OPTIMIZATION OF COMPRESSION PARAMETERS IN HEARING AIDS USING AIDED AUDIBILITY INDEX

A DOCTORAL THESIS

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

By
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Under the guidance of
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CERTIFICATE

This is to certify that the thesis entitled "**Optimization of Compression Parameters in Hearing Aids using Aided Audibility Index"** submitted by Ms. Geetha C for the degree of Doctor of Philosophy (Speech and Hearing) to the University of Mysore, Mysuru was carried out at the All India Institute of Speech and Hearing, Mysuru.

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CERTIFICATE

This is to certify that the thesis entitled "**Optimization of Compression Parameters in Hearing Aids using Aided Audibility Index"** submitted by Ms. Geetha C for the degree of Doctor of Philosophy (Speech and Hearing) to the University of Mysore, Mysuru was carried out at the All India Institute of Speech and Hearing, Mysuru, under my guidance. I further declare that the results of this work have not been previously submitted for any other degree.

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DECLARATION

I declare that the thesis entitled "**Optimization of Compression Parameters in Hearing Aids using Aided Audibility Index"** which is submitted herewith for the award of the degree of Doctor of Philosophy in Speech and Hearing to the University of Mysore, Mysuru is the result of work carried out by me at the All India Institute of Speech and Hearing, Mysuru, under the guidance of Dr. Manjula P, Professor of Audiology, All India Institute of Speech and Hearing, Mysuru. I further declare that the results of this work have not been previously submitted for any other degree.

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LIST OF ABBREVIATIONS

1.	AI	Articulation Index
2.	AAI	Aided Audibility Index
3.	$\mathrm{AAI}_{\mathrm{SLD}}$	Aided Audibility Index with Speech Level Distortion correction factor
4.	$\mathrm{AAI}_{\mathrm{SLD,\ HLD}}$	Aided Audibility Index with Speech Level Distortion and Hearing Loss Desensitization correction factors
5.	Aided Compression Conditions :	
	2S55	The first character (i.e., 2 or 3) is the compression ratio of 2:1 or 3:1. The second character (i.e., S or L) is the time constants (i.e., attack time and release time), Short and Long. The last two characters (i.e., 55, 65, and 85) represent the presentation levels.
	2S65	
	2S85	
	2L55	
	2L65	
	2L85	
	3S55	
	3S65	
	3S85	
	3L55	
	3L65	
	3L85	
6.	AT	Attack Time
7.	CF Tool	Curve Fitting Tool
8.	CR	Compression Ratio
9.	CT	Compression Threshold
10.	dB SPL	Decibel Sound Pressure Level
11.	HLD	Hearing Loss Desensitization
12.	LTASS	Long-Term Average Speech Spectrum
13.	MCR	Measured Compression Ratio
14.	REAR	Real Ear Aided Response
15.	REIG	Real Ear Insertion Gain
16.	RT	Release Time
17.	SFAT	Sound Field Aided Thresholds
18.	SII	Speech Intelligibility Index
19.	SLD	Speech Level Distortion
20.	SRS	Speech Recognition Scores
21.	TC	Time Constants
22.	WDRC	Wide Dynamic Range Compression

ABSTRACT

The present study aimed at evaluating the utility of aided audibility index (AAI) and speech recognition scores (SRS) in selection of compression parameters, and utility of AAI in prediction of SRS at 55, 65, and 85 dB SPL presentation levels. The data were collected from 30 ears with mild to moderately-severe sensorineural hearing loss (Group I) and 30 ears with severe sensorineural hearing loss (Group II). Measurement of real ear aided response (REAR), sound field aided threshold (SFAT), and aided SRS was done in both the groups in different aided conditions. The aided conditions included different combinations of compression ratios and compression time constants at three input levels. AAI was computed using SFAT, and REAR. Derivation of regression equation to predict aided SRS using AAI and AAI with speech level distortion (SLD) and hearing loss desensitization (HLD) correction factors was carried out. The derived equations were verified on two separate groups of individuals with 10 ears in each group.

Statistical analyses was performed on 25 ears from Group I and 24 ears from Group II, after excluding the outliers. The results of a repeated measures ANOVA revealed that there was no significant difference in AAI and SRS across different compression settings in Group I. The AAI and SRS improved with increase in presentation level. In Group II, at all the presentation levels, the shorter time constants resulted in significantly higher AAI when compared to longer time constants, irrespective of the compression ratios. However, the SRS was similar across compression ratios and time constants.

The results of a regression analysis of AAI and SRS showed that the AAI obtained from SFAT predicts the SRS better than the AAI computed from REAR, in

Group I. Addition of correction factors to AAI such as SLD and HLD was not required in Group I. Whereas, addition of correction factors such as SLD and HLD improved the prediction of SRS in the Group II. This implies that the SLD and HLD correction factors were not necessary for predicting SRS in a compression hearing aid for individuals with mild to moderately-severe hearing loss, but it improves prediction in individuals with severe hearing loss.

Key words: Aided Audibility Index, Compression ratio, Compression time constants, Severity of hearing loss, Speech recognition scores.

CHAPTER 1

INTRODUCTION

Hearing aids are the primary rehabilitation option for individuals with sensorineural hearing loss (Dillon, 2001). Proper fitting of the hearing aids is essential for successful rehabilitation of these individuals (Upfold & Smither, 1981). Earlier, electronic hearing aids were linear. These hearing aids provided a constant gain across different input intensities till the input level reached saturation sound pressure level of the hearing aid. The analog hearing aids had very few parameters for manipulation (Jenstad, Pumford, Seewald, & Cornelisse, 2000; Kennedy, 1997). Hence, it was relatively easier to fit these hearing aids. Lesser flexibility of the these hearing aids led to the development of non-linear compression hearing aids. The digital non-linear hearing aids provide differential gain for different input levels (Jenstad et al., 2000; Moore, 2008) and have many compression parameters that need to be optimized (Dillon, 2001).

Dillon (2001) reported that the major role of these non-linear compression hearing aids is to compress the intensity range of input signal above the compression threshold into the residual dynamic range of persons with hearing loss. This is accomplished by different settings of compression parameters to bring about the required changes in the output (Dillon, 1996; Moore, Peters, & Stone, 1999; Souza & Turner, 1998, 1999). Hence, for a given individual accurate optimization of compression parameters is mandated, as inappropriate selection of the compression parameters might bring about poor speech perception and/or speech quality (Boothroyd, Springer, Smith, & Schulman, 1988; Hickson & Thyer, 2003; Plomp, 1988; Souza, 2002), in addition to intolerance for loud sounds.

There are many prescriptive formulae that have been reported to prescribe the compression ratios (CR) for a given degree of hearing loss (Brennan, Gallun, Souza, & Stecker, 2013; Byrne, Dillon, Ching, Katsch, & Keidser, 2001; Cornelisse, Seewald, & Jamieson, 1995). However, the other compression parameters such as compression threshold (CT), time constants (TC), i.e., attack time (AT), and release time (RT) are not prescribed by any formulae (van de Laar & de Vries, 2016). Hence, setting and verification of these parameters are usually done through subjective speech perception and quality measures (Costa & Iório, 2006; Dillon, 2001; Neuman, Bakke, Mackersie, Hellman, & Levitt, 1995). These subjective measures could be time consuming. Further, one may not always be able to conduct these measures in non-verbal adult individuals and in children. Hence, an objective way of verification is warranted. Articulation index (AI) is one such measure.

The term AI has been changed to speech intelligibility index (SII) (ANSI, 1997). The SII is one such objective measure that is commonly used in research and clinical work involving hearing aid fitting (Mueller, 1992; Pavlovic, 1988; Rankovic, 1991; Studebaker & Sherbecoe, 1993). This was originally known as articulation index, AI, put forth by French and Steinberg (1947). They described the AI as an audibility based measure which reflects the relationship between audibility and speech recognition, such that, one could get information on speech recognition just by obtaining audibility (Stelmachowicz, Kopun, Mace, Lewis, & Nittrouer, 1995). This might alleviate the problems associated with carrying out the subjective speech recognition measures.

The calculation of SII has been reported to be the sum of the product of audibility and frequency importance functions at different frequencies. It ranges between ‘0’ and ‘1’ (ANSI, 1997). An SII of ‘0’indicates that there is no audibility of speech at all and ‘1’ means that all portions of speech are audible (ANSI, 1997). The SII was developed to compute speech intelligibility using frequency weighted audibility levels through telecommunication devices (French & Steinberg, 1947). Over a period of time, it has been refined and there are numerous applications of SII such as in selection of linear and compression hearing aids (Souza, Boike, Witherell, & Tremblay, 2007), prediction of speech recognition in adults (Manjula, 2007; Souza & Turner, 1999), and in elderly individuals (Humes, 2001; Magnusson, Karlsson, & Leijon, 2001; Souza et al., 2007), in noisy situations (Ma, Hu, & Loizou, 2009), and in selection of non-linear frequency compression (McCreery et al., 2014), among other applications.

Aided audibility index (AAI) is a variation of the SII that was put forth by Stelmachowicz, Lewis, Kalberer, and Cruetz (1994). Stelmachowicz et al. (1994) described AAI as a frequency-weighted audibility index computed for hearing aids, for compression hearing aids as well. Like the SII, the AAI is the sum of the product of the audibility and frequency importance functions at different frequencies. The AAI also ranges between ‘0’ and ‘1’ (Dillon, 1993; Souza & Turner, 1999; Stelmachowicz et al., 1994). However, the authors reported that the AAI assumes the peaks of speech to be 15 dB below and the valleys of speech to be 15 dB above the long-term average speech spectrum (LTASS) for linearly amplified speech, considering the dynamic range of speech to be 30 dB. Whereas, for compression hearing aids, the dynamic range of speech, which is normally 30 dB (Fletcher, 1953), is squeezed into a smaller range depending on the compression ratio. Hence, the *dynamic range of speech would be lesser than 30 dB for a non-linear hearing aid*. Stelmachowicz et al. (1994) recommended *measuring the compression ratio* for speech signal and re-scaling the speech range based on the measured compression ratio (MCR) for the calculation of AAI. The above component makes AAI appropriate for calculation of AAI in compression hearing aids.

There are a few research studies on the efficacy of SII / AAI to compare and select the linear hearing aids, and to compare linear hearing aids with compression amplification, for individuals with mild to moderately-severe sensorineural hearing loss (Magnusson et al., 2001; Manjula, 2007; Souza & Turner, 1999). Manjula (2007) assessed the efficacy of SII in selecting an appropriate linear analog hearing aid for 34 ears of adults with different degrees of flat sensorineural hearing loss. The SII was computed, using sound field aided thresholds (SFAT) obtained for three hearing aids, in an excel spreadsheet format. In addition, speech recognition score (SRS) was obtained for words for all the three hearing aids. The hearing aids were ranked based on the aided SRS. She reported that SII was highest for the hearing aid that was ranked as the best based on the SRS. Hence, it was concluded that SII could be used to select the appropriate linear hearing aids. The advantage of using SII for selection is that, the SII was able to differentiate the hearing aids better even when two of the three hearing aids had similar SRS.

Stelmachowicz et al. (1995) compared the AAI between linear and compression circuits in three adult individuals with moderate sensorineural hearing loss. The settings used for compression system were approximately a release time of 100 ms and a compression ratio of 2:1. They presented eight non-sense syllables at presentation levels of 50, 65, and 80 dB SPLs, and traced syllable recognition scores. They measured compression ratio (MCR), acoustically, for the non-sense syllable at 65 dB SPL, and calculated the AAI at 50, 65, and 80 dB SPL levels of presentation.

They found that AAI was able to reflect the difference in the processing between linear and compression hearing aids. However, the number of participants in their study was less, which limits the generalization of the findings.

