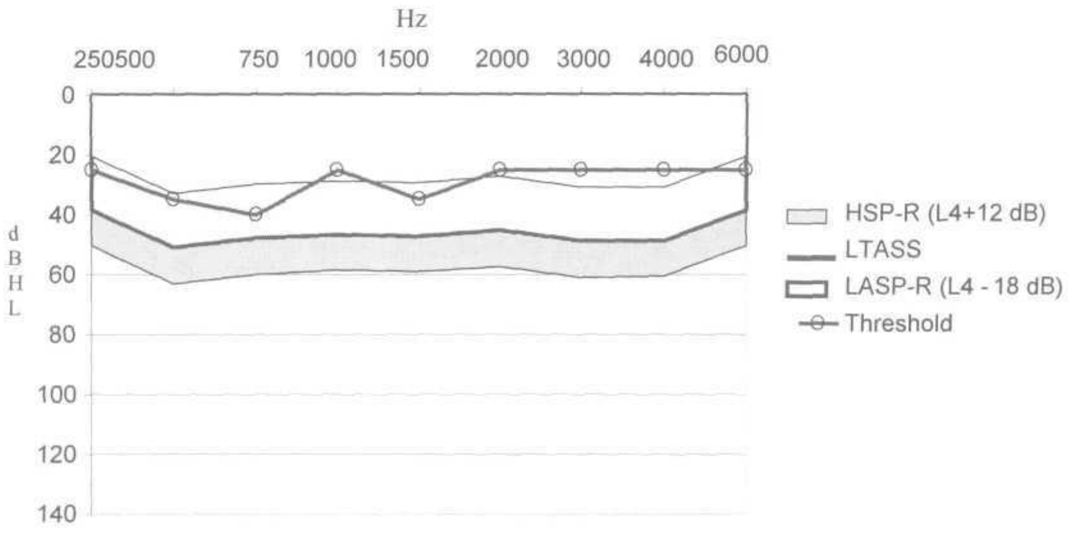

Figure 3.1. Graphical representation of the hearing threshold in relation to the speech spectrum.

The formula for speech intelligibility index (SIIw) with SLD and HLD correction factors that were used, were as follows:

$SIIw = \quad \Sigma \quad Ai \quad Ii$ … ***Equation 3.1***

where Ai is the audibility function at i^{th} frequency and I, is the band importance function at the i^{th} frequency for W-22 word list.

In order to incorporate the speech level distortion and hearing loss desensitization in the SIIw, the SLD and HLD correction factors were added to the Equation 3.1. Thus, for deriving SIIw with a correction factor for speech level distortion ($SIIw_{SLD}$), the following computation was done:

$SIIw_{SLD} = \quad \Sigma \quad Ai \quad Ii \quad Li$ … ***Equation 3.2***

where, the speech level distortion, Li, was obtained using the following equation:

$$L_i = 1 - \frac{(E_i - U_i - 10)}{160}$$

where Ei is the speech spectrum level and Ui is the standard speech spectrum level for normal vocal effort for the i^{th} band. The SLD factor was incorporated since it was noted by Ching et al. (1998) that the intelligibility of speech decreased from unity once the overall level exceeded 73 dB SPL. Further, to include the hearing loss desensitization (HLD) in the $SIIw_{SLD}$, the following equation was used:

$$SIIw_{SLD}\ HLD = \Sigma\ Ai\ Ii\ Li \qquad Hi \qquad \textit{... Equation 3.3}$$

where A, is the audibility function at the $i^{th"}$ frequency band, Ii is the band importance function at the i^{th} band, Lj is the speech level distortion factor at the i^{th} band and Hi is the hearing loss desensitization factor in the i^{th} band. The HLD was derived from a series of linear equations reported by Sherbecoe and Studebaker (2003). Thus, Equation 3.3 gives the SIIw with SLD and HLD correction factors.

The formula to calculate the Silas was similar to Equation 3.1, except that the band importance function for average speech was used instead of the band importance function of words. The Silas was used in hearing aid selection. Equation 1 was used to compute the SIIw and Silas using the procedure given in Tables 3.2 and 3.3 respectively. The corrections for SLD and HLD were applied to compute $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ in Table 3.2, using Equation 3.2 and Equation 3.3 respectively. The band importance function for CID W-22 words was utilized in Table 3.2 for the computation of SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ in the unaided and aided conditions. The computed SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ were used for formulating regression equations to predict speech recognition scores (SRS).

The software program shown in Table 3.3 was used for computing the unaided and aided Silas for hearing aid selection. Here, the band importance function for average speech was used for computation of Silas. The correction factors for SLD and HLD were not required as the results obtained with various hearing aids were compared with each other for a single participant. Thus, the two programs, one for predicting speech recognition ability, without and with corrections; and another for selection of hearing aids were developed using the Microsoft Excel spreadsheet.

The functioning of the programs was verified by changing the hearing threshold values in line 1 of Tables 3.2 and 3.3. In addition, the overall speech level and speech level in the different frequency bands in lines 11 and 12 respectively were also varied to confirm the working of the software in Table 3.2. The corresponding changes in the SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ and Silas values that were being computed by the computer software were noted. It was observed that by varying the hearing threshold level and the speech levels, the SIIw, $SIIw_{SLD}$and $SIIw_{SLD\ HLD}$ and Silas values did change correspondingly. This ensured the proper working of the programs.

Stage II: Computing Unaided and Aided SIIw, $SIIw_{SLD}$and $SIIw_{SLD\ HLD}$ for Predicting SRS

In this stage, data were obtained to compute SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ in two separate groups. Group I was used to derive the regression equations for prediction of SRS. They were further sub-divided into three sub-groups based on the type and slope of audiogram. Group II was utilized to verify the efficacy of the equations in predicting the SRS.

A. Participants

In order to derive equations for the prediction of SRS, data were collected from 93 participants in the age range of 15 to 55 years (mean age being 37.59 years; standard deviation being 12.68 years). Of them, 58 were males and 35 were females. All the participants had a post-lingually acquired hearing-impairment and were first time hearing aid users. They reported of no other significant problem. All the participants had normal speech and were fluent speakers of Kannada, a language spoken in the state of Karnataka in South India. They gave informed consent to participate in the study.

The 93 ears of 93 participants were divided into three sub-groups. The first sub-group consisted of 39 ears with conductive hearing impairment. The ears with a conductive hearing loss either had A, As, Ad, B or C type tympanogram and absent reflexes.

The second sub-group included 34 ears of participants who had a flat sensorineural hearing impairment. The test ears in the first and the second sub-groups were classified as having mild, moderate and moderately-severe degrees of hearing loss based on the Clark's (1981) modification of Goodman's classification. The participants with a mild hearing loss from the first and second sub-groups participated in Stage III of the study also.

The third sub-group comprised of 20 ears of participants with a sloping sensorineural hearing impairment. Of these 20 ears, 10 had a gradual slope (5 to 12 dB increase in threshold per octave) and 10 had a steep slope (15 to 20 dB increase in threshold per octave) configuration. The criterion recommended by Lloyd and Kaplan (1978) to classify the slope of the audiogram was used. The demographic details of the participants from the three sub-groups are provided in Table 3.4. The mean hearing thresholds of the test ears of the different sub-groups of participants is shown in Figure 3.2.

All ears with a sensorineural hearing loss had normal middle ear on immittance evaluation, i.e., Type A tympanogram, acoustic reflex thresholds at normal hearing levels and negative reflex decay. They had no complaint of a neurological or psychological problem.

To verify the efficacy of the equations in predicting the SRS, one ear each (either right or left) of 26 additional participants (Group II) were evaluated. The audiological inclusion criteria of these participants were similar to that mentioned earlier. These participants were in the age range from 17 to 55 years (mean age being 43.23 years; standard deviation being 10.95 years). Of these, 14 were males and 12 were females. Table 3.5 depicts the demographic details of these participants.

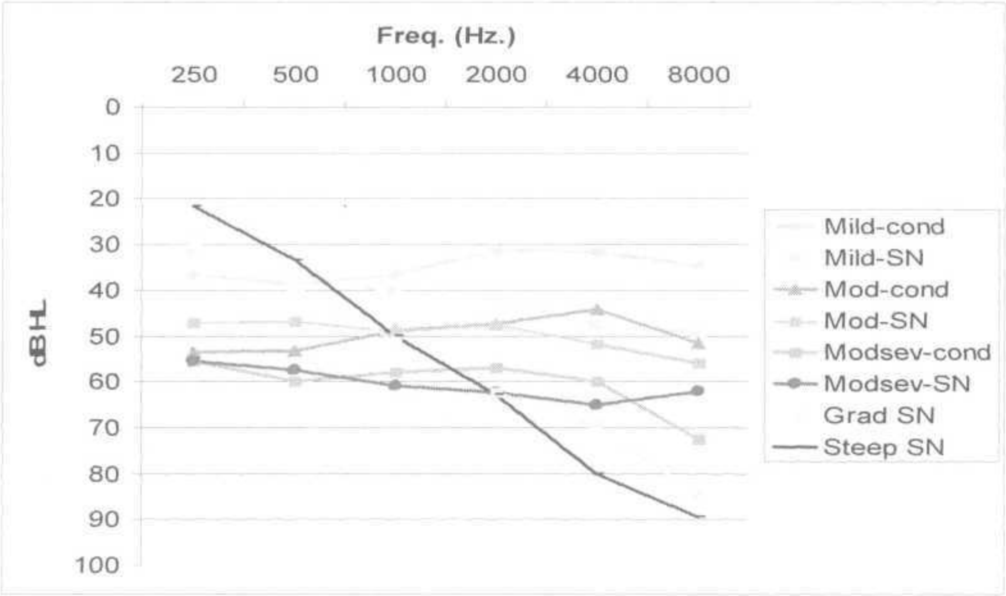

Figure 3.2. Mean hearing thresholds of the test ears in different sub-groups of participants in Group I.

Table 3.4

Demographic details of participants in Group I used to derive equations to predict SRS

Type of hearing loss	*Degree/Slope* ***of*** *hearing loss*	*No. of participants*						*Total no. of ears (N)*
		Males			*Females*			
		N	*Mean (SD)*	*Range*	*N*	*Mean (SD)*	*Range*	
Conductive	Mild	6	24.17 (9.28)	15-38	*6*	24.33 12.72)	18-50	12
	Moderate	8	37.20 14.10)	18-55	*7*	34.43 13.32)	15-52	15
	Moderately-severe	7	36.29 11.07)	23-50	5	39.20 13.63)	18-53	12
Sensorineural	Mild	5	51.00 (3.94)	45-55	6	47.00 (5.66)	40-55	11
	Moderate	8	40.38 13.28)	20-55	3	35.67 (10.69)	29-48	11
	Moderately-severe	11	36.73 (11.08)	16-50	1	44 (0)	44-44	12
Sloping sensorineural	Gradual	6	31.67 (15.19)	16-55	4	44.5 (7.55)	34-50	10
	Steep	5	41.20 (15.43)	22-55	5	40.20 (12.85)	21-55	10

Table 3.5

Demographic details of participants in Group II used to verify the efficacy of equations in predicting SRS

Type of hearing loss	*Degree/Slope* ***of*** *hearing loss*	*No. of participants*						*Total* ***no. of*** *ears (N)*
		Males			*Females*			
		N	*Mean (SD)*	*Range*	*N*	*Mean (SD)*	*Range*	
Conductive	Mild	3	46 (1.73)	44-47	-			3
	Moderate	3	26 (3.46)	24-30	-			3
	Moderately-severe	2	43.5 (10.61)	36-51	2	48.5 (4.95)	45-52	4
Sensorineural	Mild	-			3	50 (8.66)	40-55	
	Moderate	2	51 (4.95)	48-55	2	45 (0)	45-45	*4*
	Moderately-severe	3	45.33 (10.02)	35-55	1	32 (0)	32-32	*4*
Sloping sensorineural	Gradual	1	17 (0)	17-17	2	55 (0)	55-55	*3*
	Steep	-			2	43 (9.90)	36-50	*2*

B. Test Environment

All the testing was carried out in a two-room, test-cum-control, sound treated suite. The ambient noise levels were within the limits permitted by ANSI S3.1 - 1991.

C. Instrumentation

The following instruments were used for the study:

- A calibrated two-channel clinical audiometer, Madsen Orbiter 922 (version 2), with TDH 39P earphones housed in MX-41/AR ear cushions, enclosed in noise excluding headset ME70 was used. Also used with the audiometer were a Radioear B71 bone vibrator and a Martin Audio Cl 15 sound-field speaker (with a power amplifier) located at 45° Azimuth at a distance of one meter from the test ear of the participant.
- A calibrated middle ear analyzer, GSI - Tympstar (version 2) was utilized for middle ear evaluation.
- A Philips 729K DVD player was used to play the recorded speech material. The electrical output of the CD player was routed to the sound field speaker through the auxiliary input of the audiometer.
- A Pentium IV computer with software programs was used for computing speech intelligibility index.
- Commercially available linear analogue behind-the-ear hearing aids, with non-automatic gain control were also used. Hearing aids having electroaoustic characteristics such that, the responses were in the fitting range

for a particular hearing loss, were pre-selected. The total harmonic distortion of these hearing aids was less than 3% at 800 and 1000 Hz and less than 5% at 500 Hz. Output limiting was not used because none of the participants reported of any discomfort with the presentation levels used as well as with loud noise. The hearing aids were coupled to the test ear through hard ear moulds.

- Fonix 6500 C hearing aid test system was used to measure the electroacoustic characteristics of the hearing aids and to measure the sound pressure level of the signal that would be developed in the coupler.

To ensure valid results, the audiometer and immittance meter were calibrated before and during the collection of data. The calibration was done as per the instruction manual of the respective instruments. The hearing aid test system was also calibrated following the procedure given in the instruction manual.

D. Test Material

Speech material in Kannada was used for obtaining speech reception threshold (SRT) and speech recognition scores (SRS). Kannada, a Dravidian language which is the official language of the state of Karnataka, India, was used as the study was carried out in this region. The test material included:

- Paired-word list (developed in the Department of Audiology, All India Institute of Speech and Hearing, Mysore, Karnataka, India) for establishing speech reception threshold. This list is given in Appendix A.

- Phonetically balanced (PB) bi-syllabic word lists (Vandana, 1998) for speech recognition scores. This material had four half-lists each consisting of 25 words. Monosyllables were not used, as they do not occur in Kannada. This material is listed in Appendix B.

Recording the Speech Material on a CD:

A native female speaker, who was proficient in Kannada and with a good voice quality, recorded the speech stimuli on the computer, using the AudioLab (version 1) software. Care was taken to monitor the voice during the recording such that the VU meter deflection averaged to zero while the test material was recorded. The recorded material was normalized to ensure that the test items were equal in loudness. While recording the Kannada word lists, a silence interval of five seconds was maintained between two words which was sufficient to elicit a response from the participants. A 1000 Hz calibration tone was recorded at the beginning of each word list. This material was later transferred onto an audio compact disk (CD).

E. Test Procedure

Initially, a detailed case history including information regarding age, literacy, occupation (past/present) and socio-economic status was collected from all the participants. Further, information regarding onset of hearing loss, duration of hearing loss, listening difficulties and associated problems was collected. In addition, audiological tests were carried out for the following purposes:

1. Selection of participants
2. Obtaining unaided and aided sound field evaluation in order to predict SRS from SIIw, SIIw$_{SLD}$and SIIw$_{SLD,HLD}$.