Souza and Turner (1999) also compared the relationship between the audibility (using AAI) and intelligibility in compression versus linear amplification in a two- channel hearing aid. Similar to the findings reported by Stemachowicz et al. (1995), they had also used fixed compression parameters in the compression system. They used compression ratios of 2:1 and 5:1 in the low frequency channel and in the high frequency channel, respectively; and a fixed attack and release times of 8 ms and 15 ms, respectively. They also assessed non-sense syllable recognition in 16 individuals with mild to severe degree of hearing loss at low-, mid- and high-presentation levels. They measured the MCR at 65 dB SPL. The AAI was computed using the MCR and SFAT. They reported that at low- and mid- levels of presentation, the compression circuit resulted in better AAI and SRS, whereas at higher level of presentation, the performance was similar between both the types of amplification. Another important finding was that the improvement in audibility, as reflected in AAI, resulted in improvement in the speech recognition. The results of this study indicate that AAI could be used for selection of the compression circuit over linear hearing aid.

Though the AAI has been found to be useful for selection of compression hearing aids, studies reported in literature have used a single compression setting. It is a well known fact that there is an effect of compression ratio (Dillon, 2001; Stone, Moore, Alcantara, & Glasberg, 1999, among others) and TC (Hansen, 2002; Killion, 1996; Neuman et al., 2005; Plomp, 1988; Olsen, Olofssen, & Hagerman, 2004, among others) on speech acoustics and thus on speech perception. Most importantly, there also exists an interaction among the compression parameters (Hansen, 2002; Henning & Bentler, 2008). Hence, it is very essential that a range of compression ratio and time constants be studied for a complete understanding of the effect of compression parameters. There are, however, no reports available comparing a range of compression ratio and time constants, and studying the influence of these on AAI.

Apart from the selection of hearing aids, studies have also evaluated the possibility of predicting speech recognition from AAI (Dirks, Bell, Rossman, & Kincaid, 1986; Dubno, Dirks, & Schaefer, 1989; Manjula, 2007; Sherbecoe & Studebaker, 2003; Stemachowicz et al., 2005). Sherbecoe and Studebaker (2003) assessed the validity of audibility index functions to see how well it predicted speech intelligibility. They had taken a group of individuals with normal hearing and a group of individuals with hearing impairment. They found that though the difference between the measured and the predicted SRS in individuals with hearing impairment was similar to that obtained in the group of individuals with normal hearing, the variability in the group with hearing impairment was much larger.

Similar results have been reported among individuals with hearing loss fitted with hearing aids (Dirks et al., 1986; Dubno et al., 1989; Manjula, 2007; Stemachowicz et al., 2005). The studies report that SII / AAI could be used to predict SRS reliably in individuals with mild to moderately-severe hearing loss. All these above studies have used SFAT for computing SII / AAI, and SFAT have traditionally been used for the calculation of the SII / AAI (Dirks et al., 1986; Dubno et al., 1989; Manjula, 2007; Stemachowicz et al., 2005).

Dillon (1993) applied SII to predict SRS from SII that was computed using *insertion gain measures* on eight older adults with mild to moderate degree of hearing loss. The listeners wore their own linear behind the ear hearing aids. The study involved measurement of SFAT and real ear insertion gain in the ear canal of the participants along with speech perception with different test material, at a presentation level of 70 dB HL. In this study, the SII was computed using real ear insetion gain measure as well as SFAT. The results revealed that the ability to predict speech recognition scores from SII computed by using insertion gain measurements was similar to that using SFAT.

The above studies on prediction of SRS from SII or AAI, computed using SFAT or real ear insertion gain, were carried out using hearing aids either with linear circuit and/or with compression circuit. These studies were done with a single compression settings, mostly low compression ratio and short time constants. Hence, it would be interesting and useful to investigate if the SRS obtained with different compression ratios and time constants could also be predicted using the AAI.

In addition, as mentioned earlier, the prediction of SRS from AAI was good for lesser degrees of hearing loss, whereas, the prediction of SRS from AAI has been reported to be less accurate in the severe degree of hearing loss (Dubno et al., 1989; Manjula, 2007) and in steeply sloping hearing loss (Manjula, 2007; Rankovic, 1991; Skinner, 1980). This leads us to infer that audibility is not the single factor that determines speech intelligibility, and that the results pertaining to individuals with lesser degree of hearing loss could not be generalized to those pertaining to listeners with severe hearing loss (Schwartz, Lyregaard, & Lundh, 1988; Souza & Bishop, 1999; Van Tasell, 1993). In order to improve the prediction of SRS in individuals with severe hearing loss, addition of correction factors such as hearing loss desensitization (HLD) and speech level distortion (SLD) and has been found to be useful (Ching, Dillon, & Byrne, 1998; Ching, Dillon, Katsch, & Byrne, 2001; Dugal, Braida, & Durlach, 1980; Magnusson, 1995; Sherbeccoe & Studebaker, 2003; Studebaker, Sherbeccoe, McDaniel, & Gray, 1997). The HLD accounts for reduction in speech intelligibility due to reduced frequency resolution with higher degree of hearing loss (Ching et al., 1998).The SLD accounts for distortion of speech signal associated with higher presentation levels. This has been found to affect speech intelligibility even in individuals with normal hearing.

From the findings reported in literature, it is clear that there are a few reports available on SII / AAI on its use in selecting appropriate hearing aids and in predicting SRS. These reports have used a single compression setting that varies across studies. It is known that the CR and TC affect the speech perception in a huge way. However, there is a dearth of research assessing the possible use of AAI in selection of appropriate compression ratio and time constants; and the prediction of SRS with different compression ratio and time constants.

In the present study, the effect of different compression ratio and time constants on AAI and SRS were evaluated in order to choose the appropriate setting for individuals with mild to moderately-severe hearing loss and severe hearing loss. In addition, the relation or regression equation between SRS and AAI was derived to predict SRS from AAI. The need for including SLD and HLD correction factors in the regression equation was also assessed.

1.1. Need for the study

The use of AAI in selection of linear hearing aids and in prediction of SRS is well documented in the literature. However, selection of different compression parameters and prediction of SRS using different combination of the compression parameters in a hearing aid is not well established. In addition, research on the ability of AAI to predict speech recognition scores in compression hearing aids is sparse.

1.1.1. Need for studying the effect of compression ratio and time constants on AAI and SRS. The literature shows that the studies comparing linear with compression amplification have a single constant compression parameter. Though, the effect of compression on speech acoustics and perception is well known, there is no standard method to prescribe the compression ratio and time constants ratio (Dillon, 2001; Stone et al., 1999, among others) and time constants (Hansen, 2002; Killion, 1996; Neuman et al., 2005; Plomp, 1988; Olsen et al., 2004, among others). A measure such as AAI could be a useful way for selection of compression parameters, if found to be useful. However, with the available literature, it is not clear whether AAI can successfully reflect the influence of different compression ratios and time constants. Hence, there is a need to obtain AAI and SRS for different compression ratio and time constants, and assess the effect of different compression parameters on AAI and SRS.

1.1.2. Need for prediction of SRS using AAI. As mentioned earlier, the AAI has not only been used for selection of amplification strategies, but also for prediction of SRS. There are several investigators who have investigated the utility of SII / AAI in order to predict speech recognition from audibility, in linear hearing aids or comparing linear and compression hearing aids using AAI (Dirks et al., 1989; Dubno et al., 1989; Manjula, 2007; Rankovic, 1991; Skinner, 1980; Stemachowicz et al., 2005; Souza & Turner, 1999**;** Souza & Bishop, 1999). Most of these studies report a positive relationship between the two in individuals with lesser degree of hearing loss, i.e., increase in speech recognition ability was often associated with an increase in the amount of audibility; and thereby the AAI (Souza & Bishop, 1999; Souza & Turner, 1999). It was mentioned earlier that studying a range of compression parameters is very much essential. None of the earlier studies included different compression ratios and time constants for evaluating the validity of AAI in predicting SRS.

Further, if AAI is found to be able to reliably predict SRS for different compression ratios and time constants, it could be a very useful tool in the Indian context. India is a multi-lingual country and several languages are spoken in different parts of the country. In addition, there are several dialectical variations of each language. This mandates the need for a hearing aid verification tool that is independent of the speech material in the native language. Hence, there is a need to systematically evaluate the ability of AAI to predict SRS.

1.1.3. Need for studying predictions using AAI across different degrees of hearing loss. The compression settings that are found to be beneficial for a person with mild to moderate degree of hearing loss may not be beneficial for a person with severe hearing loss (Schwartz et al., 1988; Souza & Bishop, 1999; Van Tasell, 1993). The individuals with severe hearing impairment have broader auditory filters and hence, have poor spectral resolution (Rosen, 1989; Van Tasell, Soli, Kirby, & Widin, 1987; Moore, 1996). Hence, these individuals have to depend primarily on amplitude envelope cues for speech perception (Moore, 1996). The compressor in hearing aids alters the amplitude envelope. This has been found to negatively influence the perception in individuals with severe hearing loss (Souza & Bishop, 1999). The prediction of SRS from SII / AAI has been found to be less accurate for individuals with severe degree of hearing loss (Ching et al., 1998; Dubno et al., 1989; Pavlovic, 1984). Hence, while studying the effect of compression it is inappropriate to combine the data from those having mild to moderate with those having severe hearing loss. There is a need to study the two groups of individuals separately, one with lesser degree of hearing loss and the other with severe degree of hearing loss. Hence, in the present study, the effect of interaction of the compression parameters is being analyzed separately in persons with mild to moderate and severe hearing loss.

1.1.4. Need for SLD and HLD correction. Several studies have shown that SII or any variations of SII resulted in poor prediction of speech intelligibility in the severe degree of hearing loss (Dubno et al., 1989; Manjula, 2007) and in steeply sloping hearing loss (Manjula, 2007; Rankovic, 1991; Skinner, 1980). The inference was that factors other than the audibility contribute to speech recognition. In order to improve the predictive ability, Ching et al. (2001) and others (Ching et al., 1998; Dugal et al., 1980; Magnusson, 1995; Manjula, 2007; Sherbeccoe & Studebaker, 2003; Studebaker et al., 1997) have recommended applying correction factors, such as SLD and HLD, to SII /AAI. Inclusion of both of the factors, SLD and HLD, has been reported to significantly improve the prediction ability of AI or SII or AAI in individuals with severe degree of hearing loss (Ching et al., 1998; Ching et al., 2001; Dugal et al., 1980; Magnusson, 1995; Sherbeccoe & Studebaker, 2003; Studebaker et al., 1997). Since, in the present study, listeners with severe hearing loss were also included as participants, there is a need to correct the AAI for SLD and HLD factors, and study the prediction of SRS from AAI.

1.1.5. Need for studying the use of real ear aided response in calculating AAI.

Earlier attempts were made to relate the subjective measure (i.e., speech tests) and insertion gain measures with the help of SII. Dillon (1993) used SII to predict speech perception using sound field thresholds and real ear insertion gain. The results revealed that the SII computed using real ear insertion gain could predict speech scores. This study involved only linear hearing aid in listeners with mild to moderate hearing loss. Surprisingly, this topic has been least researched since then and hence, there is a dearth of reports pertaining to the use of real ear insertion gain in computation of SII.

From the literature, it is clear that SFATs have been used traditionally for the calculation of the SII / AAI. The insertion gain measure, though gained popularity later, has been a useful addition to complement the sound field measurements. It gained popularity because of its objectivity and simplicity, and to overcome the many disadvantages of sound field measurements. The major disadvantages of SFAT include the influence of factors such as noise, standing waves, head and body movement, and non-linear processing in hearing aids (Kuk, Keenan, Lau, & Ludvigsen, 2004).

In addition, the SFAT reflects the behavior of a hearing aid for a soft signal only (Kuk, et al., 2004). The main characteristics of a non-linear hearing aid is the differential gain as the input level changes (Jenstad et al., 2000; Moore, 2008). Whereas, the insertion gain measurement could be done across different input levels, and hence, a better option to predict the performance of a non-linear hearing aid.

None of the studies have evaluated this aspect. Hence, there is a need for a systematic evaluation of the use of AAI calculated using real ear insertion response or real ear aided response in prediction of SRS. In the present study, real ear aided response (REAR, which is the absolute SPL across different frequencies measured in the ear canal) has been used to obtain AAI as it gives the absolute SPL in the ear canal and can be directly compared with the LTASS for audibility calculations of AAI.

The AAI computed with REAR has been used only in prediction of SRS and not in optimization of compression parameters as the use of REAR is well established in comparing different signal processing algorithms (Baumfield & Dillon, 2001; Jespersen & Moller, 2013).

1.2. Aims of the study

The present study aimed at investigating the utility of AAI and SRS in optimizing the compression parameters in a hearing aid, and in predicting the SRS from AAI obtained using SFAT and REAR, in individuals with mild to moderately-severe hearing loss and severe hearing loss.

1.3. Objectives of the study

There were four main objectives. These specific objectives were-

1. To compute AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ using SFAT and REAR in the following compression conditions for stimuli presented at 55, 65, and 85 dB SPL, in two groups of participants (i.e., participants with mild to moderately-severe as Group I and those with severe degree of hearing loss as Group II).

    a. For a compression ratio of 2:1

            i. With short time constants
            ii. With long time constants
        b. For a compression ratio of 3:1
            i. With short time constants
            ii. With long time constants

2. To investigate the combination of compression parameters that results in best AAI computed with SFAT and SRS, in both the groups at three different input levels. This was done by assessing the effect of compression ratio and time constants on AAI and SRS.

3. To derive a regression equation for predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed using SFAT and REAR, in the above compression conditions at three presentation levels, in both the groups.

4. To verify the equation derived for prediction of SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed using SFAT and REAR, on a different group of participants.

1.4. Hypotheses

1. There is no effect of compression ratio and time constants on AAI and SRS-
    a) in individuals with mild to moderately-severe hearing loss, and
    b) in individuals with severe hearing loss.

2. The AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed using SFAT are not significant predictors of speech recognition scores for different compression settings -

    a) in individuals with mild to moderately-severe hearing loss, and
    b) in individuals with severe hearing loss.

3. The AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed using REAR are not significant predictors of speech recognition scores for different compression settings -

    a) in individuals with mild to moderately-severe hearing loss, and
    b) in individuals with severe hearing loss.

CHAPTER 2

REVIEW OF LITERATURE

The most common complaint in individuals with hearing loss is reduced ability to hear. An individual with hearing loss will have problem in hearing soft and average level sounds. However, he or she will be able to hear the loud sounds nearly as well as a person with normal hearing.

In addition to the reduced ability to hear, intolerance to loud sounds is also observed in individuals with sensorineural hearing impairment. This phenomenon, i.e., recruitment or softness imperception, can be overcome to some extent by use of non-linear hearing aids with compressor circuits (Dillon, 2001).

During the process of hearing aid fitting, verification of non-linear hearing aids can be done using sound field measurements and insertion gain measurements. The latter being a more appropriate measure for non-linear hearing aids, as it measures performance of a hearing aid across a large range of input levels (Fabry, 2003). Nevertheless, additional information provided by the subjective measures cannot be underestimated.

Hence, both functional gain and real ear insertion gain measures have been included in the protocol for hearing aid verification. Apart from these commonly used measures, another measure that has been researched widely is the speech intelligibility index (SII). The SII provides a relationship between audibility and speech recognition. It ranges from '0' to '1'; '0' represents no audibility and '1' represents 100% audibility. The major application of SII lies in hearing aid selection and prediction of the SRS (Mueller, 1992; Pavlovic, 1988; Rankovic, 1991; Studebaker & Sherbecoe, 1993).

The current study evaluates the use of aided audibility index (AAI), a variation of SII, in selection of a digital amplitude compression hearing aid. Hence, the following review of literature concentrates on the working of compression system, the outcome from compression system, the SII / AAI, parameters used for its derivation and for improving the predictive ability of SII, selection of compression parameters in hearing aids using AAI, and comparison of sound field subjective measurement and insertion gain measurements.

2.1 Amplitude compression in hearing aids

The major role of the amplitude compression in hearing aids is to squeeze the entire intensity range of the signal into the residual dynamic range of persons with hearing impairment. There are several ways to achieve this by varying the compression parameters. If the input signals are compressed more slowly by having lower compression threshold (CT) and compression ratio (CR), it is termed as Wide Dynamic Range Compression (WDRC). If all high input levels are squashed into an extremely small range of inputs, it is referred to as high level compression (Dillon, 2001).

The WDRC is associated with lower compression threshold (55 dB SPL or below) and lower CR (less than 5:1) (Kuk, 1996; Venema, 2000). The hearing aid with WDRC is most often in compression as the CTs are lower. That is, the device is in compression for a larger range input levels, i.e., from soft speech to very loud speech.

There are also some major drawbacks of WDRC. The hearing aids with WDRC increase the gain for low level inputs, thus liable for the occurrence of feedback. This may also increase the likelihood of internal noise in the hearing aid. In addition, placing the CT at a lower level may also result in pumping of background noise (Dillon, 2001). For an individual with cochlear pathology, the use of WDRC results in comfortable listening over a large range of input signals, without the need to change the volume control.

Compression in hearing aids can be included either in single channel, two channel or multichannel compression hearing aids. The findings of the studies in literature reveal that the multichannel compression boosted the speech intelligibility when compared to single channel compression (Woods, van Tasell, Ricket, & Trine, 2006). This is because, the compression parameters can be set differently at different channels depending on the thresholds at different frequency regions leading to better audibility across different bands of speech. According to Dillon (2001), multichannel compression decreases some of the essential differences between different phonemes. The compressors give less amplification to strong signals. They tend to lessen the height of spectral peaks and elevate the floor of spectral valleys and hence, flattening the spectrum. Spectral flattening makes it harder for the user of the hearing aid to identify the place of articulation of consonant and hence offsets the positive effect of increased audibility (De Gennaro, Braida, & Durlach, 1986; Lindholm, Dorman, Taylor, & Hannley, 1988; Lippman, Braida, & Durlach, 1986).

Considering these differing effects of multichannel compression, it is not surprising that there are equivocal findings reported in literature. Some studies have revealed that multichannel compression are better than single channel compression

(Kiessling & Steffens, 1991; Moore & Glasberg, 1986; Moore & Glasberg, 1988) and some have failed to show any advantage for multichannel compression (Moore et al., 1999; Walker, Byrne, & Dillon, 1984). Studies have shown no detrimental effects with as many as four to eight channels of WDRC (Keidser & Grant, 2001; Moore et al., 1999). In the opinion of Keidser and Grant (2001), hearing aids with two channels have been found to be effective for a flat hearing loss.

The manipulation of other compression parameters such as CT, CR and time constants (TC) have been reported to bring about different changes in the input signal. There are very few studies comparing the effects of different CT on speech perception, possibly because it is difficult to separate the effects of CT from those of other parameters, such as CR, number of channels, and attack and release times (Henning & Bentler, 2008). The current review is concentrated on the dynamic parameters of compression, that is, TC and CR.

2.1.1. Dynamic parameters of compression. The main aim of a compression in hearing aids is to provide audible and comfortable speech over the wide range of input levels; this range extends from around 50 dB SPL to over 90 dB SPL (Pearsons, Bennet, & Fidell, 1977). Hearing aids use compression that has dynamic aspects such as attack and release times. Different attack and release times are used to categorize different types of dynamic compression. Different methods of providing attack / release times also separate one type of dynamic compression from another (Venema, 1999).

It has been reported that the goal of audibility and comfort can be achieved in two quite distinct ways. They are a) fast acting compression, sometimes called syllabic compression or dynamic compression (Hohmann & Kollmeier, 1995) and b) slow acting compression acting on the whole speech signal (Moore, Glasberg, & Stone, 1991).

a) Syllabic Compression / Fast Acting Compression.

Fast acting compression amplifiers are those with TC sufficiently short that the gain of the amplifier changes significantly during a syllable or word (Walker et al., 1984). The average length of a syllable is usually between 200 to 300 ms. The attack/release time in fast acting compression systems are lesser than the length of a speech syllable (Hickson, 1993). This results in lesser intensity variation within the on-going speech syllable. Hence, fast acting compression hearing aids have short attack and release times. Typically, the attack time is between 1 to 10 ms and the release time is between 10 to 150 ms (Dillon, 2001). Further, the gain across frequencies also varies from time to time depending on the short-term spectrum of the speech (Moore et al., 1999).

Moore and colleagues reported that fast acting compression, compared to linear amplification, provided small but significant benefits in individuals with hearing impairment particularly when listening to speech in a noisy background that contained temporal and spectral dips (Moore et al., 1999). The fast acting compression was able to improve the audibility of speech in spectral and temporal dips in the noise, but it does not restore performance to normal.

The syllabic compression compresses the peak amplitude of speech and makes the waveforms of ongoing speech more uniform, noise can easily fill in the small gaps in between the speech segments (Johnson, 1998). In noisy situations, the hearing aid may amplify the noise that is situated between peaks of speech. According to Killion (1996), fast attack/release time of 50 ms can distort the waveform of speech and, thus compromises speech intelligibility. Kuk (1999) suggested that use of fast AT (< 10 ms) and short RT (< 100 ms) will compromise the intensity differences between the various phonetic elements of speech. Specifically, in the time waveform of speech, the differences between the “peaks” or loud elements and “valleys” or soft elements are compromised or lessened by fast attack / release time. Such a reduction, in turn, can distort the spectral content of speech cues.

Several studies have evaluated the effect of release time on speech intelligibility and quality. Neuman et al. (1995) varied release times (60, 200 & 1000 ms) and studied the effect of RT on quality for different CRs. They used a round-robin tournament to select a hearing aid having better sound quality in the presence of different types of noise. Clients showed preference for longer release time for higher noise levels. Further, the preference of the subjects depended on the type of noise.

Hansen (2002) measured speech identification and quality of compression TC (RT of 40 ms, 400 ms and 4 s) in a simulated non-linear 15 channel hearing aid. They found that the listeners preferred the release time of 4s over the shorter release times of 40 ms and 400 ms. Further, there was an interaction between RT and CT. When the RT was short, a lower CT (20 dB SPL) was preferred.

Similar results were found by Olsen et al. (2004). They studied the performance with linear and fast compression systems in individuals with normal hearing sensitivity and in individuals with hearing impairment. The results showed that performance with linear system was better than with fast acting compression system. However, listeners with normal hearing showed good benefit from compression system. Similar results were reported by Plomp (1988). He reasoned that the negative influence of fast acting compression could be because of the reduction of the temporal and the spectral contrasts in the speech signal. Other researchers too have pointed out that the distortion of temporal cues could be the reason for poor performance with compression (Boothroyd et al., 1988; Plomp, 1988; Souza & Turner, 1998).

A potential problem is that fast compression alters the intensity relationships between different phonemes and syllables. However, if the hearing aid wearer uses the relative intensities of sounds as a cue for identification, altering relative intensities may decrease the intelligibility of some speech sounds, even if it increases their audibility (Plomp, 1994).

Another potential problem is the effect compression has on brief weak sounds that follow closely after sustained intense sounds. The weak sounds followed by an intense sound will be reduced in intensity if the release time is longer. Release times of 50 ms or less may be sufficiently short to eliminate this problem (Dillon, 2001).

b) Dual compressors / automatic volume control.

A type of compression called Automatic Volume Control (AVC) is used in broadcast audiovisual equipment. A compression system can enhance the audibility of either the long-term and/or short-term speech levels depending on the TC. The AVC is slow acting, which accounts for the overall level of speech and thus enhances the audibility of the long-term speech levels. The AVC is known to have relatively long attack and long release times, and it contributes to the time lag or delay in loudness changes in the announcers' voice relative to the sudden-onset cheers of the audience. Its release times are usually more than 150 ms and may extend to several seconds (Hickson, 1994).

Neuman et al. (1995) evaluated the effect of release time in compression hearing aids. They found that, listeners preferred the longer release times of 200 ms and 1000 ms, for the higher level noises such as apartment noise, cafeteria noise. In spite of this, the slow-acting compressor is at disadvantage when the input level varies suddenly. Suppose a person, for some time, has been listening to a softly spoken person in a quiet place, the hearing aid will react by turning up the gain appropriately. If a loud noise then occurs, or a loud talker joins the conversation, the new sound will be amplified with the high gain that was appropriate to the weaker talker. Thus, the output will thus be excessive and must be decreased with an appropriate limiter of some type, preferably a compression limiter. Sudden increases in level are very common, they will probably occur every time the aid wearer talks, because his or her mouth is probably closer to the hearing aid than is anybody else’s (Dillon, 2001). If everyone at a gathering suddenly stops talking to hear what one person is saying, the wearer of an automatic volume control hearing aid may miss the important announcement if the hearing aid still has the gain appropriate to the higher input level that was present a moment before. This problem would reduce if a release time that is shorter than the brief pauses between the gaps is used.