1. Selection of Participants

Pure-tone audiometry, speech audiometry and immittance evaluation were carried out for selection of participants of the study. The air-conduction pure-tone and speech tests were carried out using TDH-39P earphones. The bone-conduction testing was carried out using B-71 bone vibrator. For selection of the participants the following steps were used:

(i) Pure -tone audiometry was carried out using the modified Hughson-Westlake procedure (Carhart & Jerger, 1959). Pure-tone audiometry included estimation of air-conduction and bone-conduction thresholds. Air-conduction thresholds were obtained at 250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000 and 8000 Hz. Bone-conduction thresholds were estimated at 250, 500, 750, 1000, 1500, 2000, 3000 and 4000 Hz. The better ear, as reported by the participant, was tested first. In participants who did not report of one ear being better than the other, the right ear was tested first. The non-test ear was masked through insert phones, whenever indicated.

(ii) The uncomfortable loudness level (UCL) for broad band noise was established for both ears. This was done using an ascending procedure.

(iii) Immittance evaluation included tympanometry and measurement of acoustic reflex thresholds, both ipsilateral and contralateral. For tympanometry, the air pressure in the external ear was varied from + 200 to - 400 daPa. The acoustic reflexes were established at 500, 1000, 2000 and 4000 Hz. To rule out retrocochlear pathology in participants with a sensorineural hearing loss, the reflex decay test was performed.

(iv) Speech audiometry included estimation of speech reception threshold (SRT) and speech recognition scores (SRS).

SRT was established using the recorded Kannada paired word lists. The recorded material was played using a Philips 729K DVD player. The signal from the DVD player was routed to the loud speaker of the diagnostic audiometer Madsen Orbiter 922. Prior to the presentation of the speech signal, the VU-meter was adjusted to zero using the 1 kHz calibration tone. To obtain SRT, four paired words were presented at 20 dB SL (re: pure tone average). The participant was asked to repeat the word heard. The intensity was then decreased in 10 dB steps and increased in 5 dB steps to determine the minimum intensity at which the participant repeated 50% of the paired words.

For SRS, the recorded Kannada bi-syllabic words were presented at 40 dB SL (re: SRT). It was ensured that the presentation level was within the UCL of the participant. The participants were instructed to give oral responses. Written responses were not obtained as some of them were unable to write Kannada. A response was recorded as correct only if the entire word was repeated correctly. Each correctly repeated word was given a score of one and a wrong response was given a score of zero. The maximum score for each list was 25, as there were 25 words in each of them.

The results of the pure-tone, speech and immittance tests were used to determine the type, degree and configuration of hearing loss of the participants. This information was used to categorize them into different sub-groups.

2. *Procedure for Unaided and Aided Sound Field Evaluation in order to Predict SRS from SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$.*

In order to predict SRS from SIIw, $\mathrm{SIIw}_{\mathrm{SLD}}$ and $\mathrm{SIIw}_{\mathrm{SLD\ HLD}}$, unaided and aided hearing thresholds to frequency modulated (FM) tones and SRS were obtained. The procedure used to determine these are described below.

(i) Unaided Sound Field Evaluation

Two tests were carried out in the unaided condition for all participants. These included threshold estimation for FM tones and speech recognition testing. The former test was carried out to compute the SIIw, $\mathrm{SIIw}_{\mathrm{SLD}}$ and $\mathrm{SIIw}_{\mathrm{SLD\ HLD}}$. The latter test was required in order to check the utility of the SIIw, $\mathrm{SIIw}_{\mathrm{SLD}}$and $\mathrm{SIIw}_{\mathrm{SLD\ HLD}}$ in predicting the SRS.

(A) *Unaided sound field thresholds* for FM tones in the test ear were determined in a sound field. The thresholds were obtained at octave intervals from 250 to 500 Hz, and half-octave intervals from 750 to 6000 Hz using the modified Hughson-Westlake procedure. The threshold was defined as the lowest level at which the participant responded to two out of three FM tone presentations. The narrow band noise or speech noise was presented to the non-test ear through insert phones, when indicated, to avoid its participation in the test. These unaided sound field hearing thresholds were utilized for computing the unaided speech intelligibility index (SII) i.e., SIIw, $\mathrm{SIIw}_{\mathrm{SLD}}$and $\mathrm{SIIw}_{\mathrm{SLD\ HLD}}$ for each test ear using the software programs developed in Stage I. In the unaided condition, the $\mathrm{SIIw}_{\mathrm{SLD}}$was calculated without the correction for SLD as the presentation levels did not exceed 73 dB SPL. That is the SIIw was equal to SIIw Since SLD was not included in the unaided condition, the calculation of $\mathrm{SIIw}_{\mathrm{SLD\ HLD}}$ was done without the correction factor for SLD.

(B) The *speech recognition scores* were also obtained in sound-field. This was established using the phonetically balanced (PB) word lists developed by Vandana (1998). The recorded words were presented without a carrier phrase. The presentation level was 35 dB HL when the participant had a mild hearing loss in the test ear and 40 dB HL for the remaining participants. A lower presentation level of 35 dB HL was used for testing the ears with a mild hearing loss to create a more difficult listening situation as recommended by Kamlesh (1998). For the rest of the participants, the 40 dB HL presentation level was used as this represented a conversation level at a normal vocal effort. The participants were instructed to give oral responses. As mentioned earlier, written responses were not obtained as some of them were unable to write in Kannada. A response was recorded as correct only if the entire word was repeated correctly. Each correct word repetition was given a score of one.

(ii) Aided Sound Field Evaluation

Participants with an SRS was 21 (84%) or below (maximum SRS being 25), were tested in the aided condition. Three linear analogue behind-the-ear hearing aids were pre-selected for each participant, based on the results of audiological evaluation and the electroacoustic performance of the hearing aids. The hearing aids were set at l/3^{r} of the total volume control range or at the most comfortable level during the aided testing. The hearing aid was coupled to the participant's ear using hard ear moulds. All the participants were evaluated in a quiet situation using the following procedure, with each of the pre-selected hearing aids:

(A) The *aided sound-field thresholds* for FM tones (250, 500, 750, 1000, 1500, 2000, 3000, 4000 and 6000 Hz) were established using the modified Hughson-Westlake procedure. These thresholds were used to compute the aided SIIw, SIIw$_{SLD}$ and SIlw$_{SLD\ HLD}$ and Silas using the software programs developed in Stage I (Table 3.2). In addition, the uncomfortable level (UCLs) for broad-band noise was established. It was ensured that the maximum output for each of the three hearing aids tested, was within the uncomfortable level (UCL) of the participants.

(B) The *aided speech recognition scores* were established in quiet at 35 dB HL while testing ears with a mild hearing loss and at 40 dB HL for all other participants. This was done using the recorded Kannada PB word lists. The presentation order of the four word lists was randomized across the unaided condition, aided condition, and participants, in order to minimize the order effects. The participants were instructed to repeat the words heard. Each word correctly repeated was given a score of one and a wrong response was given a score of zero. The maximum score for each list was 25, as there were 25 words in each of them.

The sound field thresholds and the SRS were thus obtained for the three pre-selected hearing aids for each participant. For participants with a sensorineural hearing loss, three different SIIws, i.e., SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$, were calculated for the unaided as well as the aided conditions. For ears with a conductive hearing loss, only the SIIw was computed, as correction factors for speech level distortion and hearing loss desensitization were not required. This was because in ears with a conductive hearing loss in the present study, the signals reaching the cochlea after by-passing the conductive component did not exceed 73 dB SPL during the evaluation. Hence, the SLD correction was not required. The HLD correction was also not required as the cochlea was normal in these participants. However, as the SLD and HLD did influence the perception in participants with a sensorineural hearing loss, these parameters were incorporated while calculating SIIw, for this group, in the aided conditions.

The unaided and aided sound field thresholds established using FM tones and the speech recognition scores of the first group were utilized for computing the Silas also in the Stage III of the study. This is described in the next section.

STAGE III: Computing Silas for Selection of Appropriate Hearing Aids

In order to determine whether an individual with hearing impairment required a hearing aid or not, based on the Silas value, this stage of the study was carried out. In addition, the efficacy of Silas in hearing aid selection was also studied in this stage.

A. Participants

To select the cut-off criteria based on Silas, 84 participants with a pure-tone average ranging from 16 to 40 dB HL in the better ear were evaluated. The better ear served as the test ear. The demographic details of the participants for deriving a criterion based on the Silas, are given in Table 3.6. For evaluating the efficacy of the Silas in hearing aid selection, the data collected from participants of Group I in Stage II were used.

Those participants who got an SRS of 22 (88%) and above were the ones who were not considered to be candidates for hearing aids. This SRS was taken as the cut-off as Goetzinger (1978) had reported, in the guidelines for classifying the SRS, that the individuals with an SRS of 90 % and above were considered to have excellent speech recognition. It was noted in the present study that the participants who got a score of 21 and below had an SII score of 0.6325 and below.

Table 3.6

Demographic details of the participants for selection of candidates for hearing aids

Type of hearing loss	*Gender*	*Age in years*		*No. of ears tested (N=84)*
		Mean (SD)	*Range*	
Conductive	Male	35.46 (13.68)	15-60	24
	Female	38.43 (14.20)	15-60	19
Sensorineural	Male	37.66 (11.84)	17-55	20
	Female	39.10 (13.44)	15-60	21

B. Instrumentation

The instrumentation used in Stage III was the same as that used in Stage II. Hearing aids were not used while establishing a criterion based on Silas. However, they were used while evaluating the efficacy of Silas in hearing aid selection.

C. Test Material

The CD used in Stage II with recorded speech material, was utilized in Stage III also. In addition, for the purpose of evaluating the efficacy of using Silas in hearing aid selection, a recorded passage in Kannada, developed by Sairam (2002), was used to judge the quality of speech through the hearing aids. An adult female, who was fluent in Kannada, read the passage using a normal vocal effort. The voice level was monitored with the VU meter while recording. This passage contained all the speech sounds of the language, with vocabulary that was familiar with most adults (Appendix C).

D. Procedure

As in Stage II, a detailed case history was collected from all the participants. In addition, the following steps were followed:

1. Evaluation of the efficacy of Silas in selecting participants who required hearing aids.
2. Evaluation of the efficacy of Silas in selection of hearing aids.

1. Evaluation of the Efficacy of Silas in Selecting Participants who required Hearing Aids.

Sound field evaluation was carried out to evaluate if the participant required a hearing aid or not. In order to find out an Silas based criterion for hearing aid candidacy, the following steps were administered in the unaided condition.

Unaided sound field thresholds were established for frequency modulated (FM) tones at 250, 500, 750, 1000, 2000, 1500, 3000, 4000 and 6000 Hz, using the modified Hughson-Westlake procedure. These sound field hearing thresholds were used to compute the Silas using the software developed in Stage I. This index was computed for each test ear. The calculated index for each test ear was tabulated for analysis.

Unaided sound field speech recognition scores (SRS) for recorded Kannada PB word list were obtained. It was ensured that the list heard by them earlier under headphones was not repeated. The recorded material was played using a Philips DVD player. Prior to the presentation of the speech signal, the VU-meter was adjusted to zero using a 1 kHz calibration tone. The output from the audiometer was presented at 35 dB HL, through a loudspeaker located at one meter and 45° Azimuth, on the side of the ear that was considered as the test ear. This presentation level was utilized to make the test situation more difficult. The non-test ear was plugged with an EAR earplug to ensure its non-participation during the testing. The participants were instructed to repeat the words presented. A response was recorded as correct only if the entire word was repeated correctly. The maximum SRS was 25 as each of the PB lists consisted of 25 words. The SRS for each test ear was tabulated for further analysis.

2. Procedure for Unaided and Aided Sound Field Evaluation for Hearing Aid Selection.

In order to investigate the efficacy of Silas in hearing aid selection, the data on sound field thresholds for FM tones and SRS in the unaided and aided conditions, obtained on the first group in Stage II, were utilized. The sound field thresholds for FM tones were used to derive the Silas. The Silas was calculated using the software program developed in Stage I (Table 3.3). In addition, to check the efficiency of Silas in hearing aid selection, data on overall quality judgment of the aided speech were collected.

The *aided quality judgments* were obtained from each participant, for the three different hearing aids using the recorded paragraph in Kannada. The participants were instructed to compare and rate the overall quality of the recorded paragraph through the three hearing aids. A paired comparison procedure was used, where the participants compared the first two hearing aids and later compared the second and third hearing aids that were tested. The participants rated each of the three hearing aids as either 1 or 2 or 3, based on quality of amplified speech. The rating was such that the hearing aid with the best quality was rated 1, the next best rated 2 and the third best was rated 3.

The data on the SRS, the SII and its variations, and the overall quality ratings obtained in the above stages, for each participant, were tabulated. Appropriate statistical analyses, such as measures of central tendency and variation, non-linear regression, correlation, paired t-test, independent samples t-test and repeated measures ANOVA were carried out to verify the objectives of the study. The results of the study are reported and discussed in the following chapter.

RESULTS AND DISCUSSION

In order to evaluate the objectives of the study, the data on speech recognition scores (SRS) and the speech intelligibility index (SII) were analysed using the Statistical Package for Social Sciences (SPSS 10.0 for Windows version). Table curve 2D of Systat (version 11) and Matlab (version 6.5). The utility of the speech intelligibility index in predicting SRS was analysed. In addition, the utility of SII in hearing aid selection was also determined. The results of the study are discussed under two broad sections. Under each of these broad sections, the findings are further discussed under sub-headings. These include:

1. Prediction of speech recognition score (SRS) from speech intelligibility index (SIIw)
    1.1. Comparison of SRS with SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD5}$
    1.2. Prediction of SRS from SIIw, $SIIw_{SLD}$and $SIIw_{SLD\ HLD}$ by derivation of non-linear regression equations,
    1.3. Comparison of the measured SRS and the SRS predicted using SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$.
2. Efficacy of speech intelligibility index (Silas) in hearing aid selection
    2.1 . Criterion to determine the hearing aid candidacy based on Silas,
    2.2 . Comparison of SRS and Silas in hearing aid selection,
    2.3 . Relationship between the Silas and the overall quality judgments of speech through hearing aids,
    2.4 . Utility of Silas in hearing aid selection
        2.4.1 . Effect of type of hearing loss on the utility of Silas in selection of hearing aids,

2.4.2 . Effect of degree of hearing loss on the utility of Silas in selection of hearing aids,

2.4.3 . Effect of configuration of audiogram on the utility of Silas in hearing aid selection.

2.5. Effectiveness of Silas in hearing aid selection across different degrees of hearing loss and configurations of audiogram.

1. Prediction of Speech Recognition Scores (SRS) from Speech Intelligibility Index (SIIw)

For the prediction of speech recognition scores (SRS) from the speech intelligibility index (SIIw, SIIw$_{SLD}$ and SIIw$_{SLD\ HLD}$), the data obtained from the 93 participants were analysed. The SIIw, SIIw$_{SLD}$ and SIIw$_{SLD\ HLD}$ were computed from the unaided and three aided sound field audiograms obtained from hearing aids HA 1, HA 2 and HA 3. The following statistical analyses were carried out to investigate the predictive ability of the speech intelligibility index:

1.1 SRS, SIIw, SIIw$_{SLD}$ and SIIw$_{SLD\ HLD}$ were analysed using descriptive statistics,

1.2 Non-linear regression analysis was carried out to derive equations to predict SRS from SIIw, SIIw$_{SLD}$and SIIw$_{SLD\ HLDj}$

1.3 Correlation and paired samples t-test were carried out to verify whether there was any agreement and / or difference between the measured SRS and the predicted SRS of a different group of participants.