The system developed by Moore and Glasberg (1988) makes use of two control voltages with different TC. This system is called dual compression system. The system has two release times. The slower system helps to balance the changes in the overall level of the speech from one situation to another by slowly changing its gain and the faster system protects the listener from sudden intense transient sounds without affecting the long-term gain. This is achieved by two control voltages to determine the gain. One changes slowly as the listening situation changes. Normally, this determines the operation of the system. It has an attack time of roughly a few hundred milliseconds and a recovery time of a few several seconds. The other release time comes into operation when there is sudden increase in sound level, but its action ceases quickly at the end of the transient. The release time of such systems is usually within 100 ms.

Stone et al. (1999) implemented four different compression algorithms in wearable digital hearing aids. They are as follows: (1) slow acting dual compression system with CT of 63 dB SPL and CR of 3:1; (2) dual compression system with CT of 55 dB SPL and CR of 3:1; (3) fast acting full dynamic range compression in four channels; and (4) a combination of (2) and (3) above, where each applied less compression than when used alone. Speech identification testing was done in all the conditions at different input levels, and they found good results with all the systems. However, subjective preference indicated that there was slight preference for dual system with a CR of 3:1. Moore et al. (1991) have also found that in the absence of background sound or continuous speech shaped noise as a background, the dual front compression system gives significantly better performance.

2.1.2 Compression Ratio (CR). The CR is a static compression parameter. The CR has been found to have a major effect on the output of a hearing aid. In a WDRC, the CR is reported to range from 1.5:1 to 3:1. A high CR has been found to have a negative effect on the acoustics of speech. Hence, compression amplification is expected to give a good quality output.

It has also been reported that the CR has been found to be influenced by the type and duration of the signal. The term effective compression is used to explain this. For time varying signals such as speech, the effective compression ratio (ECR) is said to be lesser than that for the tonal signals (Dillon, 2001). Dillon has reported that the ECR also depends on the TC.

Several investigators have measured the ECR for various speech stimuli. Stelmachowicz et al. (1995) studied the acoustic effects of WDRC system on eight CV and VC non-sense syllables. They used a RT of approximately 100 ms and the static or nominal compression ratio i.e., the CR that was set, was 2:1. However, the CR that they found in the output, i.e., the effective compression ratio (ECR) also termed as measured compression ratio (MCR) was just 1.3:1.

Souza and Turner (1999) found a lesser MCR for speech stimuli. They studied the usefulness of compression in a two channel WDRC system, with the nominal compression ratio of 2:1 in the low frequency channel and a nominal compression ratio of 5:1 in the high frequency channel. They had used a fixed attack and release times of 8 ms and 15 ms, respectively. They reported that, for speech, the MCR for the low frequency channel was 1.2 - 1.3, and for high frequency channel was 1.7 - 2.0.

Henning and Bentler (2008) assessed the independent and interactive effects of CR, number of compression channels and RT on the dynamic range of continuous speech, and hence, the MCR. They used a digital programmable WDRC system. The dynamic range and ECR were measured for different combinations of RTs (32, 128, and 1024 ms), CRs (1:1, 2:1, and 4:1), and number of compression channels (1, 2, and 4 channels). They found that the dynamic range of speech reduced as the CR and number of channels increased, and as the release time decreased. In all the tested conditions, the MCR for speech was less than the nominal compression ratio. The MCR which describes the amount of compression for speech can be used in the calculation of the aided audibility index (AAI). The details about AAI are given later in this chapter.

2.2. Articulation Index

The Articulation Index (AI) was constructed, at Bell laboratories, based on the model of the articulation theory. The assumption of the model is that the speech intelligibility of any communication device could be determined using audibility information at different speech frequency bands. Hence, AI was basically developed to compute speech intelligibility using frequency weighted audibility levels through telecommunication devices (French & Steinberg, 1947).

Kryter (1962) defined the Articulation Index as "a weighted fraction representing, for a given speech channel and noise condition, the effective proportion of the normal speech signal which is available to a listener for conveying speech intelligibility". The AI ranges from 0.0 to 1.0. An AI of ‘0.0’ represents zero percent audibility and an AI value of ‘1.0’ represents 100 percent audibility of speech signal.

The first researchers to describe a method for calculation of AI were French and Steinberg (1947). The articulation index given by them was based on the concept that the different bands of speech frequencies contribute to the total index. The contribution of each band is independent of each other. Hence, the AI can be calculated by summing up the contribution provided by these different speech bands. The AI can be computed by multiplying band or frequency importance (I) and audibility (A) at each frequency band (i). The basic equation for the Articulation Index is as follows:

$$AI = \Sigma\, I_i A_i$$

In the above equation, the frequency-importance or band-important function (I_i) represents the amount of contribution of different frequency bands to speech intelligibility. The variable A_i, or audibility function, which ranges from 0 to 30 dB, is the amount of speech energy that is above the listener's threshold and any competing noise in a given frequency band.

The AI is calculated by multiplying the summed up audibility function at each band with band importance function (Amlani, Punch, & Ching, 2002). The implications of AI have been extended to clinical audiology to predict speech intelligibility in the unaided and aided listening situations using unaided and aided thresholds respectively. Since its origin, AI is being modified by several researchers (Humes, 1991; Kryter, 1962; Lundeen, 1996; Pavlovic, 1988; Pavlovic, 1991; Mueller & Killion, 1990) mainly, to simplify its method of calculation and to improve the accuracy of prediction of speech perception. The term AI was changed to Speech Intelligibility Index in ANSI S3.5-1997. The ANSI S3.5-1997 provides standards for revised calculation method of AI. Though there are differences among these different methods, the key factors involved in derivation of AI remain the same. These key factors include frequency importance functions, audibility functions and correction factors.

2.2.1 Frequency importance functions. For understanding speech, **c**ertain frequencies are more important than the other frequencies. This is the reason the frequencies 500 Hz, 1 kHz, 2 kHz and 4 kHz are given more weightage than the other frequencies. This reveals that certain frequencies contribute more to speech intelligibility than the other frequencies. A function that indicates the relative importance of different bands of speech spectrum for speech intelligibility is frequency importance function. These functions were developed to enable calculation of SII.

Initial frequency importance functions were derived using CV, VC, and CVC non-sense syllables (Studebaker & Sherbecoe, 1993). One of the first functions was non-sense syllable function developed by French and Steinberg (1947). They divided the speech spectrum into 20 frequency bands with equal importance. Following this, several importance functions have been developed (Black, 1959; Fletcher & Galt, 1950; Kryter, 1962). Fletcher and Galt (1950) published importance functions for different articulation tests. They divided the frequencies between 100 to 10,000 Hz into 20 bands. Black (1959) developed importance function for meaningful material.

Kryter (1962) also proposed a new method for calculation of AI. He proposed that the 20-band method, given by French and Steinberg (1947), and one-third octave band can be used for calculation of AI. In the one-third octave band method, the frequency important functions were worked out for one-third octave bands with equal importance by varying the weightages of each band.

Depending on the type of speech material, the cross-over frequency of frequency important functions has been reported to vary (Studebaker & Sherbecoe, 1993). Originally, the AI was calculated based on nonsense syllables (French & Steinberg, 1947). Following this, several other speech material have been used for the calculation. As mentioned earlier, Black (1959) developed an importance function for meaningful material. Studebaker and Sherbecoe in 1991 derived frequency importance functions for CID W-22 word lists. In 1993, they used AI for predicting speech recognition for CID W-22 word lists and they found that the frequency importance function for W-22 word lists can be used in the applications of AI.

Studebaker, Sherbecoe, and Gilmore (1993) used the derived frequency importance function for NU-6 word test. They used the procedure described by Studebaker and Sherbecoe (1991) for the derivation. They concluded that speech recognition scores can be predicted for NU-6 word test using the frequency importance function for NU-6 word test.

It has been reported that depending on the speech material, the peak of the importance function changes. Pavlovic (1987) compared the peak frequency of the frequency importance function of non-sense syllable of French and Steinberg (1947) with that of Studebaker et al. (1987) for running speech. The results revealed that the frequency importance function had a peak at 2500 Hz for nonsense syllables and at 450 Hz for running speech**.** Miller and Nicely (1955) studied the effects of filtering on consonant confusion. The errors were predictable in the low-pass filtering condition. Hence, when redundant stimulus is present, the listeners can detect and correct better, in the low-pass filtering conditions when compared to high-pass filtering conditions. More information is transmitted in low-frequency bands relative to higher frequencies when the redundancy is high. Hence, the peak of frequency importance function tends to shift to a lower band for running speech.

In order to isolate the effects of context on frequency importance function, in 1996, Depaolis, Janota, and Frank have computed frequency importance functions for words, sentences and continuous discourse. The recorded material was then low-pass and high-pass filtered at different SNRs. They reported that the frequency importance functions for different material were different in shape. There was a significant difference between words and continuous discourse. That is, the frequency importance function for word was peaky and the frequency importance function tended to flatten as the message redundancy increased. However, the shape of the octave band frequency importance functions was intermediate for the sentences. Hence, they reported that frequency importance functions of the sentences are preferable when making octave band AI calculations.

Nevertheless, the selection of the frequency importance function should depend on the application that it is being chosen for (Pavlovic, 1994). For most of the hearing aid related applications and the prediction of speech recognition scores, frequency importance function for average speech is appropriate (Pavlovic, 1994). Manjula (2007) has used the frequency importance function for average speech for selection of hearing aid and frequency importance function of CID W-22 list for prediction of speech recognition scores of words. It has been reported that when sentences are used for obtaining speech recognition scores, frequency importance function for average speech could be used for selection of hearing aids as well as for prediction of speech (Pavlovic, 1994).

2.2.2 Audibility function. Audibility function is said to be another key parameter in the calculation of AI. Audibility function provides knowledge on the amount of information available in each band that is provided to the listener. Audibility refers to the amount of audible speech in a given frequency band (Amlani et al., 2002).

In order to calculate the audibility function, the audiometric thresholds are first converted from dB HL to RET SPL values. These converted thresholds are compared to spectrum maxima of speech in each band (Amlani et al., 2002). Hence, the audibility function involves hearing thresholds of the listener, Long-Term Average Speech Spectrum (LTASS) and the dynamic range of speech. When the threshold and the speech maxima are at the same level, the energy reaching the listener in that band is zero and hence, that band is inaudible and thus does not contribute to speech intelligibility.

According to Seewald and Ross (1988), the major problem of most children with hearing impairment is that they have trouble hearing. Ching et al. (2001) also reported that the audibility of sounds is critical in the speech perception. However, maximizing audibility does not always maximize speech intelligibility. Ching et al. (1998) studied the relationship between audibility and speech recognition in different degrees of hearing impairment. They found that as hearing thresholds deteriorate, especially at high frequencies, optimal audibility occurs at a relatively lower sensation levels. They also found that increasing the audibility beyond the optimal level does not contribute to speech intelligibility and in some cases it leads to decrement in speech intelligibility.

The LTASS also plays a major role in the calculation of SII. The LTASS has been measured in several languages, for example in English by Dunn and White (1940), Pearson et al. (1977), Byrne and Dillon (1986); in German, Hungarian, Italian, Russian by Tarnoczy (1971). There have been small differences in LTASS among these studies. Byrne et al. (1994) made a comparison of LTASS of 13 languages spoken in different parts of the world. The results revealed that the LTASS was similar among different languages with some differences at few frequencies. They proposed a universal LTASS because of the similarity between LTASS of different languages. They also measured dynamic range of the speech signal and reported that all languages showed a similar dynamic range though there were small differences.

Most of the research studies, using SII, consider 30 dB as the dynamic range of speech (e.g., Boothroyd, 1990, 2000; Moore, 2008; Rankovic, 1997, 1998; Studebaker et al., 1999; Studebaker and Sherbecoe, 2002; Van Tasell, 1993). However, the compression amplification is said to alter the dynamic range of the signal (Rhebergen, Versfeld, & Dreschler, 2009).

2.3. Predicting Speech Intelligibility Using SII

The primary of goal of providing amplification is to provide audibility of different speech sounds. Thus, computing audibility is necessary in order to ensure that ample amount of acoustic cues is available to the person. The SII measure has been useful in quantifying the audibility. Further, knowledge about relationships between hearing thresholds and the speech intelligibility allowed predictions of speech scores using SII (Ching et al. 1998). This has been mainly useful in eliminating speech tests which are generally time consuming. Such prediction of speech intelligibility from audibility eliminates the use of speech material in different languages, in a multi-lingual country like India.

Investigators have shown that there is a positive correlation between the intelligibility scores and the SII (Dubno et al., 1989; Pavlovic, Skinner & Miller, 1983; Studebaker, & Sherbecoe, 1986; Zurek & Delhorne, 1987). This implies that the SII can serve as a base for selecting frequency-gain characteristic of a hearing aid (Dugal et al., 1980; Fletcher, 1953; Pavlovic, 1988; Popelka, 1987). It has also been reported that the SII can stipulate a frequency-gain characteristic that would optimize speech intelligibility scores (Dugal et al., 1980; Pavlovic, 1988).

Humes (1986), Sullivan, Levitt, Hwang, and Hennessey (1988), and Skinner (1988) have used the SII to compare hearing aid prescriptions. The application of SII in selecting linear hearing aids was assessed by Rankovic (1991). Rankovic evaluated 12 subjects with sensorineural hearing loss to examine the application of the SII model to the fitting of a linear hearing aid. The frequency-gain characteristics were as specified by two prescriptive formulae, the NAL (Byrne & Dillon, 1986) and POGO (McCandless & Lyregaard, 1983). Apart from this, optimization of the frequency-gain characteristics to maximize the audibility of the speech spectrum (AIMax) was also done. He evaluated the relationship between percent-correct scores on a non-sense syllable test and SII. His results revealed that SII was an effective choice for comparing different conditions. However, the results were variable for subjects having sloping high-frequency hearing losses as they showed poor performance at the frequency-gain settings which led to maximized audibility of the speech spectrum.

The efficacy of SII in selection of linear hearing aids was also evaluated in a study by Manjula (2007). The study utilized band importance function for CID W-22 words to compute SII for prediction of speech recognition. The study also utilized importance function for average speech for selection of an appropriate hearing aid. Unaided and aided sound field evaluations (threshold and SRS) were done on three groups of participants with different degrees of hearing impairment. Aided evaluations were carried out for three linear hearing aids. The data were utilized to derive an equation that could predict the SRS from SII; and also to test the efficacy of SII in selection of an appropriate hearing aid. It was reported that SII can be successfully used for prediction of SRS and for selection of an appropriate hearing aid.

However, the above results were restricted to lesser degree of hearing loss and for conversational level. This implies that audibility is not the only factor that contributes to intelligibility. For improving the predictive ability of the SII in all the conditions, correction factors, such as speech level distortion (SLD) and hearing loss desensitization (HLD) have been proposed.

2.3.1. Speech level distortion (SLD).

In the past, there have been several attempts to delineate the factors that contributed to speech intelligibility along with audibility, so that, accuracy of prediction using SII could be improved. Hence, several modifications have been incorporated to SII by researchers (Byrne, et al., 1990; Ching et al., 1998; Fletcher & Galt, 1950; Pavlovic et al., 1986; Rankovic, 1991).

The SLD is one of the correction factors in the SII. This correction factor accounts for distortion in the speech signal when presented at a higher presentation level. This might prevent high performance on speech intelligibility measures. Ching et al. (1998) recommended the use of SLD correction factor along with audibility to calculate SII. They gave the following equation to compute SLD.

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

In the above equation, L_i is the SLD correction at a given frequency band, E_i is the measured speech spectrum level and U_i is the standard speech spectrum level. It has been reported that when the measured speech level exceeds 73 dB SPL, there will be decrement in the speech intelligibility (ANSI S3.5,1997).

2.3.2. Hearing loss desensitization (HLD).

Byrne et al. (1990) reported that listeners with hearing impairment preferred lower gain at the frequencies with higher degree of hearing loss. Hence, HLD correction accounts for the reduction in the speech recognition with increase in the hearing loss. There are several equations that have been put forth and modified for HLD correction. Sherbecoe and Studebaker (2003) compared many approaches for calculation of HLD factor. Their study showed that the following equation is effective in calculating HLD correction factor and also is a simple one that could be incorporated in the computer applications.

$$HLD_i = A_i - B_i\,(Hi)$$

In the above Equation, HLD_i is the HLD correction at a given frequency band, Ai is the slope in the ith band, B_i is the intercept and H_i is the hearing threshold at the centre frequency at ith band. The A_i and B_i for each 1/3rd frequency band is given in a table in the article by Sherbecoe and Studebaker (2003). They computed the A_i and B_i based on a series of linear equations using a figure given by Ching et al. (1998). The figure in an article by Ching et al. provided proficiency factors for different degrees of hearing loss based on the individual data obtained in their study.

2.4. Selection of Compression Hearing Aids Using SII

Hearing aids with compression circuitry were discovered to squeeze in the incoming signal into the dynamic range of the person with hearing impairment. When the compression circuitry is active, it alters the dynamic range of the input signal. Hence, the speech dynamic range of the output from these hearing aids is lesser than that of linear hearing aids.

The speech recognition through linear hearing aid is mainly depended on the audibility. This is evident from the studies using SII for prediction of speech recognition scores using hearing thresholds. The SII has also been assessed for its usefulness in the non-linear hearing aids. Stelmachowicz et al. (1994) modified the

SII such that it could be used for compression as well as linear hearing aids. They named it Aided Audibility Index (AAI).

The AAI also ranges from 0.0 to 1.0 that represents the amount of aided speech that is audible to a listener (Dillon, 1993). This is adapted from AI that was originally developed by French and Steinberg (1947). Similar to the original AI, the calculation of AAI incorporates frequency importance functions to provide different weightage to different frequencies depending on their importance for the understanding of speech. The dynamic range of speech is reduced in compression hearing aids due to compression. Hence, the speech dynamic range of 30 dB is not used in the calculation of AAI. Instead, the effective or measured compression ratio (ECR or MCR) is used for calculation of speech dynamic range (Souza & Turner, 1999; Stelmachowicz et al., 1995) in non-linear hearing aids.

The ECR or MCR describes the amount of compression that actually occurs for speech and is used in the calculation of aided audibility index (AAI). The formula used for AAI calculation is given below.

$$\mathrm{AAI}= \left[\Sigma I_i(\mathrm{LTASS}+15\mathrm{MCR}) - \mathrm{Threshold}\right]/(30/\mathrm{MCR})$$

In this formula, I_i represents the band importance values at a specific frequency band; LTASS represents the Long-Term Average Speech Spectrum level; Threshold represents the hearing threshold of the listener; and MCR represents the Measured Compression Ratio. The MCR is the effective ratio measured in all the test conditions and presentation levels.

Stelmachowicz et al. (1994) developed a MCR for the AAI. The MCR is a prediction of the ECR for the short-term dynamic range of speech, given the nominal compression ratio for pure-tone. However, they reported that the relationship between nominal and MCR is not clear. Factors such as the magnitude of the nominal compression ratio, number of bands, TC and compression threshold may affect this relationship. Hence, they recommend computing MCR for a given amplification settings.

There are reports unveiling the predictive ability of AAI. The AAI can predict the speech identification ability with linear and non-linear compression hearing aids. It was accurate for listeners with mild to moderately-severe sensorineural hearing losses (Dillon, 1993; Magnusson et al., 2001; Manjula, 2007; Souza & Turner, 1999).

Souza and Turner (1998) evaluated the predictability of AAI using compression hearing aids and compared it with linear hearing aids. They reported that the AAI overestimates speech recognition for both linearly amplified speech and compressed speech. That is, observed performance was poorer than the predicted performance. Hence, they concluded that audibility is not the sole factor that contributes to speech recognition. There are other factors that influence speech performance.

Souza and Turner (1999) studied the relationship between recognition and audibility and the effectiveness of AAI. They examined participants with mild to severe sensorineural hearing loss with digitally processed linear and compression amplified non-sense syllables. They reported that there was a positive correlation between audibility and speech recognition. The speech recognition score increased as the audibility increased, for both linear and compression amplified speech. For soft and moderate input levels, higher AAI and higher recognition scores were obtained for compression-amplified speech when compared to linear processed speech. There was no difference between the two conditions at higher input levels.

Further, attempts have been made to study the predictive ability of AAI in selection of different compression parameters. Woods et al. (2006) have studied how the speech audibility and the Cambridge method for loudness equalization (CAMEQ) provided by compression, changed with number of channels. They found that one to five channels were sufficient to yield predicted speech performance for individuals with mild to moderate degrees of hearing loss. 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. There is, however, no standard method of specifying the most effective compression parameters such as CR and compression TC for a particular person with hearing impairment (Olsen et al., 2004).

2.5. SII and different degrees of Hearing Loss

The compression settings that are found to be beneficial for a person with mild to moderate degree of hearing loss are not beneficial for a person with severe hearing impairment. In a WDRC hearing aid, Souza and Bishop (1999) attempted to find out if increasing the audibility brought about analogous improvement in speech recognition for listeners with higher degrees of hearing loss. They suggested that listeners with severe loss did not benefit to the same extent as those with mild to moderate loss when the audibility increased, at least for the sentence recognition task. The reason for this could be that the auditory filters are broader in individuals with higher degree of hearing loss . Thus, spectral resolution gets affected (Erber, 1972; Rosen, 1989; Van Tasell et al., 1987). Hence, they tend to depend on the temporal variations in the speech signal for speech perception (Moore, 1996). The amplitude compression may alter the gross time-intensity variations inherent in speech signal. Hence, when amplitude compression is introduced, speech recognition tends to decrease (Souza & Turner, 1998). This offsets the benefits of compression hearing aids in individuals with severe degree of hearing loss (Boothroyd et al., 1988).

This is supported by studies using SII. Prediction of speech intelligibility using SII has been found to be inaccurate for individuals with severe degree of hearing loss, indicating that other factors also play a role for these individuals (Ching et al., 1998; Dubno et al., 1989; Pavlovic, 1984). However, recent technological advancements, with their improved processing schemes, might provide better speech perception even in persons having severe hearing impairment. Hence, it is important to study the effect of interaction of the compression parameters in persons with mild to moderate as well as severe hearing impairment. This would in turn aid in better understanding and selection of compression systems, in the current hearing aids.

2.6. Functional Gain Measurements Vs. Insertion Gain Measurements

For many decades, functional gain measurement, which is the difference between the unaided and aided thresholds in sound field, is in use for verifying the gain of hearing aid. However, there are many factors such as noise, standing waves, head and body movement, and non-linear processing in hearing aids, which should be considered to obtain reliable thresholds (Kuk et al., 2004).

The non-linear hearing aids change their gain characteristics depending upon the type and level of input signal. Hence, SFAT may be more variable for non-linear hearing aids. To minimize this variability, Kuk et al. (2004) suggested certain modifications in the stimulus and the procedure for obtaining SFAT for non-linear hearing aids. They recommended using modulated tones rather than pure tones with duration longer than that of release time and shorter than the time required for the noise reduction and feedback algorithms to get activated. In addition, the duration of the stimuli and the direction of the sound source will also affect the SFAT in case of directional microphones. However, if the digital signal processing algorithms are deactivated, these issues do not hold good. In spite of that, the subjective nature of functional gain measurements may not result in very reliable results at many instants.

The measured SFAT reflect the behaviour of the processing of non-linear hearing aid for soft signal. For higher levels of input, there will be a change in the characteristics. For the calculation of the Aided Audibility Index, aided sound field thresholds have traditionally been used. The Sound Field Aided Thresholds (SFAT) have been found to be reliable if measured controlling the variables that could affect the reliability, such as noise, standing waves, head and body movement (Kuk et al., 2004). Kuk and Ludvigsen (2003) reported by that the aided sound field thresholds provide information for low-level signals. When evaluating the non-linear hearing aids, it is required that the performance is evaluated at different input levels.