1.1. Comparison of SRS with SIlw, SIIw$_{SLD}$ and SIIw$_{SLD\ HLD}$ for Prediction ofSRS

The comparison of the SRS with SIIw, SIIw$_{SLD}$ and SIIw$_{SLD\ HLD}$ was made using descriptive statistics. The mean and standard deviation (SD) values of the unaided and aided SRS, SIIw, SIIw$_{SLD}$and SIIw$_{SLD\ HLD}$ for the participants were noted. This was done for participants with a conductive hearing loss, flat sensorineural hearing loss and sloping sensorineural hearing loss (Table 4.1, Table 4.2 and Table 4.3 respectively). For each participant, the hearing aid with the best SRS was labelled HA 1; the hearing aid with next best SRS was labelled HA 2 while the hearing aid with the least SRS was labelled HA 3. This was done for all those with a conductive, flat sensorineural and sloping sensorineural hearing loss. In the participants with a conductive hearing loss, the correction factors SLD and HLD were not included in the computation of SIIw (Table 4.1), as these measures did not influence their perception. The SLD was not incorporated because the presentation level did not exceed 73 dB SPL to cause a speech level distortion. Further, the HLD was also not included, since the cochlea was normal as indicated by the normal bone conduction thresholds. However, as the SLD and HLD did influence the perception in participants with a sensorineural hearing loss, these corrections were incorporated while calculating SIIw (Tables 4.2 and 4.3). This was done in all conditions except the unaided condition. While determining the unaided SIIw in those with a sensorineural hearing loss, the SLD correction was not included as here too the speech level did not exceed 73 dB SPL. Since SLD was not included in the unaided condition, the calculation of HLD was done without the correction factor for

SLD. Hence, in the unaided condition the $SIIw_{SLD}$and $SIIw_{SLD\ HLD}$ values were the same as the SIIw values.

In general, it could be observed that the SIIw scores followed a similar trend as that of the SRS. This could be noted in the unaided as well as in the aided conditions. As expected, the mean unaided SRS and SIIw scores were lower than the corresponding aided values. Generally, the mean values of SRS and SIIw decreased with the increasing degree of hearing loss, in both the unaided and aided conditions (Tables 4.1 and 4.2). This decrease was more prominent for the unaided scores than for the aided scores. This is because the hearing aid compensated for the loss of audibility in the aided condition. The mean values of SIIw reduced when SLD as well as SLD and HLD corrections were added to the basic SIIw calculation (Table 4.2).

The slope of the audiogram also influenced the mean scores, as can be seen in Table 4.3. The mean values of SRS, SIIw, $SIIw_{SLD}$and $SIIw_{SLD\ HLD}$ reduced as the dB per octave slope of sensorineural hearing loss decreased. This was observed in the unaided condition and in the aided conditions. The SD values for speech intelligibility index reduced with increased sloping configurations of hearing loss in both unaided and aided conditions.

Table 4.1

Mean and standard deviation (SD) of SRS and SIIw in mild, moderate and moderately-severe degrees of conductive hearing loss

Degree	*condition*	*SRS*[a] *Mean (SD)*	*SIIw*[b] *Mean (SD)*
Mild (N=12)	Unaided	10.92 (6.76)	0.7602 (0.1144)
	HA1	23.33 (2.23)	0.9236 (0.0551)
	HA 2	21.33 (2.81)	0.9175 (0.0632)
	HA 3	19.92 (3.90)	0.8963 (0.0654)
Moderate (N=15)	Unaided	5.53 (6.63)	0.4359 (0.1489)
	HA1	22.27 (2.81)	0.8252 (0.1176)
	HA 2	20.53 (4.79)	0.7898 (0.0963)
	HA 3	16.93 (6.45)	0.7931 (0.1229)
Mod-severe (N=12)	Unaided	2.58 (3.65)	0.1674 (0.1136)
	HA1	21.75 (4.65)	0.7505 (0.0968)
	HA 2	20.08 (4.78)	0.6998 (0.0992)
	HA 3	16.58 (6.20)	0.6254 (0.1316)

Note. HA 1 = Hearing aid No. 1; HA 2 = Hearing aid No. 2; HA 3 = Hearing aid No. 3;
[a] Maximum value for SRS being 25; [b] Maximum value for SIIw being 1.

Table 4.2

Mean and standard deviation (SD) of SRS and SIIw, SIIw$_{SLD}$ and SIIw$_{SLD\ HLD}$ in mild, moderate, moderately-severe degrees of flat sensorineural hearing loss

Degree	*Test condition*	*SRS^{a} Mean (SD)*	*SIIw^{b} Mean (SD)*	*SIIw$_{SLD}$^{b} Mean (SD)*	*SIIw$_{SLD\ HLD}$^{b} Mean (SD)*
Mild (N=11)	Unaided	8.45 (7.71)	0.5970 (0.0753)	0.5970 (0.0753)	0.5970 (0.0753)
	HA1	22.55 (2.16)	0.8865 (0.0422)	0.8390 (0.0422)	0.7794 (0.0501)
	HA 2	21.64 (2.46)	0.8745 (0.0554)	0.8314 (0.0601)	0.7677 (0.0523)
	HA 3	19.27 (5.44)	0.8454 (0.1347)	0.7961 (0.1251)	0.7191 (0.1269)
Moderate (N=11)	Unaided	6.00 (6.69)	0.4054 (0.0629)	0.4054 (0.0629)	0.4054 (0.0629)
	HA 1	20.55 (2.81)	0.8398 (0.1049)	0.7726 (0.1263)	0.6932 (0.1394)
	HA 2	18.09 (3.75)	0.8238 (0.0912)	0.7687 (0.0981)	0.6814 (0.1052)
	HA 3	16.27 (5.00)	0.8008 (0.1544)	0.7576 (0.1373)	0.6721 (0.1492)
Mod-severe (N=12)	Unaided	1.17 (4.04)	0.1161 (0.0954)	0.1161 (0.0954)	0.1161 (0.0954)
	HA1	20.42 (3.50)	0.7683 (0.1162)	0.6712 (0.0872)	0.5834 (0.0873)
	HA 2	18.50 (4.15)	0.6529 (0.1723)	0.5900 (0.1520)	0.5092 (0.1105)
	HA 3	14.92 (5.45)	0.6550 (0.2142)	0.5840 (0.1814)	0.4916 (0.1650)

Note. HA 1 = Hearing aid No. 1; HA 2 = Hearing aid No. 2; HA 3 = Hearing aid No. 3.
[a] Maximum value for SRS was 25; [b] Maximum value for SIIw, SIIw$_{SLD}$and SIIw$_{SLD\ HLD}$ was 1.

Table 4.3

Mean and standard deviation (SD) of SRS and SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ in gradual and steeply sloping sensorineural hearing loss

Configuration	*Test condition*	SRS^{a} *Mean (SD)*	*SIIw^{b} Mean (SD)*	*$SIIw_{SLD}$^{b} Mean (SD)*	*$SIIw_{SLD\ HLD}$^{b} Mean (SD)*
Gradual slope (N=11)	Unaided	3.20 (5.01)	0.3055 (0.1922)	0.3055 (0.1922)	0.3055 (0.1922)
	HA1	21.90 (2.18)	0.7221 (0.1808)	0.6242 (0.1492)	0.5537 (0.1445)
	HA 2	19.10 (4.12)	0.7210 (0.2225)	0.6697 (0.2163)	0.5979 (0.2093)
	HA 3	15.40 (6.24)	0.6757 (0.2428)	0.6363 (0.2283)	0.5711 (0.2151)
Steep slope (N=11)	Unaided	11.90 (5.90)	0.4947 (0.1326)	0.4947 (0.1326)	0.4947 (0.1326)
	HA1	21.90 (1.79)	0.7716 (0.1909)	0.6712 (0.1512)	0.6154 (0.1330)
	HA 2	19.80 (2.57)	0.7035 (0.1225)	0.6438 (0.1219)	0.5863 (0.1036)
	HA 3	18.30 (3.59)	0.7197 (0.1208)	0.6640 (0.1245)	0.6061 (0.1165)

Note. HA 1 = Hearing aid No. 1; HA 2 = Hearing aid No. 2; HA 3 = Hearing aid No. 3;
[a]Maximum value for SRS was 25; [b] Maximum value for SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ was 1.

Thus, it can be noted that the changes seen in the SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ values are also reflected in the SRS values. This is evident across the type of hearing loss, degree of hearing loss and configuration of the audiogram. Hence, from the descriptive statistics, it can be deduced that the two sets of tests, i.e., SRS and SII, provide similar information. These results of the present study are in consensus with that reported in literature. It has been noted by Byrne (1992), Dubno, and Dirks (1989), Dirks, Bell, Rossman, and Kincaid (1986), Humes (1991), Rankovic (1991) and Pavlovic (1984) that improved audibility is strongly related to SRS.

It has been reported that in individuals with a sloping sensorineural hearing loss, the variation in the SRS is not reflected by variations in SIIw alone. There could be factors other than SIIw bringing about a change in the SRS in this group. Vickers, Moore, and Baer (2001) found that a key factor in predicting aided benefit is the presence or absence of a dead region at high frequencies. They reported that the articulation index might overestimate the benefit from hearing aids in individuals with cochlear dead regions. Vickers et al. (2001) have cautioned about the use of AI, based on the reports that the audiometric pure tone thresholds (the input to the AI calculation) do not reflect the limited ability of dead regions to process supra-threshold speech components. Hence, as opined by Vickers et al. (2001), it is recommended to be careful while using SII to predict SRS in individuals with a steeply sloping hearing loss.

1.2. Prediction of SRS from SIIw, SIIw $_{SLD}$ and SIIw $_{SLD\ HLD}$ by Derivation of Non-linear Regression Equations

In order to predict the SRS from the speech intelligibility index, non-linear regression equations were derived. This was done since there is considerable evidence that the relationship between SRS and SII is best described by a non-linear transfer function (French & Steinberg, 1947; Fletcher & Gait, 1950). The non-linear regression equations were later utilized to predict the SRS from SIIw, SIIw$_{SLD}$ and SIIw$_{SLD\ HLD}$, on a different group of participants.

Table Curve 2D (version 5.01.01) from Systat (version 11) was utilized to derive the non-linear regression equations. A least square procedure was used for curve fitting to minimize the root mean square errors between the measured and predicted SRS. The non-linear regression analysis was done in order to derive power functions for predicting the aided SRS from SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$. While Equation 4.1 was derived to predict SRS from SIIw, Equations 4.2 and 4.3 were derived to predict it from $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ respectively. These equations are given below.

$$SRS = a\,(SIIw)^{b}. \qquad \textbf{Equation 4.1}$$

$$SRS = a\,(\mathbf{SIIw_{SLD}})^{\mathbf{b}}. \qquad \textbf{Equation 4.2}$$

$$SRS = a\,(SIIw_{SLD\ HLD})^{b}. \qquad \textbf{Equation 4.3}$$

where SRS is the proportion of words correct, while 'a' and 'b' are fitting constants derived from the power function in the regression analysis. The values of 'a' and 'b' are given in the Table 4.4

It can be noted from Table 4.4 that the values of a, b, r^2 are not very different in the equations when the three predictors (SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$) were used. Also all three regression equations were significant at 0.01 level,impl ying that the aided SRS could be predicted using these non-linear regression equations. Thus, for the participants evaluated in the present study, the addition of correction factors did not bring about much of a change in the values of the fitting constants and the correlation coefficient squared. It can be inferred that as long as the participants have a hearing loss not exceeding a moderately-severe degree, correction factors for SLD and HLD are not essential.

Table 4.4

Values of fitting constants for deriving SRSfrom SIIw, $SIIw_{SLD}$*and* $SIIw_{SLD\ HLD}$

	a	*b*		*F ratio*	*Std. Error Estimate*
SRSfrom SIIw	23.35	0.96	0.53	413.98**	5.40
SRSfrom $SIIw_{SLD}$	23.84	0.91	0.50	365.23**	5.58
SRSfrom $SIIw_{SLD\ HLD}$	24.49	0.79	0.44	291.26**	5.88

**:p = 0.01

Dillon (1993) reported that as the hearing loss increased above the moderately-severe degree, it was less likely that the audible energy would continue to be equally useful. This was due to the presence of distortions such as reduced frequency and temporal resolution. Thus, while calculating the SII for individuals with higher degrees of hearing impairment, correction factors such as SLD and HLD may be needed.

From the findings of the present study, it can be concluded that the SIIw can be used to predict the SRS. This makes it possible to use a non-speech based technique to predict SRS which is very essential in the Indian context where there are many languages spoken. Further, in order to evaluate whether the equations predicted the SRS adequately, the measured and predicted SRS were compared in a different group of participants.

1.3. Comparison of the Measured SRS and the SRS Predicted using - SIIw, $SIIw_{SLD}$ *and* $SIIw_{SLD\ HLD}$

In order to determine the utility of the non-linear regression equation, the aided SRS which were predicted (pSRS) using the equations were compared with the aided

SRS that were actually measured (mSRS). This was done using data obtained from 26 participants who were not included while deriving the non-linear regression equations. Using the regression equations 4.1, 4.2 and 4.3, the SRS were predicted (pSRS) using the three predictors, i.e., SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$. For the purpose of comparison of the measured and the predicted SRS, these values were transformed into rationalized arcsine unit (rau). This was done since Studebaker (1985) noted that the SRS by itself was not linear or additive. The transformation of SRS to rau was carried out using the RAT ARC Online - Rationalized arcsine transform program developed by Studebaker (1985). The mean and standard deviation (SD) values of the mSRS and the SRS (pSRS), in rau, obtained from the SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$ are given in Table 4.5. It can be observed that the mean values of measured and predicted SRS varied only marginally. However, the measured SRS had a larger SD when compared to the predicted SRS, indicating that the variability in scores were more in the former.

Table 4.5

Mean values of the measured SRS in rau (mSRS) and the SRS predicted (pSRS) in rau obtained from SIIw, $SIIw_{SLD}$ *and* $SIIw_{SLD\ HLD}$

SRS	*Mean (rau)*	*SD (rau)*
mSRS	74.22	35.44
pSRS from SIIw	72.24	14.32
pSRS from $SIIW_{SLD}$	71.57	14.11
pSRS from $SIIw_{SLDHLD}$	70.92	12.31

Further, the extent of difference between the mean values of the mSRS and the pSRS obtained from SIlw, SIIw$_{SLD}$and SIIw$_{SLD\ HLD}$ was calculated (Table 4.6). The difference between the measured and the predicted SRS was least when predicted from SIlw and most when predicted from SIlw$_{SLD\ HLD}$. The minimal disparity in the difference between the mean values of mSRS and pSRS suggests that the SII is able to predict performance without incorporation of the correction factors in those with different types, degrees and configurations of hearing loss included in the study.

Table 4.6

Difference between the mean values of the measured SRS and those derived from SIlw, SIlw$_{SLD}$ and SIlw$_{SLDHLD}$

Measures	*Difference in mean SRS values (in rau)*
mSRS - pSRS from SIlw	L98
mSRS - pSRSfrom SIIw$_{SLD}$	2.64
mSRS - pSRSfrom SIIw$_{SLD\ HLD}$	3.29

In order to examine the relationship between the measured SRS and the SRS predicted from SIlw, SIIw$_{SLD}$ and SIIw$_{SLD\ HLD}$, their *agreement* and *difference* were studied. This is discussed below.

Pearson's correlation was calculated to determine the *agreement* between the measured SRS and the SRS predicted from SIlw, SIIw$_{SLD}$ and SIIw$_{SLD\ HLD}$. The positive correlation that was obtained was significant at the 0.01 level as shown in Table 4.7. This correlation was obtained between the measured SRS and the SRS predicted from SIlw, SIIw$_{SLD}$and SIIw$_{SLDiHLD}$.

Table 4.7

Correlation between the measured SRS in rau and the three predicted SRS in rau

SRS measures	*r*
mSRS & pSRS predicted from SIIw	0.84**
mSRS & pSRS predicted from $SIIw_{SLD}$	0.72**
mSRS & pSRS predicted from $SIIw_{SLD\ HLD}$	0.82**

** : $p<0.01$ level

Paired t-test was performed to study the *difference* between the predicted and measured SRS. This was done as correlation techniques are dependent on the range of scores produced by the sample while a t-test is not. The paired samples t-test, indicated that the difference between the measured and predicted speech recognition scores was not statistically significant for all the three predictors even at the 0.05 level [SIIw: t (103) = 0.819, $p > 0.05$; $SIIw_{SLD}$: t (103) = 1.00, $p > 0.05$ and $SIIw_{SLD\ HLD}$: t (103) = 1.28, $p > 0.05$]. Thus, it can be inferred that the non-linear power functions (Equations 4.1, 4.2 and 4.3) were able to predict the SRS in individuals with a hearing impairment.