The insertion gain measurement using probe tube microphone has received considerable attention over the past decade. According to Mueller, Hawkins, and Northern (1992), insertion gain measurement is an objective measure capable of reflecting the gain/output at different input levels on hearing aids that use different signal processing algorithms. There are several other applications of insertion gain measurements which make it more desirable. These applications include measurement of directional microphone technology (Ricketts, 2001) and measurement of the occlusion effect (Revit, 1992). In insertion gain measurements, the effect of different levels of input signals could be measured, and hence may be a better option to evaluate the performance of a non-linear hearing aid. There have been attempts made to relate the subjective measure (speech tests) with results of insertion gain measurements. The AI has been utilized to assess the link between audibility and speech intelligibility (Dillon, 1993). Dillon has used AI to predict speech intelligibility using sound field thresholds and insertion gain measurements. The speech gain is the difference in level between the aided and unaided performance-intensity functions. The study evaluated participants with mild to moderate hearing impairment using different types of speech material. The results revealed that 'speech gain' can be predicted using insertion gain measurements.

From the above review, it is clear that there are a few reports available on SII / AAI on its use in selecting the appropriate hearing aids and in predicting SRS. These reports on SII / AAI have used a single compression setting that varies across studies. It is known that the CR and TC affect the speech perception in a huge way. However, there is a dearth of research assessing the possible use of AAI in selection of appropriate CR and TC; and the prediction of SRS with different CR and TC.

In the present study, AAI has been used to compare the effect of different CR and TC, along with SRS, to choose the appropriate compression setting for individuals with mild to moderately-severe hearing loss and for those with severe hearing loss, at three different input levels. In addition, the relation or regression equation between SRS and AAI was derived to see if AAI could predict SRS. The possible need of SLD and HLD correction factors was also assessed. Further, AAI computed with the SFAT and REAR (is a part of insertion gain measurement procedure) were used for prediction of SRS.

CHAPTER 3

METHODS

The primary objective of the present study was to evaluate the effect of compression ratio and time constants on aided audibility index (AAI) calculated using sound field aided thresholds and speech recognition scores at 55, 65 and 85 dB SPL presentation levels. The secondary objective was to study the ability of AAI computed with sound field aided thresholds (SFAT), and real ear aided response (REAR) in predicting the speech recognition scores (SRS) by deriving a regression equation. Further, the ability of the regression equation to predict the SRS was verified on separate groups of individuals. The study used experimental within-subjects research design in order to investigate the objectives of the study.

The data collection was carried out in four stages. Stage I involved measurement of REAR, SFAT, and aided SRS in different aided conditions. The aided conditions included hearing aid programmed in different combinations of compression ratio and time constants. Stage II comprised of measurement of the hearing aid output and calculation of measured compression ratio (MCR). In Stage III, derivation of regression equation to predict aided SRS using Aided Audibility Index (AAI) was included. Stage IV involved comparison of the predicted and measured SRS on a separate group of individuals.

3.1.Stage I: Measurement of real ear aided response (REAR), sound field aided thresholds (SFAT), and aided speech recognition scores (SRS)

Participants. Two groups of participants were considered. A total of 60 ears of participants, 30 ears in Group I and 30 ears in Group II, were included. Group I comprised of 30 ears (number of right ears = 14; number of left ears = 16) of 19 participants whose age ranged from 18 to 55 years (mean age = 37.30 years). The hearing loss ranged from mild to moderately-severe sensorineural hearing loss in the test ears. The pure-tone average (PTA) of four frequencies (500 Hz, 1000 Hz, 2000 Hz and 4000 Hz) of the test ears ranged from 34 to 61 dB HL. The test ears with mild, moderate and moderately-severe hearing loss were considered as a single group. This was done as previous research has shown that the use of AAI in predicting speech recognition scores (SRS) has been found to be similar in individuals with mild, moderate, and moderately-severe hearing loss (Manjula, 2007).

Group II comprised of 30 ears (number of right ears = 15; number of left ears = 15) of 21 participants. This group included individuals in the age range from 18 to 56 years (mean age = 38.5 years) who had severe sensorineural hearing loss (the PTA of the test ears ranged from 71 to 88 dB HL). The individuals with severe degree of hearing loss were grouped separately as it has been reported that the compression settings that are found to be beneficial for persons with mild to moderate degree of hearing loss may not be beneficial for persons with severe hearing impairment (Boothroyd et al., 1988; Souza & Bishop, 1999; Souza & Turner, 1998). The participants satisfying the following criteria were included.

Inclusion criteria.

1. The participants had sensorineural hearing impairment of flat configuration in the test ear, with thresholds across frequencies that did not vary more than 20 dB HL from each other (Pittman & Stelmachowicz, 2003)
2. The participants had normal middle ear functioning as determined through immittance evaluation

3. The participants had speech recognition ability in agreement with the degree of hearing loss
4. The participants were native speakers of Kannada, a south Indian Dravidian language
5. The participants had post-lingually acquired hearing loss with adequate speech and language,
6. The participants were naive hearing aid users, and
7. The participants had education of at least 10th standard.

Exclusion criteria. Individuals with a history or complaint of ear discharge, any other outer and/or middle ear pathology, and neurological or cognitive problems were excluded. The mean and standard deviation (SD) of hearing thresholds of test ears in the two groups are given in Figure 3.1. The demographic details of the participants are given in the Table 3.1.

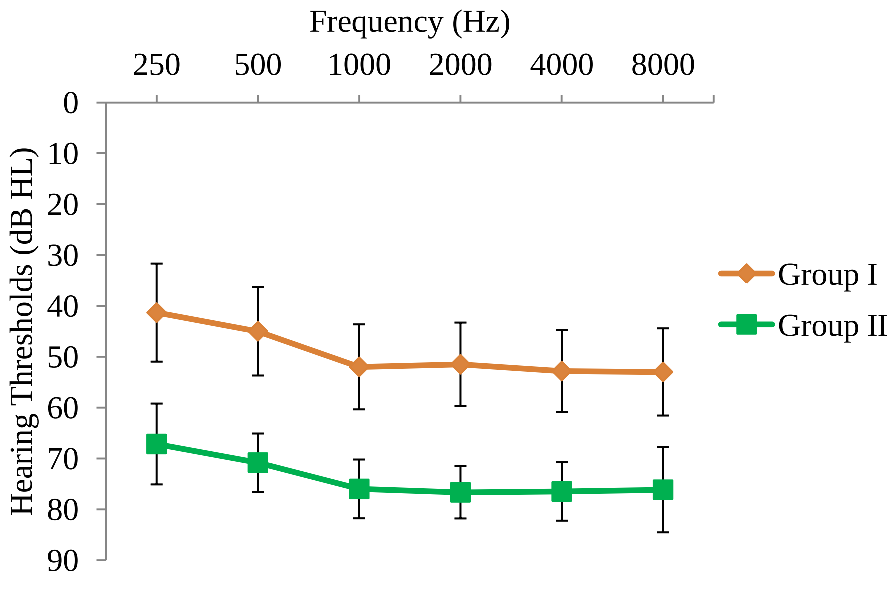


Figure 3.1. Mean and SD of hearing thresholds (dB HL) of the test ears of participants in Groups I and II.

Table 3.1

Demographic details of the participants and PTA of the test ears of participants in Group I and Group II

Sl. No.	Group I				Group II			
	Age (years)	Gender	Ear	PTA* (dB HL)	Age (years)	Gender	Ear	PTA* (dB HL)
1.	22	Female	Right	41.25	23	Male	Right	72.50
2.	22	Female	Left	41.25	23	Male	Left	71.25
3.	38	Male	Right	57.50	22	Male	Right	71.25
4.	38	Male	Left	55.00	43	Male	Right	72.50
5.	48	Female	Right	50.00	43	Male	Left	71.25
6.	33	Male	Right	56.25	42	Male	Right	76.25
7.	33	Male	Left	51.25	42	Male	Left	72.50
8.	43	Female	Right	53.75	54	Male	Right	71.25
9.	43	Female	Left	40.00	48	Female	Left	71.25
10.	55	Male	Left	56.25	43	Female	Right	81.25
11.	55	Female	Right	55.00	56	Male	Right	76.25
12.	55	Female	Left	45.00	24	Male	Left	75.00
13.	25	Male	Right	51.25	30	Male	Left	73.75
14.	25	Male	Left	56.25	45	Male	Left	73.75
15.	24	Male	Right	51.25	46	Female	Right	76.25
16.	24	Male	Left	47.50	26	Male	Right	76.25
17.	18	Female	Right	33.75	26	Male	left	72.50
18.	19	Female	Right	48.75	31	Female	Left	75.00
19.	19	Female	Left	51.25	25	Male	Right	77.50
20.	48	Male	Right	58.75	25	Male	Left	73.75
21.	48	Male	Left	52.50	50	Male	Right	73.75
22.	56	Male	Left	57.50	50	Male	Left	73.75
23.	52	Female	Right	57.50	42	Male	Right	75.00
24.	52	Female	Left	57.50	42	Male	Left	71.25
25.	41	Male	Left	61.25	18	Male	Left	75.00
26.	47	Male	Left	45.00	55	Male	Right	72.50
27.	50	Male	Right	40.00	55	Male	Left	73.75
28.	50	Male	Left	37.50	30	Male	Right	82.50
29.	18	Female	Right	53.75	48	Male	Right	88.75
30.	18	Female	Left	46.25	48	Male	Left	82.50

Note. *: PTA was calculated by averaging the thresholds at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.

The methods of the study were approved by the AIISH ethical committee prior to initiating the study (given in Appendix A). An informed written consent was obtained from each participant before the collection of data.

Test material. Paired-word lists in Kannada developed at the Department of Audiology, AIISH, were used to obtain speech reception thresholds (SRT). For finding out SRS as a part of routine evaluation, phonemically balanced (PB) bi-syllabic word test in Kannada (Yathiraj & Vijayalakshmi, 2005) were used. The test has four phonemically-balanced word lists with 25 words in each list. The sentence test developed by Geetha, Sharath, Manjula, and Pavan (2014) were used to obtain SRS in different aided conditions through sound field. This sentence test has 25 equivalent sentence lists with ten sentences in each list.

Selection of prescriptive formula. National Acoustical Laboratory - Non-linear 1 (NAL-NL1) prescriptive formula, with an acclimatization level of 2, was used for fitting the hearing aid to the participant. Further, optimization of the gain settings was done based on the insertion gain measurement and audibility of Ling's six sound test.

Test Environment. Routine audiological evaluation, programming the hearing aid to the test ear of the participant, as well as evaluating the performance with the hearing aid were carried out in an air-conditioned sound treated single/double room situation.

Instruments. A calibrated two-channel diagnostic audiometer was used for testing. The audiometer had TDH-39 earphones housed in MX-41/AR ear cushions and audiocups; Radioear B71 bone vibrator; and, Martin Audio CI 15 sound field speakers (2 nos., with a power amplifier). The two loud speakers of the audiometer were located in the patient room at a distance of 1 metre at ± 45^{o} Azimuth from the participant. A computer connected to a HiPro was used for programming the hearing aid. This computer had NOAH 3 software and the hearing aid specific software installed. The programming cable was used to connect the hearing aid to the HiPro for programming the hearing aid. Fonix 7000 real ear system was used for the insertion gain measurements.

Hearing aid description. A non-linear, two-channel digital behind-the-ear (BTE) hearing aid with a fitting range from mild to severe hearing loss was used for evaluation. This two-channel hearing aid was selected as the participants had a flat audiogram configuration (Keidser & Grant, 2001). This hearing aid had the option to vary the compression ratio, attack time (AT), and release time (RT). The attack time and release time are the time constants.

The output of the hearing aid at different frequencies was measured on a mannequin (Head torso from GRAS sound and vibration) along with pressure microphone (Type 40AG) and ear simulator (IEC 711). The output from the microphone in the mannequin was connected to sound level meter (Bruel-Kjaer SLM 2270). The stimulus for this was presented from a work station (Lynx AURORA) through a loud speaker (Genelec) placed at 45^{o} Azimuth at a distance of 1 meter from the mannequin.

Procedure for routine hearing evaluation for participant selection. Routine audiological evaluation included pure-tone audiometry, speech audiometry and immittance evaluation. During pure-tone audiometry, the pure-tone thresholds were traced by using the modified Hughson-Westlake procedure (Carhart & Jerger, 1959). This was used for obtaining air-conduction thresholds for frequencies from 250

Hz to 8000 Hz and for obtaining the bone-conduction thresholds from 250 Hz to 4000 Hz. The air-conduction threshold at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz was used to calculate the pure-tone average (PTA). The SRT and SRS for words were also obtained. The SRT of the participants was in agreement with the PTA.

Immittance evaluation was done on all the test ears of the participants in order to ensure normal functioning of the middle ear. Tympanometry and acoustic reflex assessment were carried out using a calibrated middle ear analyzer. Based on the results of the above tests, participants who fulfilled the selection criteria underwent further evaluations for the study.

Programming the hearing aid. The participants fulfilling the stated criteria were included in the study. The pure-tone thresholds, from 250 Hz to 8000 Hz for air-conduction and from 250 Hz to 4000 Hz for bone-conduction, were fed into the NOAH software. The hearing aid was programmed using NAL-NL1 prescriptive formula. An acclimatization level of '2' was selected for programming. The other features of the hearing aid such as the directional microphone and noise reduction algorithm were switched off during the complete evaluation. The hearing aid was programmed with 'first fit'.

The compression threshold was fixed at 55 dB SPL. The compression ratios of 2:1 and 3:1 were chosen as the WDRC hearing aids have lower compression ratio, typically less than 5:1 (Kuk, 1996; Venema, 2000), and a compression ratio of ≤ 3:1 is usually preferred by the listeners (Kuk, 1996; Neuman, Bakke, Hellman, & Levitt, 1994; Souza, 2002). A compression ratio of more than 3:1 has been found to negatively affect the speech intelligibility (Souza, 2002; Verschuure et al., 1996). For the fast compression condition, short time constants, i.e., AT of 2 ms and RT of 40 ms

(Dillon, 2001; Muller, Harris, & Ellison, 2004; Souza, 2002; Verschuure et al., 1996) were used. For the slower compression condition, long time constants, i.e., AT of 20 ms and RT of 640 ms (Muller, Harris, & Ellison, 2004) were used.

Verification of the hearing aid programming was carried out through insertion gain measurements. Changes in the settings of the hearing aid were done till the gain of the hearing aid matched the NAL-NL1 target curve displayed on the real ear measurement system. In addition, audibility and identification of Ling's six sounds, when presented through the audiometer at 40 dB HL, was ensured. This was done to optimize the hearing aid and to ensure audibility of speech frequencies.

The data collection for evaluating the objectives of the study was carried out after optimization of the hearing aid using different aided conditions. The aided conditions include different combinations of compression ratios (2:1 and 3:1) and time constants (short and long) were used at presentation levels of 55, 65 and 85 dB SPL in the current study. They are as given below:

1. For a compression ratio of 2:1
    a. short time constants i.e., AT of 2 ms and RT of 40 ms; and
    b. long time constants i.e., AT of 20 ms and RT of 640 ms.
2. For a compression ratio of 3:1
    a. short time constants i.e., AT of 2 ms and RT of 40 ms; and
    b. long time constants i.e., AT of 20 ms and RT of 640 ms.

The total number of aided test conditions were twelve, i.e., four compression conditions (2S, 2L, 3S and 3L) at three presentation levels. They are represented as: 2S55, 2S65, 2S85, 2L55, 2L65, 2L85, 3S55, 3S65, 3S85, 3L55, 3L65 and 3L85. Here, the first character (i.e., 2 or 3) represented the compression ratio of 2:1 or 3:1.

The second character (i.e., S or L) represented the time constants, short and long. The last two characters (i.e., 55, 65 and 85) represented the presentation levels.

Procedure for measurement of real ear aided response. For the insertion gain measurements, Fonix 7000 real ear system was used. The hearing thresholds of the participants were fed into the Fonix 7000 system. The target gain curves were derived using the NAL-NL1 formula. An otoscopic examination was done to ensure that there was no contraindication i.e., wax / debris or foreign body in the ear canal. The sound field loud speaker of Fonix 7000 was placed 12 inches from the participant at ± 45^o Azimuth, as specified in the user manual of Fonix 7000. The height of the loudspeaker was adjusted to the level of the ear of the participant.

The calibration of the insertion gain measuring instrument was ensured by levelling the system prior to each measurement session. For measurement of real ear unaided and aided response, the probe tube was placed inside the ear canal. The probe tube insertion depth was estimated based on geometrical positioning method (Hawkins & Mueller, 1992). In this method, the length of the probe tube insertion is 5 mm more than the length of the ear canal portion of the ear mould of the participant. Then, Real Ear Unaided Response (REUR) was measured for digi speech at 65 dB SPL. After the measurement of REUR, the test hearing aid was carefully placed in the ear following the instructions provided in the user manual of Fonix 7000. The REAR for digi speech in twelve different aided conditions were obtained using the parameters given in the Table 3.2.

Table 3.2

Protocol for measurement of REAR

Parameters	Settings
Stimulus type	ANSI weighted digi speech
Stimulus level	55, 65, and 85 dB SPL
Reference microphone	On
Prescriptive formula	NAL-NL1
Placement of probe microphone	5 mm more than the length of the ear canal portion of the ear mould
Placement of loud speaker	+ or - 45^o Azimuth, 12 inches

The Fonix 7000 system generated the real ear insertion gain (REIG) curve. The hearing aid gain was programmed till REIG curve closely matched the target gain curve generated by NAL-NL1 at different input levels. The REAR values were noted down at or around octave and mid-octave frequencies from 250 Hz to 6000 Hz. These REAR values were used for calculation of AAI in Stage III. This procedure was carried out for each test ear for different aided conditions mentioned under the section titled ‘Hearing aid programming’.

Measurement of SFAT and SRS. SFAT for the frequencies at octave and mid-octave frequencies from 250 Hz to 6000 Hz using warble tones were obtained in different aided conditions. Modified Hughson-Westlake procedure was used to obtain the aided thresholds.

In addition, the SRS was obtained for recorded Kannada sentence lists presented at 55, 65, and 85 dB SPL. The SRS was obtained for each test ear in the 12 different aided conditions, i.e., hearing aid set at different compression settings as mentioned under the section titled ‘Hearing aid programming’.

Kuk et al. (2004) reported that a modulated sinusoid of one to two seconds in duration with longer and random inter-stimulus intervals would be adequate to achieve reliable SFAT in many non-linear hearing aids. Thus, warble tones that were approximately two seconds in duration with longer and varied inter-stimulus interval, were used in the present study.

To obtain SRS, the participant listened to a recorded list of ten sentences in each of the aided conditions. The participant was instructed to repeat the sentences as they heard. The tester noted down the responses and each correctly identified key word in the sentence was given a score of 1. The maximum number of key words for each list was 40. In order to avoid the order effect, the order of the aided conditions was randomized for each participant. The practice effects for the sentence lists were taken care of by presenting a different list in each of the aided conditions. Before the actual test, a practice sentence list was presented in order to familiarize the participants with the task.

3.2. Stage II: Measurement of the hearing aid output and measured compression ratio (MCR)

The hearing aid programmed for a moderate sensorineural hearing loss, using the same procedure as described in the section on ‘Hearing aid programming’ in Stage I, was used. The recorded sentence list from the Kannada sentence test (Geetha et al., 2014) was given as input to the hearing aid. The sentences were presented from the Lynx AURORA work station, through a loud speaker placed at 45^o Azimuth at a distance of 1 meter. The output of the hearing aid was measured in the ear of the mannequin which was picked up by the microphone connected to the SLM. A 1000 Hz tone of RMS equal to that of sentences in the sentence test developed by Geetha et al. (2014) was presented for the calibration of the system. The hearing aid was placed on the pinna of the mannequin. The stimuli were presented at 55, 65, and 85 dB SPL.

The output from the hearing aid at different aided conditions (compression ratios of 2:1 and 3:1, and with attack times of 2 ms and 20 ms; and release times of 40 ms and 640 ms) was then recorded and measured using the SLM. The output was recorded in the unaided (unprocessed) condition, that is, without the hearing aid, using the same stimuli, intensities, and procedure as mentioned above.

The recorded output was then analyzed to measure the compression ratio. A code to calculate the compression ratio of the measured output was designed which could be run with MATLAB 7.9.0.529 (R2009b). This code was designed to analyze the one-third octave band energy from 250 Hz to 6000 Hz and to calculate the compression ratio of the signal using the method given by Henning and Bentler (2008). The method is explained below.

The code allowed an FFT of approximately every 124 ms sample of the sentences and measurement of short-term levels. This is similar to that used in a few other studies (Byrne et al., 1994; Cox, Matesich, & Moore, 1988; Henning & Bentler, 2008). The average syllable length of Kannada has been reported to be a minimum of 150 ms (Savithri, Jayaram, Kedarnath, & Goswamy, 2006). Hence, this sample duration was short enough to analyze segments of syllables (Verschuure et al., 1996). In addition, it has also been reported that having an analysis time lesser than 124 ms, though provides information on phoneme segments, results in larger dynamic range of speech (Cox et al., 1988).

The short-term levels measured were used for calculation of 10% and 90% *exceedance levels*. Henning and Bentler (2008) defined the exceedance level as “the level that exceeded a specific percentage of the time during the entire duration of the signal”. The peaks were estimated by 10% exceedance level and the valleys were estimated by the 90% exceedance level. The level that is exceeded for 10% of the time (peaks) is 10% exceedance level and the level that is exceeded for 90% of the time is the 90% exceedance level. The difference between the peaks and valleys in the stimuli was the short-term dynamic range of the signal. The short-term dynamic range of the signal was estimated for unprocessed and the processed stimuli in all the aided conditions. The measured compression ratio was then calculated by dividing the short-term dynamic range of the input (unprocessed) by short-term dynamic range of the output (processed) in a given aided condition. For example, if the dynamic range of input signal was 30 dB and the dynamic range of output signal was 22 dB, then the compression ratio was (30/22) 1.36:1.This compression ratio, in the current study, is known as measured compression ratio (MCR) as defined by Stelmachowicz et al. (1994) and, Souza and Turner (1998). The entire system was shut down and after restarting, the reliability of MCR was assessed once again.

3.3. Stage III: Calculation of Aided Audibility Index

The AAI was calculated using SFAT and REAR. The AAI was also calculated with speech level distortion (SLD) correction factor, i.e., AAI_{SLD} and hearing loss desensitization (HLD) along with SLD, i.e., $AAI_{SLD,\,HLD}$.

3.3.1. Calculation of Aided Audibility Index using sound field aided thresholds. The AAI for compression hearing aids was originally devised by Stelmachowicz et al. (1994). The same was modified and this version for calculation of AAI has been described in Souza and Turner (1997). The formula is as given below:

$$AAI= \left[\Sigma I_i(LTASS+15MCR) - Threshold\right]/(30/MCR) \text{ .... Equation 3.1}$$

In this equation, I_i is the band-importance function ‘I’ at a particular frequency ‘i’; LTASS is the Long-Term Average Speech Spectrum level; Threshold is the hearing threshold of the participant; MCR in the above equation stands for Measured Compression Ratio. The MCR is the measured or effective ratio measured in each condition in the second stage. In this, the dynamic range of speech was considered to be 30 dB; the higher and lower speech peaks were 15 dB higher and 15 dB lower from the LTASS, respectively (ANSI S3.5-1997). In the current study too, the MCR is referred to as measured compression ratio. The MCR was measured for low frequency channel and high frequency channel of the hearing aid, as the hearing aid had two channels. It was noted that the MCR was the same in both the channels.

In the above equation, the audibility was calculated by subtracting the hearing threshold at each frequency band from the speech peaks. However, the speech peaks get compressed in compression hearing aids, and thus reducing the dynamic range of speech. Using the MCR, the dynamic range of speech was re-calculated and was used for computing the audibility in each frequency band (Souza & Turner, 1998).