The findings of the present study are in consensus with that reported in the literature. Studebaker and Wark (1980) had found a significant correlation (r = 0.77 to 0.85) between a modified AI and the average speech intelligibility in listeners with normal hearing. Studebaker and Marincovich (1989) in a study using equation relating AI to performance score derived by Fletcher and Galt (1950) in listeners with normal hearing, have reported a significantly high correlation between the predicted SRS and the SRS measured (in rau) in the presence of low level all pass noise and low pass noise condition. However, they found that the correlation was low and non-significant between the predicted SRS and the SRS measured (in rau) in a high pass noise condition.

These results suggest that the variations in audibility might account for a large proportion of variance in speech performance.

Similar findings have also been reported on participants with a mild to moderate hearing loss (Kamm, Dirks and Bell, 1985). Kamm et al. noted that in all but one subject with a moderate hearing loss with reduced speech recognition scores; the AI was a good predictor of performance. Similar findings have been observed in listeners with moderate, severe and profound hearing losses (Dugal, Braida & Durlach, 1980; Pavlovic, 1984; Ching, Dillon & Byrne, 1998) and listeners with steeply sloping high-frequency hearing losses (Skinner, 1980; Rankovic, 1991).

Magnusson, Karlsson, and Leijon (2001) also noted a good agreement between the predicted and measured speech intelligibility, substantiating the utility of SII to predict SRS. However, Kamm, Dirks, and Bell (1985) reported that for listeners with poor recognition abilities, the index appeared to be a poor predictor. Such reports support the inclusion of correction factors to improve the prediction ability of the articulation index. In the present study too, on observation of the raw data obtained from those with an SRS of less than 50 rau, the prediction was better when the correction factors were included. Of the 26 participants, two had mSRS of less than 50 rau, the difference between the mSRS and the pSRS was lesser when correction factors were incorporated. The difference was even less when both SLD and HLD corrections were incorporated.

The finding in the present study is in concurrence with that reported in literature for participants with a mild to moderate degree of hearing impairment. However, in the present study, the SII with and without correction factors seemed to be good predictor even for those with moderately-severe degree of hearing loss. This implies that correction factors are not required for individuals up to a moderately-severe degree of hearing loss. It is reported in literature that the ear can function almost normally when it has a mild or a moderate hearing loss except for the loss of audibility (Dubno, Dirks & Shaeffer, 1989; Humes, Dirks, Bell, Ahlstrom & Kincaid, 1986; Kamm, Dirks & Bell, 1985). It has also been reported that once the hearing threshold reaches a severe degree, reduced audibility is not the only factor contributing to speech recognition deficits. To compensate for these deficits, the use of correction factors such SLD and HLD were recommended (Ching, Dillon, & Byrne, 1998; Sherbecoe and Studebaker, 2003). Studies have not been reported in literature on participants with moderately-severe hearing loss. From the findings of the present study, it is evident that individuals with moderately-severe hearing loss function in a similar way as those with a mild or moderate hearing loss. Like those with a lesser degree of hearing loss, they do not require corrections for SLD and HLD. Thus, it can be inferred again that in individuals with hearing loss up to a moderately-severe degree, it is unlikely that factors other than a reduced audibility would affect their perception. Hence, SRS can be predicted from SIIw without the need for a correction factor.

Further, it was investigated as to how adequately the SII predicted the performance of a particular individual, as opposed to the mean values predicted with the paired t-test. This was done to ensure whether the SII would be able to determine the most suitable hearing aid, during clinical practice. In Figure 4.1 (A, B and C), the mean predicted scores based on SII are represented by open blue circles and the blue plus marks represent the ± 2 standard deviation values. While the red triangle indicates the measured SRS in each participant with hearing aid one (HA 1), the black triangle and the green star represents the measured SRS in the participants with hearing aids two (HA 2) and three (HA 3) respectively. From these figures it can be observed that the scores are predicted with good accuracy, with SIIw being a slightly better predictor than the other two predictors. This again reveals that the ability of the SII to predict performance similarly whether a correction factor was incorporated or not in those with different types, degrees and configurations of hearing loss included in the study.

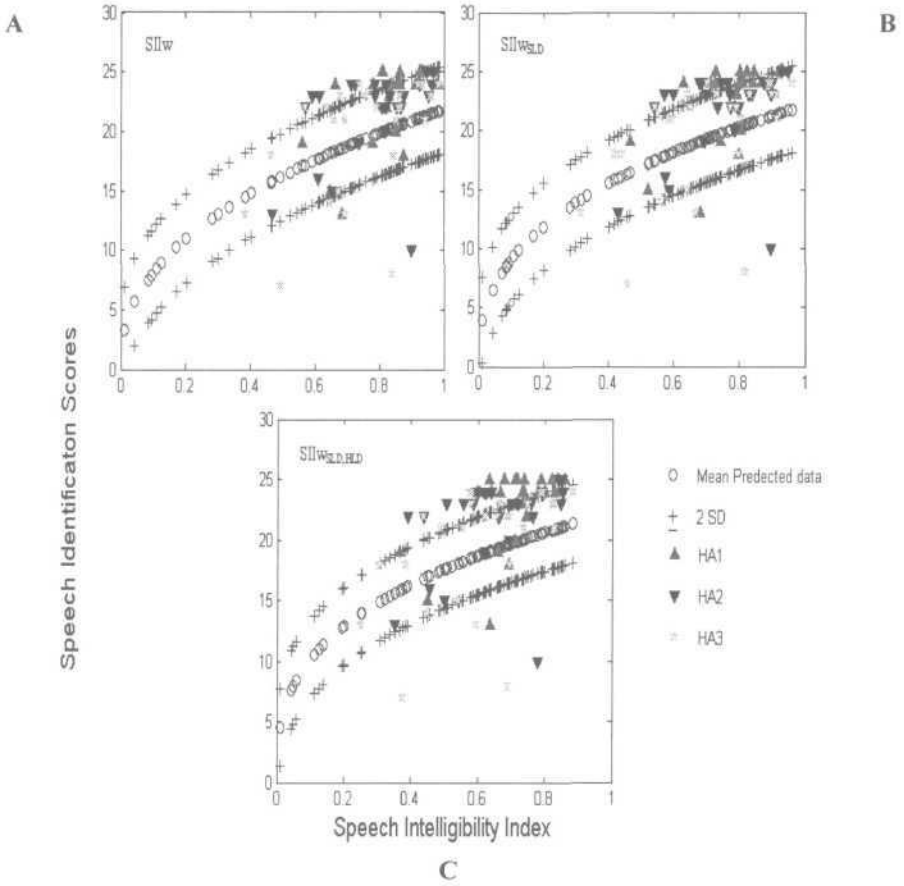

Figure 4.1: The measured and the predicted scores when SIIw (A), SIIw$_{SLD}$ (B) and SIIw$_{SLD\ HLD}$ (C) were the predictors.

In conclusion, it can be said that the Sllw can be used in the prediction of speech recognition performance. The addition of correction factors such as SLD and HLD to the original audibility index is not necessary to improve the predictive ability of the speech recognition scores in those with hearing losses up to moderately-severe degree of hearing loss or sloping hearing loss. This is true as long as the person does not have very poor speech identification ability.

2. Efficacy of Silas in Hearing Aid Selection

The efficacy of Silas was evaluated to determine whether an individual with hearing impairment required a hearing aid or not. Further, the usefulness of Silas in selecting the most appropriate of the three hearing aids was also evaluated. All the three hearing aids were in the fitting range of the hearing loss of the participants.

The Silas, used for hearing aid selection was derived using the frequency band importance function of average speech. In order to investigate the efficacy of Silas in hearing aid selection, the data obtained for the prediction of SRS were utilized. The Silas and SRS measured in the unaided and in the three aided conditions (HA 1, HA 2 and HA 3) were analysed. This was done using descriptive statistics and analyses of variance.

2. 1. Criterion to Determine Hearing Aid Candidacy Based on Sllas

The data collected from the 84 participants having mild hearing loss were analysed in order to arrive at a criterion to differentiate those who required hearing aids from those who did not. Details of the unaided mean, standard deviation (SD) and range of the SRS and Silas values are shown in Table 4.8.

An initial decision as to whether a participant required a hearing aid or not was determined based on the SRS values obtained at 35 dBHL. Those with an unaided SRS of 22 (88 %) or above (maximum SRS being 25), were not considered candidates for hearing aids. This value was selected, since it had been noted by Goetzinger (1978) that difficulties in the perception of speech start when the speech recognition scores are below 90%.

In the present study, it was found that 61 participants had an SRS of 22 (88%) or above. The Silas of these participants was equal to or greater than 0.6325 (maximum Silas being 1). Thus, among the 84 participants tested for this purpose, 61 were not candidates for hearing aids, based on the above criteria (Table 4.8).

Table 4.8

Mean, standard deviation and the range (minimum and maximum) of unaided SRS and unaided Silas

Test Condition	*Hearing aid Candidacy*	*Mean*	*S.D*	*Range*	
				Minimum	*Maximum*
Unaided SRS	*Not candidates (N=61)*	23.64	0.95	22	25
	Candidates (N=23)	12.74	7.52	0	21
Unaided Silas	*Not candidates (N=61)*	0.8989	0.1084	0.6325	1.0000
	Candidates (N=23)	0.6271	0.0838	0.4538	0.7586

Figures 4.2 and 4.3 depict the mean with range of the SRS and Silas for participants who did not require hearing aids (N = 61) and those who did (N = 23). Based on the apriori criterion, those with an SRS of 22 and above were not advised hearing aids while those with a score of 21 and below were considered as candidates for hearing aids. From Figure 4.2 it is evident that the SRS of those who required hearing aids and those who did not, were distinctly different.

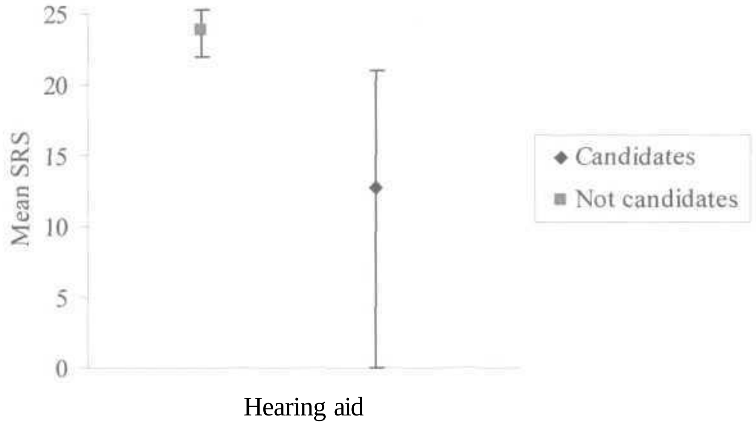

Figure 4.2: Mean and range of SRS of participants who were hearing aid candidates and those who were not.

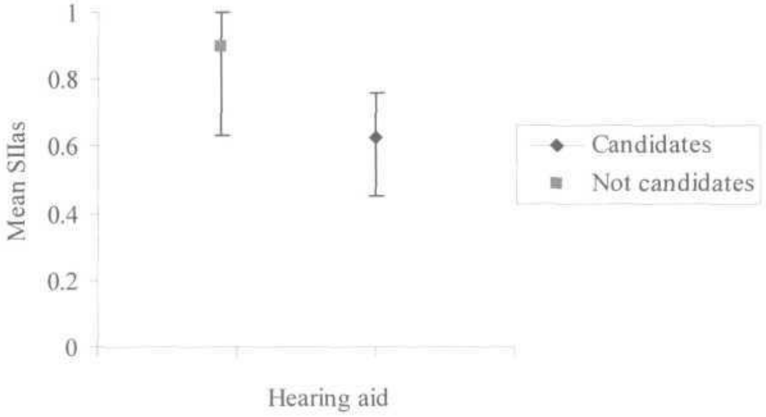

Figure 4.3: Mean and range of Silas of participants who were hearing aid candidates and those who were not.

Further, the Silas were analysed for those who were considered as candidates or not, based on the SRS scores. It is evident from the Figure 4.3 that the mean Silas values are distinctly different between those who required hearing aids and those who did not. However, there was a slight overlap in the range of the unaided Silas. An independent samples t-test revealed that the mean values of unaided Silas differed significantly between these two groups [t (82) = 10.851, $p < 0.01$]. This statistical measure reflected that Silas is also able to differentiate candidates who required hearing aids from those who did not.

The criterion of not prescribing hearing aids to those with a Silas of 0.6325 and above agrees closely with that recommended by Moog and Geers (1990). They reported that an articulation index (AI) ranging from 0.7 to 1.0 brought about consistent good speech identification and that such individuals did not require any hearing device. Earlier, Beranek (1947) had also reported that an AI of 0.7 and above resulted in a very good or excellent speech communication through communication systems. Steeneken and Houtgast (1980) reported a speech intelligibility index criterion of 0.75 to differentiate good and fair speech intelligibility. This cut-off criterion closely resembles the criterion obtained in the present study.

A slightly lower cut-off criterion was reported by Roth, Lankford, Meinke, and Long (2001). In their study, an AI of 0.50 or less was considered an excellent predictor for the need for amplification. They selected this cut-off criterion based on the number of clients who purchased hearing aids within a specific time frame and not based on speech perception performance. However, they did report of a few clients with AI ranging from 0.5 to 0.62, who did procure hearing aids. This latter value of AI (0.62) for selecting candidates for hearing aid is similar to that recommended in the present study.

Additional measures have been reported in literature, to differentiate hearing aid candidates from non-candidates when the test scores are in the borderline. These measures include assessing the listening needs or testing speech recognition in the presence of noise. While Hornsby (2004) suggested determining the listening needs of the clients, Sweetow (1989) recommended evaluating the speech recognition in noise. Similarly, it is suggested that for those who get an Silas score of 0.6325 to 0.7586, the listening needs of the clients should be determined before making a decision about hearing aid requirement. Individuals with Silas values in this range may not require or may not want to use a hearing aid if they had fewer listening needs, while individuals with an active life would require and would want to use hearing aids.

2.2. Comparison of SRS and the Silas in Hearing Aid Selection

The relationship between Silas and SRS in hearing aid selection was analysed using descriptive statistics. This was done for the unaided as well as aided responses. The mean and standard deviation (SD) values of the SRS and Silas in the participants having a conductive hearing loss, flat sensorineural hearing loss and sloping sensorineural hearing loss are summarized in Tables 4.9, 4.10 and 4.11 respectively. The SRS and Silas values are given for the unaided (UA) and the three aided conditions (HA1, HA2 and HA3). As mentioned earlier, for each participant, the three aided responses were labelled such that HA 1 represented the hearing aid with the highest SRS and HA 3 the hearing aid with the least SRS.

The mean values of unaided SRS and Silas were lesser than those in the aided condition, for those with a conductive and flat sensorineural hearing loss (Tables 4.9 and 4.10). Thus, both SRS and Silas were able to indicate an improvement in performance with the use of hearing aids. With an increase in the degree of hearing loss, the mean unaided SRS as well as Silas decreased. However, in the aided conditions, the mean responses for the different degrees of hearing loss were comparable. Such a trend was seen for both the tests in participants with a conductive hearing loss (Table 4.9) as well as for those with a flat sensorineural hearing loss (Table 4.10). This finding is consistent with the recommendation of Sandlin (1990) who contended that the aim of every fitting method is to make the speech spectrum audible to the person with a hearing impairment. In the present study, the gain of the hearing aids was pre-selected enabling the aided responses to be in the audible range of the listener. Thus, the gain of the hearing aids compensated for the loss in audibility. This would account for the similarity in aided responses across groups of participants in the present study.

Table 4.9

Mean and standard deviation (SD) of SRS and Silas in conductive hearing loss

Degree	*Test condition*	*SRS*[a] *Mean (SD)*	*Sllas* [b] *Mean (SD)*
Mild (N=12)	Unaided	10.92 (6.76)	0.7933 (0.1120)
	HA1	23.33 (2.23)	0.9469 (0.0444)
	HA 2	21.33 (2.81)	0.9512 (0.0427)
	HA 3	19.92 (3.90)	0.9341 (0.0443)
Moderate (N=15)	Unaided	5.53 (6.63)	0.4744 (0.1663)
	HA1	22.27 (2.81)	0.8721 (0.1026)
	HA 2	20.53 (4.79)	0.8449 (0.0852)
	HA 3	16.93 (6.45)	0.8309 (0.1178)
Mod-severe (N=12)	Unaided	2.58 (3.65)	0.1808 (0.1365)
	HA1	21.75 (4.65)	0.7877 (0.1026)
	HA 2	20.08 (4.78)	0.7391 (0.1060)
	HA 3	16.58 (6.20)	0.6547 (0.1483)

Note. HA1 = Hearing aid No. 1, HA 2 = Hearing aid No. 2, HA 3 = Hearing aid No. 3.

[a] Maximum value for SRS was 25; [b] Maximum value of Silas was 1.

Table 4.10

Mean and standard deviation (SD) of unaided and aided SRS and Silas in flat sensorineural hearing loss

Degree	*Test condition*	*SRS*[a] *Mean (SD)*	*Silas*[b] *Mean (SD)*
Mild (N =12)	Unaided	8.45 (7.71)	0.5923 (0.0902)
	HA1	22.55 (2.16)	0.8889 (0.0280)
	HA 2	21.64 (2.46)	0.8829 (0.0525)
	HA 3	19.27 (5.46)	0.8442 (0.1365)
Moderate (N=15)	Unaided	6.00 (6.69)	0.4102 (0.0555)
	HA1	20.55 (2.81)	0.8638 (0.0966)
	HA 2	18.09 (3.75)	0.8552 (0.0857)
	HA 3	16.27 (5-45)	0.8173 (0.1458)
Mod-severe (N=12)	Unaided	1.17 (4.04)	0.1050 (0.0824)
	HA1	20.42 (3.50)	0.7904 (0.1077)
	HA 2	18.08 (4.44)	0.6841 (0.1674)
	HA 3	14.92 (5.45)	0.6767 (0.2124)

Note. HA1 = Hearing aid No. 1, HA 2 = Hearing aid No. 2, HA 3 = Hearing aid No. 3.
[a] Maximum value for SRS was 25; [b] Maximum value for Silas was 1.

From Table 4.11, it is evident that the SRS and Silas in the unaided condition were lesser than in the aided condition. In the unaided condition, the participants with a gradual slope had poorer SRS and Silas scores compared to those with a steep slope. This marked difference between the two groups with different slopes, disappeared in the aided condition for both the fitting techniques, SRS and Silas. This once again showed that both the measures provided comparable results.

Table 4.11

Mean and standard deviation (SD) of SRS and Silas in sloping sensorineural hearing loss

Audiogram configuration	*Test condition*	*SRS*[a] *Mean (SD)*	*Silas*[b] *Mean (SD)*
Gradual slope (N=10)	Unaided	1.17 (4.04)	0.2813 (0.1872)
	HA1	20.42 (3.50)	0.6945 (0.1839)
	HA 2	18.08 (4.44)	0.7086 (0.2167)
	HA 3	14.92 (5.45)	0.6624 (0.2351)
Steep slope (N=10)	Unaided	11.90 (5.90)	0.4314 (0.1311)
	HA1	21.90 (1.79)	0.7342 (0.2074)
	HA 2	19.80 (2.57)	0.6526 (0.1348)
	HA 3	18.30 (3.59)	0.6700 (0.1289)

Note. HA 1 = Hearing aid No. 1; HA 2 = Hearing aid No. 2; HA 3 = Hearing aid No. 3.
[a] Maximum value for SRS was 25; [b] Maximum value for Silas was 1.

The better performance of the participants with a steep slope configuration in the unaided condition can be accounted for by the availability of more audible information in the low frequencies and mid frequencies, when compared to the participants with a gradual slope. From this finding it can be inferred that Silas is also able to detect the poorer performance in participants with a gradual slope.

2.3. Relationship between Silas and Quality of Aided Speech Perception

To evaluate the usefulness of Silas for hearing aid selection, the overall quality judgments of speech heard through hearing aids were determined. The relationship between Silas and overall quality judgement was evaluated using a rank correlation between the two. Also a rank correlation was computed between the SRS and the overall quality judgement. The rank correlations were obtained only for the aided responses.

A significant negative correlation was obtained between the SRS and overall quality judgment ($p < 0.01$ level) and also between the Silas and overall quality judgment ($p < 0.05$ level). This information is depicted in Table 4.12. The correlation was negative since a higher value of SRS or Silas indicated a better performance while a higher value regarding a quality judgement indicated a poorer hearing aid. It was thus observed that as the Silas or SRS varied, the overall quality judgments also varied similarly. Since the Silas matched the way the participants perceived the quality of a device, it indicates that the former measurement was able to select hearing aids that listeners perceived as being of good quality.

Table 4.12

Spearman's rank correlation between SRS and quality and Silas and quality (N = 93)

	Rank correlation
SRS with quality	-0.341**
Silas with quality	-0.143*

** $p <$ *0.01 level;* *: *p< 0.05 level*

An analysis of the raw data indicated that in 34.4 % of participants (N = 32 out of 93), the hearing aid with the highest SRS and hence the highest Silas score was not the preferred hearing aid, as per the quality judgment. These 32 participants perceived either the two hearing aids with the higher SRS as almost equal, or the hearing aid with second best SRS to be best. Hence, it can also be inferred that a hearing aid may be perceptually acceptable to a client, as long as it is in their audibility range. Based on this finding, it is recommended that the quality judgment of the clients be used to supplement the information in selection of an appropriate hearing aid.

The findings of the present study are in agreement with that of Eisenberg, Dirks, Takayanagi, and Martinez (1998). It was noted by them that the primary goal of hearing aid was to make the sounds audible and acceptable in quality. They also observed that the individuals with a hearing impairment were more likely to use a hearing aid if they approved of the quality of the device. In addition, Magnusson, Karlsson, Ringdahl, and Israelsson (2001) also reported that there was an agreement between speech intelligibility and sound pleasantness.

The findings of the present study and those reported in literature bring to light that there does exists a relationship between audibility and quality judgment with hearing aids. However, these findings are restricted to clients who have a hearing loss of the type, degree and configuration included in the present study.

2.4. Utility of Silas in Hearing Aid Selection

To check whether the Silas could differentiate between the three hearing aids, their *mean values* were compared with that of the SRS as mentioned earlier. In addition, *two-way and repeated measures ANOVA* were carried out. The two-way ANOVA was done to determine the interaction effect of the type and degree of hearing loss on SRS and Silas. Further, this was done to study the main effect of type and degree of hearing loss on SRS and Silas. The repeated measures ANOVA was carried out to find out the efficiency of Silas in differentiating the performance of the three hearing aids in relation to the SRS.

The two way ANOVA revealed that there was a non-significant interaction effect between the type and degree of hearing loss on the mean SRS [F (2, 213) = 0.34, p > 0.05] as well as on the mean Silas [F (2, 213) = 1.94, p > 0.05]. Figure 4.4 and Figure 4.5 reveal the nature of interaction of type and degree of hearing loss. The non-intersecting lines in Figure 4.4 indicated no interaction between the type of hearing loss and SRS or Silas. In contrast, the intersecting lines in Figure 4.5 revealed a significant interaction between the degree of hearing loss and SRS as well as Silas. From this it can be noted that the effect of degree of hearing loss was similar on SRS and Silas irrespective of the type of hearing loss.

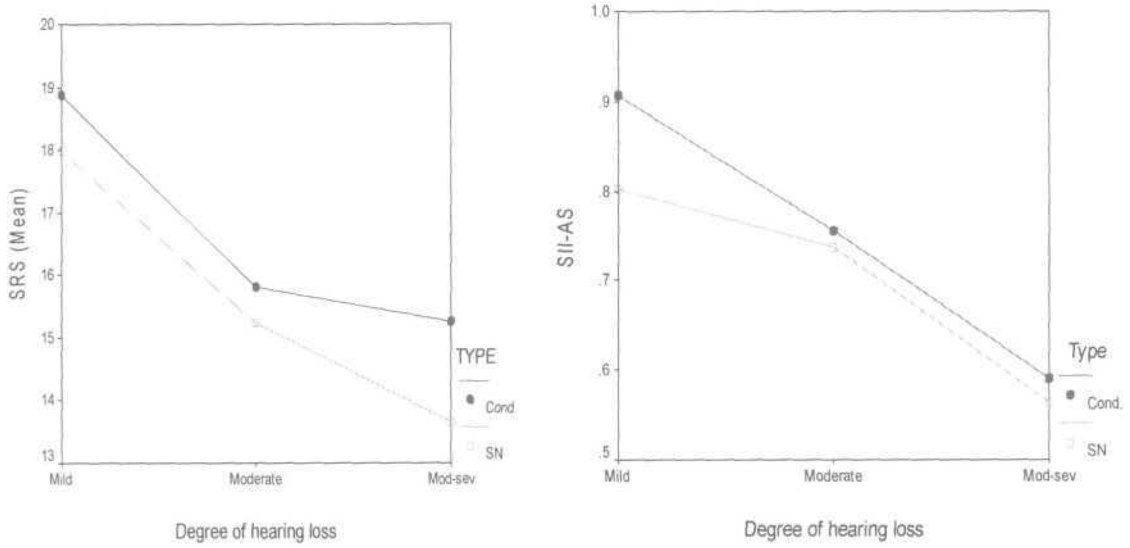

Figure 4.4: Interaction of type of hearing loss on mean SRS and Silas.

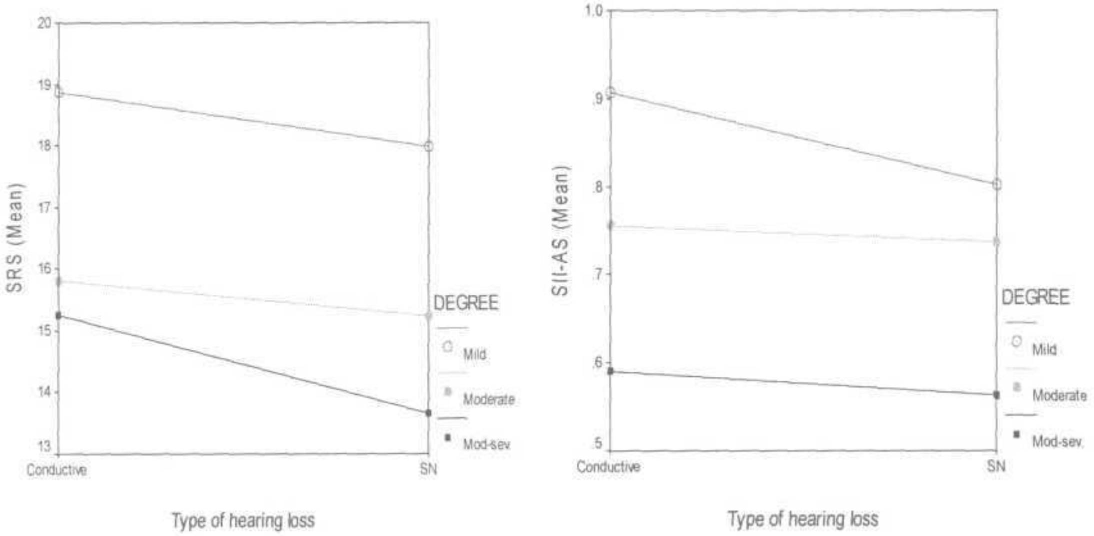

Figure 4.5: Interaction of degree of hearing loss on mean SRS and Silas.

2.4.1. Effect of Type of Hearing Loss on the Utility of Silas in Hearing Aid Selection

The mean SRS and Silas values with the three hearing aids in conductive and flat sensorineural hearing loss are given in Table 4.13. From the information it can be observed that there were only slight differences between the mean SRS and Silas values. This was observed both in those with a conductive and sensorineural hearing loss.

Table 4.13

Mean SRS and Silas values in conductive and sensorineural hearing loss

Type of hearing loss	*Mean SRS*	*Mean Silas*
Conductive	20..02	0.8409
Sensorineural	19,.05	0..8087

To find out whether the type of hearing loss had any differential effect on SRS and Silas in hearing aid selection, a two-way ANOVA was carried out. It revealed that the type of hearing loss had a non-significant main effect on the mean SRS [F (1, 213) = 2.44, $p > 0.05$]. The type of hearing loss had a non-significant main effect on the Silas [F (1,213) = 3.42, $p > 0.05$] also. Thus, the type of hearing loss neither influenced the mean SRS nor the mean Silas values.

The reason the mean scores did not differ across the two types of hearing loss, was on account of the degree of hearing loss. In the present study, only those up to a moderately-severe degree were considered. The main problem is due to audibility in those with hearing losses of up to moderately-severe degree (Dugal, Braida & Durlach, 1980). As there was no significant difference between types of hearing loss, the scores of those with conductive hearing loss and sensorineural hearing loss were combined together. This was done for all further analyses.

2.4.2. Effect of Degree of Hearing Loss on the Utility of Silas in Hearing Aid Selection

The mean SRS and Silas values of the three hearing aids in individuals with mild, moderate and moderately-severe degrees of hearing loss are given in Table 4.14. It can be noted that for both the mean SRS and Silas, participants with a mild hearing loss obtained the highest scores followed by those with a moderate and moderately-severe degrees of hearing loss.

Table 4.14
Mean SRS and Silas values in mild, moderate and moderately-severe degrees of hearing loss.

Degree of hearing loss	*Mean SRS*	*Mean Silas*
Mild	21.35	0.9096
Moderate	18.85	0.8477
Moderately-severe	18.64	0.7221

Further, to find out whether the degree of hearing loss had any differential effect on SRS and Silas in hearing aid selection, two-way ANOVA was carried out. This revealed that there was a significant main effect of degree of hearing loss on the mean SRS [F (2, 213) = 7.43, $p < 0.01$]. A similar trend, as seen in SRS, was noticed for the mean Silas values also, where there was a significant main effect of degree of hearing loss on the Silas [F (2, 213) = 49.07, $p < 0.01$]. This indicates that the degree of hearing loss did influence the SRS as well as the Silas values.

Within each degree of hearing loss, the influence of type of hearing loss was analyzed using ANOVA. It was observed that within each degree of hearing loss, there was no significant difference between the two types of hearing loss. Hence, the scores of those with a conductive and sensorineural hearing loss were grouped together within each degree of hearing loss.

Since a significant main effect was noted for the degree of hearing loss on SRS and Silas, a post-hoc Duncan test was performed. This was done in order to compare the effect of all different pair-wise combinations of degrees of hearing loss on SRS and Silas. The Duncan test revealed that there were two sub-sets of mean values of SRS and three sub-sets of the mean values of Silas. There was no significant difference between the SRS of those with moderate and moderately-severe degree of hearing loss. However, there was a significant difference between the SRS of those with mild and moderate degrees of hearing loss. For the mean Silas values, there was a significant difference between those with mild and moderate and also between those with moderate and moderately-severe degrees of hearing loss. Hence, while analysing whether the SRS and Silas could differentiate the three hearing aids, the three degrees of hearing loss were analysed separately.

To evaluate the effectiveness of SRS and Silas in differentiating hearing aids, repeated measures ANOVA was used. The mean SRS and mean Silas values of the participants were compared within each of the three degrees of hearing loss. Table 4.15 depicts the mean SRS and Silas values in the three aided conditions. As can be noted, the mean values across the three hearing aids differed slightly. The mean values for HA 1 were the highest while those for HA 3 were the lowest. This was observed for both tests at all three degrees of hearing impairment.

Table 4.15

The mean SRS and Silas values with the three aided conditions in mild, moderate and moderately-severe degrees of hearing loss.

Degree of hearing loss	*Aided conditions*	*Mean SRS*	*Mean Silas*
Mild	HA 1	22.96	0.9192
(N = 23)	HA 2	21.48	0.9185
	HA 3	19.61	0.8911
Moderate	HA 1	21.54	0.8686
(N = 26)	HA 2	18.92	0.8492
	HA 3	16.08	0.8252
Moderately-severe	HA1	21.08	0.7890
(N = 24)	HA 2	19.08	0.7116
	HA 3	15.75	0.6657

The mean values of SRS and Silas with different hearing aids in different degrees of hearing loss are also graphically depicted in Figure 4.6 and Figure 4.7 respectively. On inspection of the mean values (Table 4.15 and Figures 4.6 & 4.7), it can be noted that the SRS differentiated the three hearing aids better when compared to the Silas. This could be noted for all the degrees of hearing loss.

The difference in the Silas values between the three hearing aids in those with a mild degree of hearing loss was lesser compared to that noted in those with a moderate and moderately-severe degree. In the participants with a mild hearing loss, as the loss in audibility was less, there was a lesser difference not only between the unaided and the aided conditions, but also across the different hearing aids. Similar findings have been noted by Hornsby (2004). He noted that in individuals with a mild degree of hearing loss, the actual aided mean Silas values did not differ much because of the high unaided SII values that were unlikely to show large aided benefits.

As the Silas value increased with different hearing aids, SRS performance also improved proportionately. It has also been reported by pioneers in AI that improved audibility improved speech recognition scores. This is because audibility was one of the important variables affecting the speech recognition scores (Fletcher & Galt, 1950; Fletcher & Steinberg, 1947). The results of the present study are in consonance with this finding. Similar results have also been noted by Pavlovic, (1989) and Studebaker, and Marincovich (1989). Further, it has been reported by Souza, Yueh, Sarubbi and Loovis (2000) that improved audibility was related to hearing aid use adherence, with participants who achieved better audibility using their hearing aids more frequently.

To evaluate the effectiveness of Silas in differentiation of hearing aids within each of the degrees of hearing loss, repeated measures ANOVA was carried out. The F ratios and significance of difference in mean values of SRS and Silas across hearing aids for different degrees of hearing loss are given in Table 4.16. From this table it could be noticed that the SRS could significantly differentiate the three hearing aids in those with different degrees of hearing loss. However, there was a significant difference in the Silas values with the three hearing aids only in moderately-severe degree and not in mild, moderate degrees of hearing loss. Though there was no significant difference in the mean Silas values in the mild and moderate degrees of hearing loss, the actual mean values did differ across the hearing aids (Table 4.15). The mean Silas with HA 1 was higher than that with HA 2 which in turn was higher than that with HA 3 (Table 4.15). Hence, it can be inferred that Silas can be used in differentiating the hearing aids.

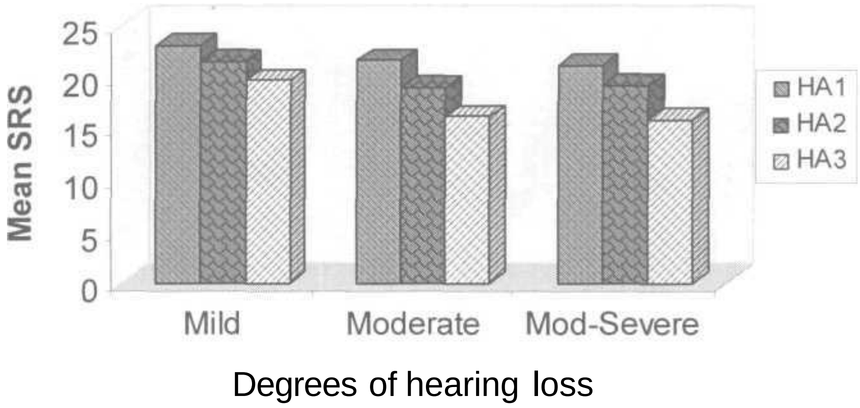

Figure 4.6: Mean SRS with different hearing aids in different degrees of hearing loss.

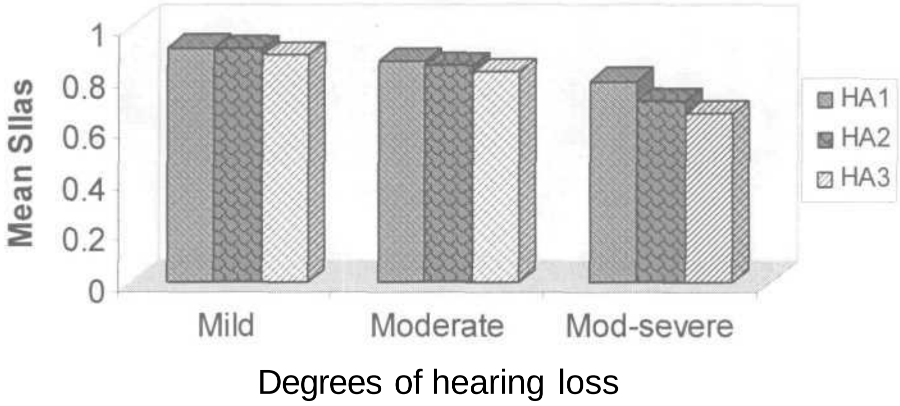

Figure 4.7: Mean Silas with different hearing aids in different degrees of hearing loss.

In the present study, the difference in mean Silas values with the three hearing aids may not be significant since the pre-selected three hearing aids were within the fitting range of the hearing loss of the participants. However, from the mean values it was observed that the Silas values could reveal subtle differences as it can differentiate hearing aids even when they are within the fitting range.

Table 4.16

F ratios and significance values of the difference in mean values of SRS and Sllas with different hearing aids, in different degrees of hearing loss.

Degree of hearing loss	*Aided conditions*	*Mean SRS*	*Mean Silas*
Mild *(N = 23)*	HA1 vs. HA2 vs. HA3 (Main effect)	$F(2, 44) = 18.20$, $p<0.01$	$F(2, 44) = 2.04$, $p>0.05$
	HA 1 vs. HA 2	$p<0.01$	-
	HA 2 vs. HA 3	$p>0.05$	-
Moderate *(N = 26)*	HA1 vs. HA2 vs. HA3 (Main effect)	$F(2, 50) = 32.05$, $p < 0.01$	$F(2,50) = 1.83$, $p> 0.05$
	HA 1 vs. HA 2	$p<0.01$	-
	HA 2 vs. HA 3	$p<0.01$	-
Moderately-Severe *(N = 24)*	HA1 vs. HA2 vs. HA3 (Main effect)	$F(2,46) = 38.49$, $p< 0.01$	$F(2, 46) = 9.74$, $p < 0.01$
	HA 1 vs. HA 2	$p<0.01$	$p<0.01$
	HA 2 vs. HA 3	$p<0.01$	$p>0.05$

From this it can be deduced that the Silas can differentiate the performance between the hearing aids which are within the fitting range of the hearing loss of the participant. The difference may not be as marked as that observed while using SRS, but none-the-less large enough to differentiate between the hearing aids. This indicates that Silas can also be used in differentiating the performance with the hearing aids during hearing aid selection.

2.4.3. Effect of Configuration of Audiogram on the Utility of Silas in Hearing Aid Selection

In the present study, the effect of audiogram configuration on the utility of Silas in hearing aid selection was evaluated. The Silas was able to select the best hearing aid better in those with a steep slope than those with a gradual slope. To find out whether variation in the slope of the audiogram (gradual and steep) had any significant differential effect on SRS and Silas in hearing aid selection, independent samples t-test was carried out. This revealed that there was a non-significant effect of slope of audiogram on the mean SRS [F (1, 59) = 0.04, p > 0.05]. A similar trend, as seen in SRS, was noticed for the mean Silas values also. There was a non-significant effect of slope of audiogram on the Silas [F (1, 59) = 1.22, p > 0.05] as well. This indicates that the slope of audiogram did not influence the SRS as well as the Silas. Hence, the scores obtained for those with a gradual and steep configuration of audiogram were combined in each of the tests.

Further, in order to check if the SRS and Silas could differentiate the three hearing aids in those with a sloping configuration of audiogram, their mean values were compared. Table 4.17 shows the mean SRS and Silas values for the three aided conditions. As can be observed, the mean values across the three hearing aids differed. The mean values for HA 1 were the highest and those for HA 3 were the lowest. This trend was observed in both the measuring methods, SRS and Silas.

Table 4.17

The mean SRS and Silas values with the three aided conditions in sloping configuration of sensorineural hearing loss.

Configuration of audiogram	*Aided conditions*	*Mean SRS*	*Mean Silas*
Sloping sensorineural hearing loss (N = 20)	HA1	21.90	0.7144
	HA 2	19.45	0.6806
	HA 3	16.85	0.6662

The mean values of SRS and Silas with different hearing aids in sloping configuration of audiogram are also graphically depicted in Figure 4.8 (A & B).

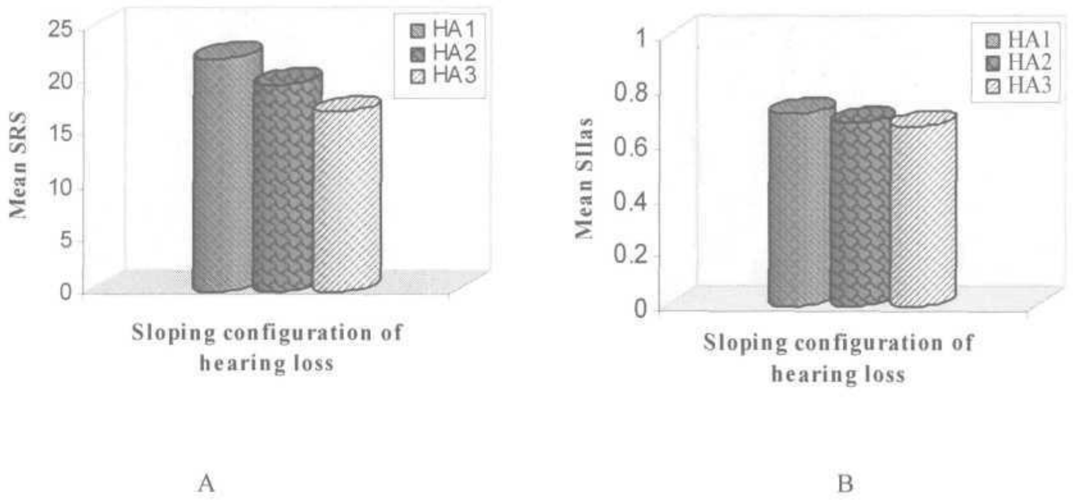

Figure 4.8: Mean SRS (A) and Mean Silas (B) with different aided conditions in sloping configuration of hearing loss.

In order to statistically confirm the utility of SRS and Silas in differentiating the three hearing aids in those with sloping configuration of audiograms, repeated measures ANOVA was performed. The significance of difference in mean values of SRS and Silas across hearing aids for individuals with sloping configuration of the audiograms was studied. It was noticed that the SRS could significantly differentiate the three hearing aids ($p < 0.05$ between HA 1 and HA 2; $p < 0.01$ between HA 2 and HA 3). However, there was no significant difference in the Silas values with the three hearing aids in sloping configuration of audiogram ($p > 0.05$). The difference in mean Silas values with the three hearing aids may not be significant since the extent of benefit was not large in those with a sloping configuration of audiogram. Though there was no significant difference in the mean Silas values of the three hearing aids in the sloping configuration of audiogram, the actual mean values did differ across the three hearing aids. The mean Silas with HA 1 was the highest while that with HA 3 was the lowest (Table 4.17). Hence, it can be construed that Silas could be used in differentiating the hearing aids.

The result of the present study agrees with that of Rankovic (2002). She noted that AI, calculated according to Fletcher's method, predicted hearing aid performance well for subjects with high frequency hearing loss, regardless of the presence or absence of dead regions. The study highlights that the audibility can be used to select hearing aids. However, it has been found that speech intelligibility can be optimized better by amplification that maximizes effective audibility rather than absolute audibility (Ching, Dillon & Byrne, 1998). With effective audibility, instead of providing more gain across all frequencies to increase the audibility, the hearing aid can be adjusted to give more gain at some frequencies where it is more useful, by reducing gain at other frequencies. This would enable an individual with hearing impairment to make use of the information contained in the audible signal more effectively, and at frequencies that are more important to speech intelligibility.

Further in the present study, individual differences between the hearing aids were better demonstrated in a large number of cases when the speech intelligibility index was used rather when the speech recognition test was used. In 29% (27 out of 93) of the participants in the present study, the value of SRS was the same with two of the three hearing aids. However, in 63% (17 out of 27) of such participants, the Silas was able to differentiate the hearing aid performance. This is in agreement with the finding reported by Magnusson, Karlsson, and Leijon (2001). Hence, it was found that Silas was not only able to differentiate the performance between the hearing aids, but was also able to provide additional information when there were similar SRS values with two or more hearing aids. Hence, in order to verify small but important differences between hearing aids SII would be a better test.

2.5 . Effectiveness of Silas in Hearing Aid Selection Across Different Degrees of Hearing Loss and Configurations of Audiogram

In addition to evaluating the usefulness of Silas in hearing aid selection, as done in previous sections, the usefulness of this measure across different degrees of hearing loss and configuration of audiogram was also determined. This was done by noting the number of times the hearing aid with the best SRS was also the hearing aid with the best Silas. This observation was recorded in each of the individuals with different degrees of hearing loss and slopes of audiogram. Among those with different degrees of hearing loss, the Silas could select the best hearing aid in participants with moderately-severe degree of hearing loss (75% of the time) followed by those with moderate (52.73% of the time) and then by mild (38.26% of the time) degree of hearing loss. From this data, it is evident that as the degree of hearing loss increased, the Silas was found to be more efficient in selecting the best hearing aid. As reported earlier, similar findings have been noted by Hornsby (2004). He noted that in individuals with a mild degree of hearing loss, the actual aided mean Silas values did not differ much because of the high unaided SII values that were unlikely to show large aided benefits.

Among those with a sloping configuration of audiogram, the Silas was better able to pick out the best hearing aid in steep slope (70% of the time) compared to gradual slope (60% of the time). Thus, the Silas was better able to pick out the best hearing aid in those with a steep slope than those with a gradual slope.

Besides determining the utility of Silas across groups of participants with different degrees of hearing loss and slopes of audiograms, the usefulness in selecting hearing aids in individual participants was also obtained. This was done on 16 participants who were randomly selected out of the 93 participants. Two participants were selected from each of the sub-groups. It was observed that in a majority of these individuals (75%), the Silas was able to predict that HA 1 was the best hearing aid, which also happened to be the device with the highest SRS. This again confirmed the utility of Silas in selecting the most appropriate hearing aid for participants having different type, degree of hearing loss and configurations of audiogram.

Overall, it was noted while carrying out the present study, that obtaining aided thresholds by calculating SII took lesser time than obtaining the speech recognition scores. Thus, in clinics where a large number of clients are required to be evaluated for hearing aid selection, use of SII would be time-effective. Therefore, it can be concluded from the findings of the present study as well as from the supporting literature that Silas is a useful technique in selection of hearing aids.

In addition, during the course of the study, it was observed that Silas could not only be used in selection of hearing aids, but was very useful in counselling too. The graphical representation (Figure 3.1) of the unaided and aided performance with different hearing aids could visually demonstrate to the individuals why they continued to have problems in speech intelligibility, though they had been fitted with seemingly appropriate hearing aids. Hence, it is recommended that audiologists use a simple and accurate graphical representation of Silas to help themselves as well as the client in analyzing the reason for selecting hearing aids or to determine the extent to which hearing aids would be beneficial.

From the results of the present study the following can be concluded regarding the utility of speech intelligibility index in prediction of SRS and in hearing aid selection:

I. With respect to the prediction of SRS from SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD, HLD}}$, it was observed that:

1. The variations in audibility or speech intelligibility index also resulted in similar variations in the SRS. This was evident across the different types of hearing loss and degrees of hearing loss. Thus, the SRS and SII provide comparable information for different degrees and types of hearing losses.
2. The mean valu es of SRS, SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$ reduced as the dB per octave slope of sensorineural hearing loss decreased.

3. Non-linear regression power functions were derived to predict SRS from SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$. Using these equations, the speech recognition scores were consistently predicted by SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$.
4. There was a highly significant positive correlation between the measured SRS and predicted SRS.
5. There was no significant difference between the measured SRS and predicted SRS, whether a correction factor was included in the computation of SIIw or not. Thus, correction factors are not required as long as the hearing loss of the participants does not exceed that of the participants of the present study.
6. Not only were mean SRS predicted adequately, but also individual speech recognition scores were predicted well by the three predictors, SIIw, $SIIw_{SLD}$ and $SIIw_{SLD,HLD}$-
7. In individuals in whom the SRS was less than 50 rau, the difference between the measured SRS and the predicted SRS was lesser when correction factors were incorporated. The difference was least when both SLD and HLD corrections were incorporated.

Thus, it is possible to use a non-speech based technique to predict SRS which is very essential in the Indian context where there are many languages spoken.

II. With regard to the efficacy of Silas in hearing aid selection, it was noted that:

1. Participants with an unaided Silas of 0.6325 or above (maximum index being 1.00) did not require hearing aids. Hence, for a participant to be considered as a

candidate for hearing aids, he/she should have an unaided Silas of less than 0.6325.

2. In the three aided conditions, the rank correlation indicated that a variation in Silas brought about a similar variation in the overall quality ratings. This implied that the Silas reflected the perceptual judgement of quality.
3. The mean Silas values differentiated the performance across the hearing aids in different degrees of hearing loss and sloping configurations of the audiogram. Hence, the Silas can be used as a tool in the selection of hearing aids.
4. Silas was able to differentiate the subtle differences in the performance with the three hearing aids better than the SRS.
5. Among those with different degrees of hearing loss, Silas was most efficient in selection of hearing aids in those with a moderately-severe degree of hearing loss followed by those with a moderate and then by mild degree.
6. In those with a sloping hearing loss, the variations in Silas were not reflected with variations in SRS to the same extent as that seen in those with different degrees and types of hearing losses.
7. The Silas was found to be more efficient in selection of hearing aids for those with a steeply sloping configuration than for those with a gradual slope.

From the results of the present study it can be inferred that the speech intelligibility index is a promising tool not only in prediction of speech recognition but also in selection of hearing aids.

SUMMARY AND CONCLUSION

Over the years, various procedures have been put forth to select appropriate amplification devices for individuals with hearing impairment. The primary goal of hearing aid selection is to make speech audible, comfortable and better in quality, as far as possible (Palmer, Lindley & Mormer, 2000). The hearing aid selection approaches make use of the audibility of speech spectrum as the guiding principle for setting the gain requirements for the amplified low and high frequency range of the hearing aid (Sandlin, 1990). A procedure based on the audibility for hearing aid selection, which has gained prominence in the last two decades, is the articulation index (AI).

The original AI given by French, and Steinberg (1947) has been expressed and calculated as the sum of contributions of a number contiguous frequency bands which are necessary for speech recognition. This procedure has been modified several times to simplify the computation and to improve the predictability of speech recognition. When such corrections are incorporated, the term speech intelligibility index (SII) has been preferred. In order to improve the predictive ability of the AI, the correction factors have been included to account for speech level distortion (SLD) and hearing loss desensitization (HLD). The SLD factor accounts for the deterioration in speech recognition performance at high sound pressure levels, which is seen even in individuals with normal hearing. The HLD factor accounts for the reduced ability of the cochlea to extract useful information from increased audibility once the hearing loss crosses 70 dB HL (Ching, Dillon, Katsch & Byrne, 1998).

The articulation index (AI) or speech intelligibility index (SII) not only allows an audiologist to predict speech recognition ability, but also to evaluate the benefit derived from hearing aids. This is done by comparing the speech recognition and SII under unaided and aided conditions (Humes, 1986; Rankovic, 1991; Studebaker & Shebecoe, 1993).

In the present study, the aims were to evaluate the efficacy of using SII in prediction of speech recognition and in hearing aid selection. The specific objectives of the study included:

1. Development of software programs for computation of SII with a frequency band importance function for CID W-22 words, i.e., SIIw, and SII with a frequency band importance function for average speech, i.e., Silas. In addition, development of software programs for SIIw with correction factors for SLD and HLD, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$
2. To investigate the utility of SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$ in predicting SRS by:
    - 2.1. Comparing the SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$ with SRS,
    - 2.2. Determining if SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$ can predict SRS, and
    - 2.3. Determining whether there is any significant difference between the measured SRS and the SRS predicted by SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$.
3. To investigate the utility of Silas in hearing aid selection by:
    - 3.1. Determining a criterion based on Silas to decide about the hearing aid candidacy,
    - 3.2. Investigating the relationship between unaided and aided SRS with Silas, during hearing aid selection,

3.3. Evaluating the relationship between the Silas and the quality judgments of hearing aids,

3.4. Investigating the effect of the types (conductive and sensorineural), degrees (mild, moderate and moderately-severe) and configurations (gradual and steep slope) of hearing impairment on Silas in hearing aid selection, and

3.5. Evaluating the effectiveness of Silas in hearing aid selection for those having different degrees of hearing loss and configurations of audiogram.

In order to investigate the above objectives, the study was carried out in three stages. In *Stage I* the software programs to compute SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$ and Silas were developed using Microsoft Excel. In *Stage II*, the unaided and aided sound field hearing thresholds for FM tones and speech recognition scores (SRS) were obtained from 93 participants with different types (conductive and sensorineural), degrees (mild, moderate and moderately-severe) and configurations (gradual and steep slopes) of hearing loss. The hearing thresholds were used to calculate the SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$ using the software programs developed in Stage I. These data were used to derive non-linear power regression equation to predict SRS from SIIw, SIIw_{SLD} and $\text{SIIw}_{\text{SLD HLD}}$. In addition, the utility of the non-linear power regression equation was evaluated on a separate group of 23 participants.

In *Stage III*, data on the unaided SRS and unaided hearing thresholds for FM tones were collected from 84 of the participants with hearing thresholds being less than 40 dB HL. This was done in order to derive a criterion for selection of candidates for hearing aids based on Silas. Further, the data on unaided and aided sound field hearing thresholds and SRS collected from the 93 participants in Stage II were utilized in Stage III also in order to study the efficacy of Silas in hearing aid selection. The sound field hearing thresholds data were used to compute the Silas. The data thus collected were subjected to statistical analysis. The results on the efficacy of speech intelligibility index in prediction of SRS as well as in selection of hearing aids are given below:

I. With respect to the prediction of SRS from SIIw, $\mathrm{SIIw}_{\mathrm{SLD}}$ and $\mathrm{SIIw}_{\mathrm{SLD,\ HLD}}$, it was observed that:

1. The variations in audibility or speech intelligibility index were reflected in the variations in the SRS, as indicated by descriptive statistics. This was evident across the different types of hearing loss and degrees of hearing loss. Hence, it can be deduced that the SRS and SII provide similar information.
2. In individuals with a sloping hearing loss, the variations in SIIw were not reflected with variations in SRS to the same extent as that seen in those with different degrees and types of hearing loss.
3. To predict SRS from SIIw, $\mathrm{SIIw}_{\mathrm{SLD}}$ and $\mathrm{SIIw}_{\mathrm{SLD\ HLD}}$ non-linear regression power functions were derived for the three predictors (SIIw, $\mathrm{SIIw}_{\mathrm{SLD}}$ and $\mathrm{SIIw}_{\mathrm{SLD\ HLD}}$). The equations derived were $\mathrm{SRS} = a\ (\mathrm{SIIw})^{b}$; $\mathrm{SRS} = a\ (\mathrm{SHw}_{\mathrm{SLD}})^{b}$ and $\mathrm{SRS} = a\ (\mathrm{SIIw}_{\mathrm{SLD\ HLD}})$ where 'a' and 'b' are fitting constants. Using these equations, the speech recognition scores were consistently predicted by the speech intelligibility index values.
4. There was a highly significant positive correlation between the measured SRS and the SRS predicted by SIIw, $\mathrm{SIIw}_{\mathrm{SLD}}$ and $\mathrm{SIIw}_{\mathrm{SLD\ HLD}}$. Further, there was no

significant difference between the measured SRS and predicted SRS whether a correction factor was included in the computation of SIIw or not. Thus, correction factors are not required as long as the hearing loss of the participants does not exceed that of the participants of the present study.

5. Not only were mean SRS predicted adequately, but also individual speech recognition scores were predicted well by the three predictors, SIIw, $SIIw_{SLD}$ and $SIIw_{SLD\ HLD}$
6. In individuals in whom the SRS was less than 50 rau, SRS could be predicted better when both SLD and HLD corrections were incorporated.

II. With regards to the efficacy of Silas in hearing aid selection, it was noted that:

1. Participants with an unaided Silas of 0.6325 or above (maximum index being 1.00) did not require hearing aids. Hence, it is recommended that the Silas cut-off value should be 0.6325 to decide whether an individual requires hearing aids or not.
2. In the three aided conditions, the rank correlation indicated that a variation in Silas brought about a similar variation in the overall quality ratings. This indicates that the Silas reflects the perceptual judgments of quality by individuals using a hearing aid.
3. The Silas, like the SRS, was found to be a useful tool in differentiating the performance with different hearing aids in participants with different degrees of hearing loss and sloping configurations of audiogram included in the present study.

4. In a few participants in whom the SRS was similar across two hearing aids, the SIIas was able to differentiate subtle differences.
5. In addition to the mean Silas differentiating between hearing aids, it also did so when individual scores were utilized. It could select the best hearing aid in individual participants, irrespective of the type, degree of hearing losses and configuration of audiogram.
6. Among those with different degrees of hearing loss, Silas was most efficient in selection of hearing aids in those with a moderately-severe degree of hearing loss followed by those with a moderate and then by mild degree. Thus, as the degree of hearing loss increased, the Silas was found to be more efficient in selecting hearing aids.
7. In those with a sloping hearing loss, the variations in Silas were not reflected with variations in SRS to the same extent as that seen in those with different degrees and types of hearing losses.
8. Among those with sloping configurations, the Silas was able to select the best hearing aid better in those with a steep slope than those with a gradual slope.

The implications of the present study are as follows:

1. It is possible to use a non-speech based technique to predict SRS and select hearing aids in the Indian context where there are many languages spoken.
2. Speech intelligibility index would also be highly useful while evaluating the benefit of hearing aids in young children and in clients with a limited verbal output.

3. Speech intelligibility index could not only be used in prediction of SRS and selection of hearing aids, but was very useful in counselling too. The graphical representation of the unaided and aided performance with different hearing aids could visually demonstrate to the individuals why they continued to have problems in speech intelligibility, though they had been fitted with seemingly appropriate hearing aids.

Thus, it can be concluded that the speech intelligibility index proves to be a promising technique in the prediction of speech recognition scores as well as in the selection of hearing aids. In addition, it can serve as a useful tool to explain the utility of hearing aids to a person with hearing impairment.

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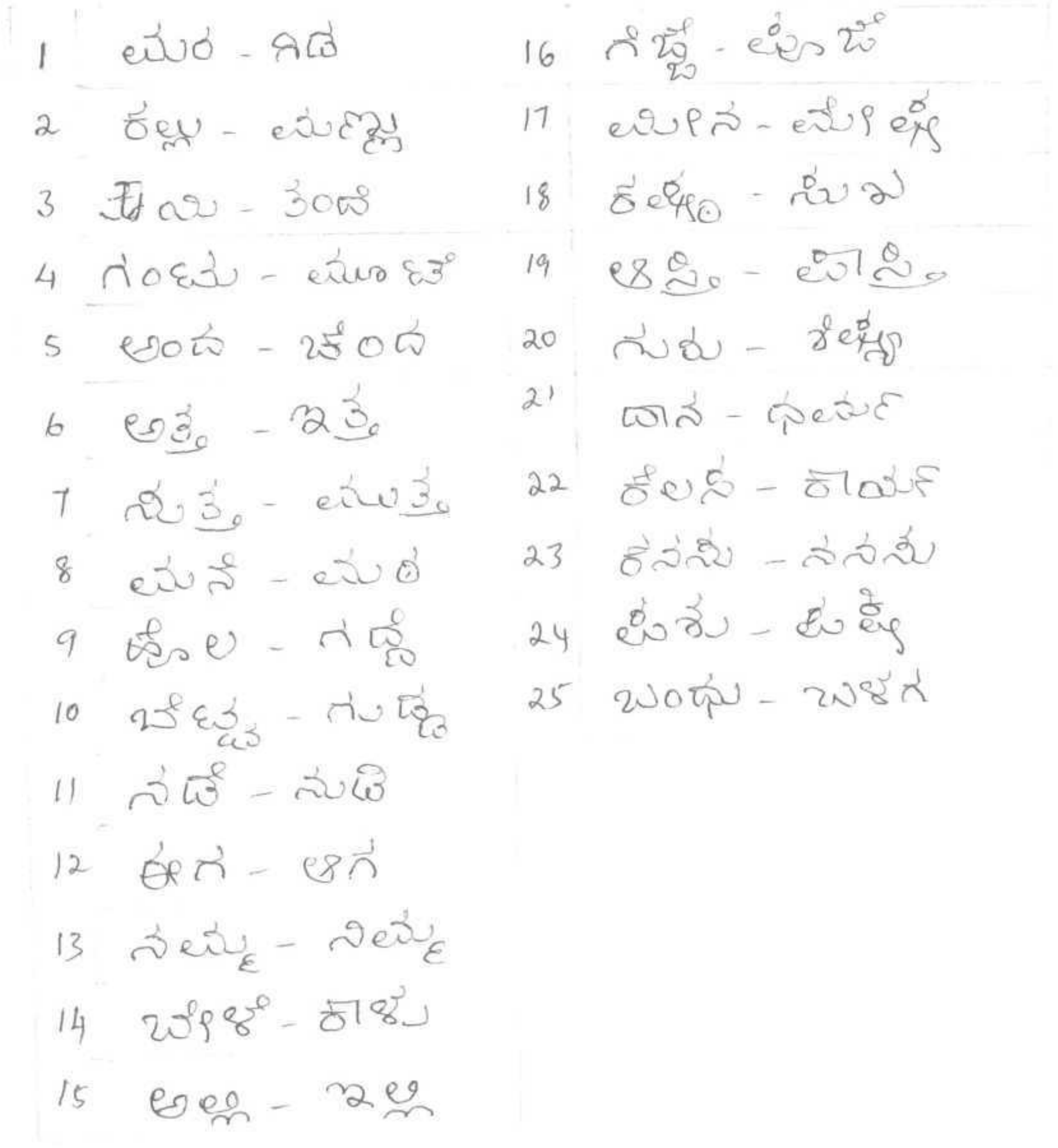
APPENDIX A

Paired word-list for speech reception threshold in Kannada.

(International Phonetic Alphabet - IPA).

1. mara - giḍa
2. kallu - maṇṇu
3. ta:yi - tande
4. ganṭu - mu:ṭe
5. anda - tʃenda
6. atta - itta
7. sutta - mutta
8. mane - maṭ^{h}a
9. hola - gadde
10. beṭṭa - guḍḍa
11. naḍe - nuḍi
12. i:ga - a:ga
13. namma - nimma
14. be:ḷe - ka:ḷu
15 alli - illi
16. gedzdze - pu:dze
17. mi:na - me:ça
18. kaçṭa - suk^{h}a
19. a:sti - pa:sti
20. guru - ʃiçja
21. da:na - d^{h}arma
22. kelasa - ka:rya
23. kanasu - nanasu
24. paʃu - pakçi
25. band^{h}u - baḷaga

Paired word-list for speech reception threshold in Kannada.

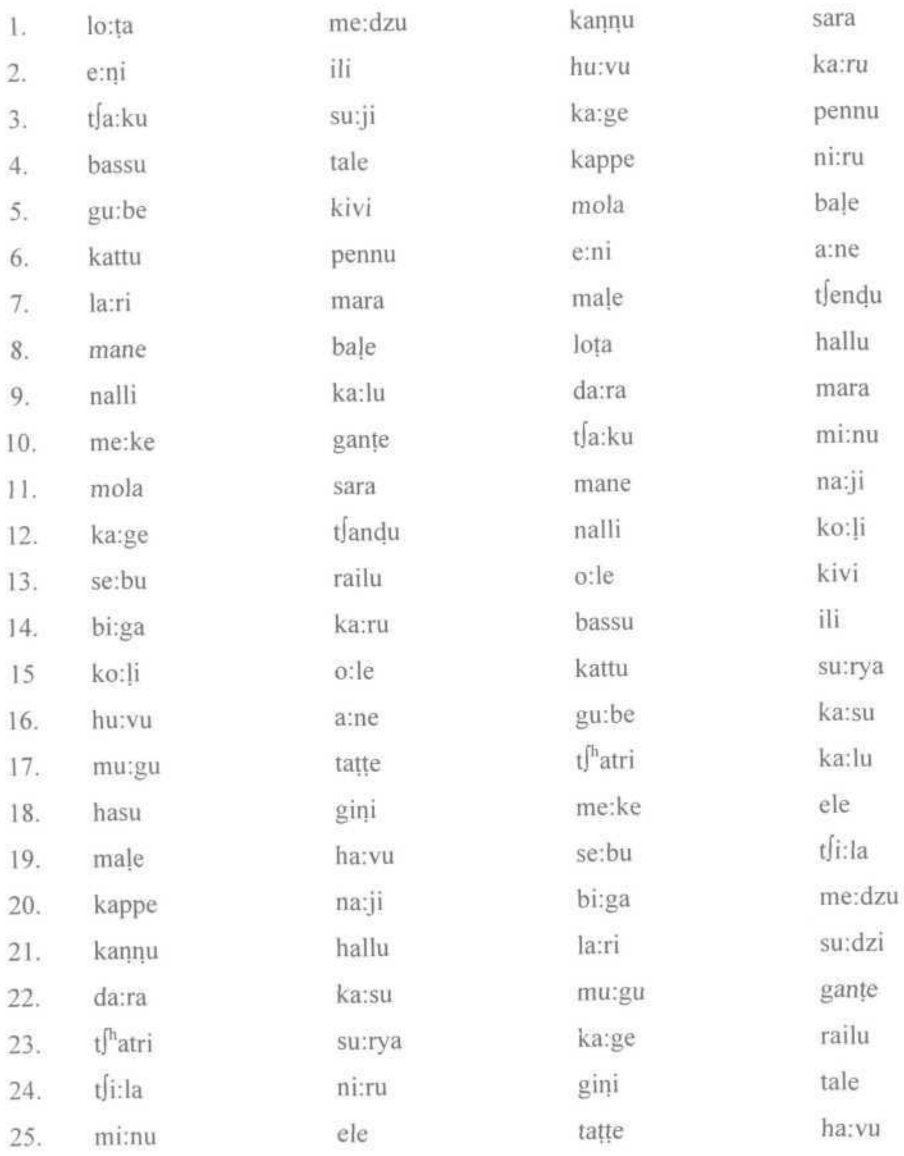


1 ಮರ - ಗಿಡ
2 ಕಲ್ಲು - ಮಣ್ಣು
3 ಚಳಿ - ತಂಡಿ
4 ಗಂಟು - ಮೂಟೆ
5 ಅಂದ - ಚಂದ
6 ಅತ್ತ - ಇತ್ತ
7 ಸುತ್ತ - ಮುತ್ತ
8 ಮನೆ - ಮಠ
9 ಹೊಲ - ಗದ್ದೆ
10 ಪೆಟ್ಟು - ಗುದ್ದು
11 ನಡೆ - ನುಡಿ
12 ಈಗ - ಆಗ
13 ನಮ್ಮ - ನಿಮ್ಮ
14 ಬೇಳೆ - ಕಾಳು
15 ಅಲ್ಲಿ - ಇಲ್ಲಿ
16 ಗೆಜ್ಜೆ - ಪೂಜೆ
17 ಮೌನ - ಮೌಲ್ಯ
18 ಕಷ್ಟ - ಸುಖ
19 ಆಸ್ತಿ - ಪಾಸ್ತಿ
20 ಗುರು - ಶಿಷ್ಯ
21 ದಾನ - ಧರ್ಮ
22 ಕೆಲಸ - ಕಾರ್ಯ
23 ಕನಸು - ನನಸು
24 ಪಶು - ಪಕ್ಷಿ
25 ಬಂಧು - ಬಳಗ

APPENDIX B

Phonemically balanced word-list for speech recognition in Kannada

(International Phonetic Alphabet - IPA).



1.	lo:ṭa	me:dzu	kaṇṇu	sara
2.	e:ṇi	ili	hu:vu	ka:ru
3.	tʃa:ku	su:ji	ka:ge	pennu
4.	bassu	tale	kappe	ni:ru
5.	gu:be	kivi	mola	baḷe
6.	kattu	pennu	e:ni	a:ne
7.	la:ri	mara	maḷe	tʃenḍu
8.	mane	baḷe	loṭa	hallu
9.	nalli	ka:lu	da:ra	mara
10.	me:ke	ganṭe	tʃa:ku	mi:nu
11.	mola	sara	mane	na:ji
12.	ka:ge	tʃanḍu	nalli	ko:ḷi
13.	se:bu	railu	o:le	kivi
14.	bi:ga	ka:ru	bassu	ili
15	ko:ḷi	o:le	kattu	su:rya
16.	hu:vu	a:ne	gu:be	ka:su
17.	mu:gu	taṭṭe	tʃʰatri	ka:lu
18.	hasu	giṇi	me:ke	ele
19.	maḷe	ha:vu	se:bu	tʃi:la
20.	kappe	na:ji	bi:ga	me:dzu
21.	kaṇṇu	hallu	la:ri	su:dzi
22.	da:ra	ka:su	mu:gu	ganṭe
23.	tʃʰatri	su:rya	ka:ge	railu
24.	tʃi:la	ni:ru	giṇi	tale
25.	mi:nu	ele	taṭṭe	ha:vu

Phonemically balanced word-list for speech recognition in Kannada

1	ಲೋಟ	ಮೇಜು	ಕಣ್ಣು	ಶಿರ
2	ಏಣಿ	ಇಲಿ	ಹೂವು	ಕಾರು
3	ಚಾಕು	ಸೂಜಿ	ಕಾಗೆ	ಪೆನ್ನು
4	ಬಸ್ಸು	ತಲೆ	ಕಪ್ಪೆ	ನೀರು
5	ಗೂಬೆ	ಕಿವಿ	ಮೊಲ	ಬಳೆ
6	ಕತ್ತೆ	ಪೆನ್ನು	ಏಣಿ	ಆನೆ
7	ಊಟ	ಮರ	ಮಳೆ	ಚೆಂಡು
8	ಮನೆ	ಬಳೆ	ಮೋಡ	ಹಲ್ಲು
9	ನಲ್ಲಿ	ಕಾಲು	ದಾರ	ಮರ
10	ಮೇಕೆ	ಗಂಟೆ	ಚಾಕು	ಮೀನು
11	ಮೊಲ	ಶಿರ	ಮನೆ	ನಾಯಿ
12	ಕಾಗೆ	ಚೆಂಡು	ನಲ್ಲಿ	ಕೋಳಿ
13	ಜೇಬು	ರೈಲು	ಓಲೆ	ಕಿವಿ
14	ಬೀಗ	ಕಾರು	ಬಸ್ಸು	ಇಲಿ
15	ಕೋಳಿ	ಓಲೆ	ಕತ್ತೆ	ಸೂರ್ಯ
16	ಹೂವು	ಆನೆ	ಗೂಬೆ	ಕಾಸು
17	ಮೂಗು	ತಟ್ಟೆ	ಛತ್ರಿ	ಕಾಲು
18	ಹಸು	ಗಿಣಿ	ಮೇಕೆ	ಎಲೆ
19	ಮಳೆ	ಹಾವು	ಜೇಬು	ಚೀಲ
20	ಕಪ್ಪೆ	ನಾಯಿ	ಬೀಗ	ಮೇಜು
21	ಕಣ್ಣು	ಹಲ್ಲು	ಊಟ	ಸೂಜಿ
22	ದಾರ	ಕಾಸು	ಮೂಗು	ಗಂಟೆ
23	ಛತ್ರಿ	ಸೂರ್ಯ	ಕಾಗೆ	ರೈಲು
24	ಚೀಲ	ನೀರು	ಗಿಣಿ	ತಲೆ
25	ಮೀನು	ಎಲೆ	ತಟ್ಟೆ	ಹಾವು

APPENDIX C

Passage in Kannada

(International Phonetic Alphabet - 1PA).

sullina p^{h}ala

ondu haḷḷijalli obba kuruba huḍuga va:sava:giddanu. avanu mundza:neje: ka:ḍige ho:gi allije: dz^{h}arijalli sna:na ma:ḍi sandzejavarege kurijannu me:jisi, sandze haḷḷige va:pa:sa:gu- ttidda. omme avanu kuri me:jisuva:ga iddakkiddanteje: hattirada holadalli kelasa ma:ḍuttidda raitarannu tama:çe ma:ḍa be:ku endu konḍa. anteje: avanu ajjo! huli! huli! ka:pa:ḍi endu ku:ga toḍagida. idannu ke:ḷida raitaru k^{h}aḍgagaḷannu tegedukonḍu hulijannu kollalu sidd^{h}ara:gi o:ḍi bandaru. idannu noḍida huḍuga nakku biṭṭa. raitaru ko:pagonḍu va:pa:sa:daru. huḍuga ide: ri:ti aida:ru ba:ri ma:ḍida. raitaru a: huḍugana me:lina nambike kaḷedu konḍaru.

omme suma:ru hanneraḍu g^{h}anṭe, bisilu ta:ḷala:rade huḍuga tʃ^{h}atri jannu hiḍidu kuḷittidda. iddakkiddante nidzava:giju ṭ^{h}akka huli bande: biṭṭittu. huḍuga matte ka:pa:ḍi! ka:pa:ḍi ! endu tʃi:rida. a:dare ja:ru saha avana sahajakke baralilla. huliju avana saṇṇa saṇṇa kurigaḷannu kolla la:ramb^{h}isitu. adannu ka:pa:ḍalu ho:da a: huḍugana mele a: huli ha:ri, avanannu konditu. i: kat^{h}eja ni:ti enendare - "suḷḷu ga:ranige ʃikçetappadu".

Passage in Kannada

ಸುಳ್ಳಿನ ಫಲ

ಒಂದು ಹಳ್ಳಿಯಲ್ಲಿ ಒಬ್ಬ ಕುರುಬ ಹುಡುಗನು ವಾಸವಾಗಿದ್ದನು. ಅವನು ಪ್ರತಿ ನಿತ್ಯವೂ ಕುರಿಗಳನ್ನು ಮೇಯಿಸಲು ಕಾಡಿಗೆ ಹೋಗುತ್ತಿದ್ದನು. ಅವನು ಮುಂಜಾನೆಯೇ ಕಾಡಿಗೆ ಹೋಗಿ ಅಲ್ಲಿಯೇ ಝರಿಯಲ್ಲಿ ಸ್ನಾನಮಾಡಿ ಸಂಜೆಯವರೆಗೆ ಕುರಿಯನ್ನು ಮೇಯಿಸಿ, ಸಂಜೆ ಹಳ್ಳಿಗೆ ವಾಪಾಸಾಗುತ್ತಿದ್ದ. ಒಮ್ಮೆ ಅವನು ಕುರಿ ಮೇಯಿಸುವಾಗ ಇದ್ದಕ್ಕಿದ್ದಂತೆಯೇ ಹತ್ತಿರದ ಹೊಲದಲ್ಲಿ ಕೆಲಸ ಮಾಡುತ್ತಿದ್ದ ರೈತರನ್ನು ತಮಾಷೆ ಮಾಡಬೇಕು ಎಂದುಕೊಂಡ. ಅಂತೆಯೇ ಅವನು ಅಯ್ಯೋ! ಹುಲಿ! ಹುಲಿ! ಕಾಪಾಡಿ ಎಂದು ಕೂಗ ತೊಡಗಿದ. ಇದನ್ನು ಕೇಳಿದ ರೈತರು ಶಸ್ತ್ರಗಳನ್ನು ತೆಗೆದುಕೊಂಡು ಹುಲಿಯನ್ನು ಕೊಲ್ಲಲು ಸಿದ್ಧವಾಗಿ ಓಡಿಬಂದರು. ಇದನ್ನು ನೋಡಿದ ಹುಡುಗ ನಕ್ಕುಬಿಟ್ಟ. ರೈತರು ಕೋಪಗೊಂಡು ವಾಪಾಸಾದರು. ಹುಡುಗ ಇದೇ ರೀತಿ ಎರಡು ಬಾರಿ ಮಾಡಿದ. ರೈತರು ಆ ಹುಡುಗನ ಮೇಲಿನ ನಂಬಿಕೆ ಕಳೆದುಕೊಂಡರು. ಒಮ್ಮೆ ಸುಮಾರು ಹನ್ನೆರಡು ಘಂಟೆ, ಬಿಸಿಲು ತಾಳಲಾರದೆ ಹುಡುಗ ಛತ್ರಿಯನ್ನು ಹಿಡಿದು ಕುಳಿತಿದ್ದ. ಇದ್ದಕ್ಕಿದ್ದಂತೆ ನಿಜವಾಗಿಯು ದೊಡ್ಡಹುಲಿ ಬಂದೇ ಬಿಟ್ಟಿತು. ಹುಡುಗ ಮತ್ತೆ ಕಾಪಾಡಿ! ಕಾಪಾಡಿ! ಎಂದು ಚೀರಿದ. ಆದರೆ ಯಾರು ಸಹ ಅವನ ಸಹಾಯಕ್ಕೆ ಬರಲಿಲ್ಲ. ಹುಲಿಯು ಅವನ ಸಣ್ಣ ಪುಟ್ಟ ಕುರಿಗಳನ್ನು ಕೊಲ್ಲಲಾರಂಭಿಸಿತು. ಅದನ್ನು ಕಾಪಾಡಲು ಹೋದ ಆ ಹುಡುಗನ ಮೇಲೆ ಆ ಹುಲಿ ಹಾರಿ, ಅವನನ್ನು ಕೊಂದಿತು. ಈ ಕಥೆಯ ನೀತಿ ಏನೆಂದರೆ, "ಸುಳ್ಳುಗಾರನಿಗೆ ಶಿಕ್ಷೆ ತಪ್ಪದು."