A Microsoft Excel 2007 spread sheet was prepared to incorporate all the above components to calculate AAI, as in the Equation 3.1. The procedure for this was adopted from Manjula (2007), Pavlovic (1987), and Popelka (1987). Table 3.3 shows the Microsoft Excel spread sheet used for calculation of AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with SFAT. In Table 3.3, Line 2 represents LTASS in dB HL; the LTASS values at different frequencies for universal speech spectrum given by Byrne et al. (1994) were used. Byrne et al. (1994) compared the LTASS of 12 different languages and gave a universal LTASS that could be used in all the applications including audibility index. For the calculation of AAI, the LTASS in dB SPL was converted into dB HL using the RET SPL values (Morgan, Dirks, & Bower, 1979), as the hearing thresholds were in dB HL. The dynamic range of speech is assumed to be 30 dB without compression (Amlani et al., 2002; Souza & Turner, 1999). The ANSI standard (S3.5-1997) also considers ±15 dB of the LTASS as the dynamic range of speech. Thus, a dynamic range of 30 dB was used in the present study. The Line 3 shows the MCR measured in the Stage II. In the Line 4, the MCR was used to re-scale the dynamic range (i.e., 30 dB) into the compressed dynamic range (CDR) (Souza & Turner, 1999). For example, if the MCR was 1.4, the dynamic range of speech was 21.42 (i.e., 30/1.4 = 21.42).

Table 3.3

Excel spreadsheet used for computing AAI using SFAT

Line no.	Parameters	Frequency (Hz)								
		250	500	750	1000	1500	2000	3000	4000	6000
1	Hearing threshold	30	35	25	25	35	35	25	55	80
2	LTASS	40.1	54.3	52.6	50	49.4	44.9	49.7	50	40.8
3	MCR	1.47								
4	CDR	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4
5	HSP-R (L2+(L4/2))	50.30	64.50	62.80	60.20	59.60	55.10	59.90	60.20	51.00
6	HSP (Greater of L1 & L5)	50.30	64.50	62.80	60.20	59.60	55.10	59.90	60.20	80
7	LASP-R (L4-L4/2)	29.89	44.09	42.39	39.79	39.19	34.69	39.49	39.79	30.59
8	LASP (Greater of L7 and L1)	30	44.09	42.39	39.79	39.19	35	39.49	55	80
9	Audibility (L6-L8)	20.30	20.41	20.41	20.41	20.41	20.10	20.41	5.20	0
10	AI weights	0.0617	0.1344	0.1035	0.1235	0.1321	0.1328	0.1285	0.1039	0.0796
11	AAI band (L9*L10)	1.2527	2.7428	2.1122	2.5204	2.6959	2.6698	2.6224	0.5407	0
12	Sum across L11	17.1								
13	AAI((L12)/(30/MCR))	0.8407								

Note. L: Line number; L1: Hearing thresholds;
L2: LTASS: Long-term average speech spectrum converted into dB HL;
L3: MCR, i.e., Measured Compression Ratio measured in Stage II ;
L4: CDR, i.e., Compressed Dynamic Range, (re-scaled dynamic range using the MCR, i.e., speech dynamic range/MCR, i.e., 30/MCR);
L5: Higher speech level in the compressed speech dynamic range. This was calculated by adding LTASS with the half of CDR;
L7: Low speech level in the compressed dynamic range. This was calculated by subtracting half of CDR from LTASS;
L6 and 8: Comparison of thresholds with high speech levels and lower speech levels, respectively;
L9: Audibility. This is computed by calculating the difference between Line 6 and Line 8;
AAI: Aided Audibility Index;

Table 3.3 continued ...

Excel spreadsheet used for computing AAI_{SLD} and $AAI_{SLD,HLD}$ using SFAT

Line no.	Parameters	Frequency (Hz)								
		250	500	750	1000	1500	2000	3000	4000	6000
14	Overall level	103.6								
15	Speech Spectrum level, E_i	68.5	81	89.6	88.8	96.7	96.7	92.6	66.7	57.4
16	Std. speech spectrum level, U_i	60.3	62.1	56.8	53.7	52	48.7	46.8	45.6	44.3
17	E_i-U_i-10	-1.8	8.9	22.8	25.1	34.7	38	35.8	11.1	3.1
18	L_i = (E_i-U_i-10)/160	-0.0112	0.0556	0.1425	0.1568	0.2168	0.2375	0.2237	0.0693	0.0193
19	SLD_i = 1-L_i	1.01125	0.9443	0.8575	0.8431	0.7831	0.7625	0.7762	0.9306	0.9806
20	SLD_i, Only if overall level > 73 dB SPL	1.01125	0.9443	0.8575	0.8431	0.7831	0.7625	0.7762	0.9306	0.9806
21	SLD_i	1.2668	2.5902	1.8112	2.1250	2.1112	2.0357	2.0356	0.5031	0
22	AAI_{SLD}/(30/L4)	0.7094								
23	A	1.042	1.0345	1.0285	1.0255	1.114	1.159	1.258	1.3075	1.405
24	B	0.0028	0.0023	0.0019	0.0017	0.0076	0.0106	0.0172	0.0205	0.027
25	B(H)	0.084	0.0805	0.0475	0.0425	0.266	0.371	0.43	1.1275	2.16
26	HLD	0.958	0.954	0.981	0.983	0.848	0.788	0.828	0.18	-0.755
27	AAI_i (SLD, HLD band)	1.2136	2.4711	1.7768	2.0888	1.7903	1.6041	1.6855	0.0905	0
28	$AAI_{SLD, HLD}$ /(30/L4)	0.6233								

Note. L14: Overall SPL recorded in the ear canal of the participant;
L15 to L22: Calculated based the Equation 3.2;
L23: Slope;
L24:Intercept;
In L25, H is the hearing threshold; L25 and 26 represent calculation of HLD using Equation 3.4;
L27 and L28 represent inclusion of SLD and HLD corrections to AAI using Equation 3.5;
AAI: Aided Audibility Index
SLD: Speech Level Distortion
HLD: Hearing Loss Desensitization

This compressed dynamic range was divided by two and this was added to and subtracted from LTASS to calculate peaks and valleys of speech levels, respectively. The Lines 5 and 7 in Table 3.3 represent the lower and higher levels. For example, if the CDR was 21.42 (21.42/2=10.71) and the LTASS in the given band was 54.30; then the higher speech level was 65.01 (i.e., 54.30 + 10.71) and the lower level was 43.59 (i.e., 54.3-10.71). The same has been represented in Figure 3.2. The lower (better) the hearing thresholds, more is the audible range of speech.

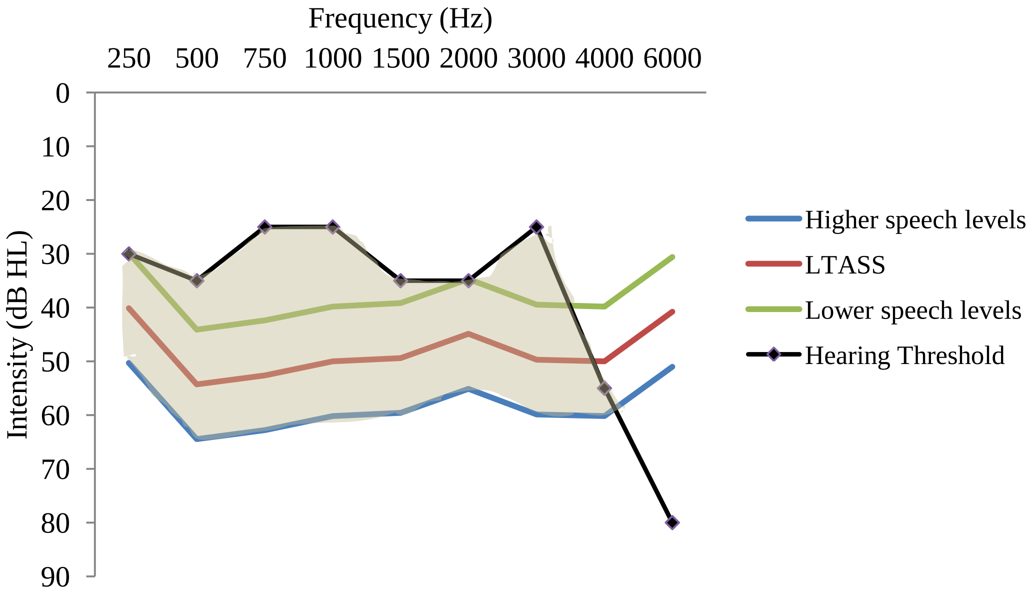


Figure 3.2. Representation of the LTASS along with peaks (higher speech levels) and valleys (lower speech levels), and hearing threshold of a participant. The shaded area represents the audible range of speech.

In the Lines 6, 8, and 9, the hearing thresholds (Line 1) at each frequency were compared with the speech levels to determine the audibility. The Line 10 represents the *band-importance function*. Pavlovic (1994) has reported that for hearing aid selection and for prediction of sentence recognition, it is appropriate to use the band-importance function of average speech. Hence, the band-importance function for the average speech developed by Pavlovic (1987) was used. The product of the band-importance function and the audibility was the AAI, as shown in the Lines 11 and 12.

The AAI was calculated using an adaptation of Equation 3.1. AAI_{SLD} was computed by adding the correction factor SLD to AAI. The following equation was used for obtaining the correction factor SLD or Li. This was given by Ching et al. (1998).

$$SLD_i = \frac{(1 - E_i - U_i - 10)}{160} \quad \text{............................ Equation 3.2}$$

In the Equation 3.2, E_i is the measured speech spectrum level and Ui is the standard speech spectrum level at the i^{th} band. It has been reported that when the measured speech level exceeds 73 dB SPL, there will be decrement in the speech intelligibility. Hence, whenever the measured speech levels exceeded 73 dB SPL (ANSI, R1997), SLD correction factor was applied. Final calculation of AAI_{SLD} was done by using the Equation 3.3. This is represented in Table 3.3, from Lines 15 to 22.

$$AAI_{SLD} = \sum AAI_i * SLD_i \quad \text{.......................... Equation 3.3}$$

In addition to SLD, HLD correction factor was also applied. The HLD was calculated using the Equation 3.4. The equation was given by Sherbecoe and Studebaker (2003).

$$HLD_i = A_i - B_i (H_i) \quad \text{........................... Equation 3.4}$$

In the Equation 3.4, A_i is the slope in the i^{th} band, B_i is the intercept and Hi is the hearing threshold at the centre frequency at i^{th} band. The A_i and B_i for each 1/3rd frequency band is given in a table in the article by Sherbecoe and Studebaker (2003).

The same has been used in the current study. They computed the A_i and B_i based on a series of linear equations using a figure given in an article by Ching et al. (1998). The figure in the study by Ching et al. provided proficiency factors for different degrees of hearing loss based on the individual data obtained in their study. In Table 3.3, the A_i and B_i are given in Lines 23 and 24, respectively. The $AAI_{SLD,\ HLD}$ was computed using the Equation 3.5 (as shown from Lines 23 and 28 in Table 3.3).

$$AAI_{SLD,\ HLD} = \sum AAI_i * SLD_i * HLD_i \quad \text{............................. Equation 3.5}$$

3.3.2. Calculation of Aided Audibility Index using real ear aided responses. The AAI was also calculated using the REAR. The excel spreadsheet for the same is given in Table 3.4. The LTASS was used in dB SPL itself as the REAR was in SPL. The other steps of calculating audibility and AAI were same as was done using SFAT (Table 3.3). The calculation of compressed dynamic range, calculation of the higher and the lower speech levels are same as that for AAI using SFAT (Table 3.3).

In addition, the REAR that was obtained at the gain settings of the hearing aids at which the REIG matches the target gain curve has been reported to maximize the audibility (Fabry, 2003). The use of Excel spreadsheet for computing AAI_{SLD} and $AAI_{SLD,\ HLD}$ using REAR was similar to the one using SFAT given in the Table 3.3, from L14 to L28.

Table 3.4

Excel spreadsheet used for computing AAI using REAR

Line no.	Parameters	Frequency (Hz)								
		250	500	750	1000	1500	2000	3000	4000	6000
1	REAR	58.1	64.3	69.6	67.1	69.7	78.8	76.2	43.2	32.5
2	LTASS	60.3	62.1	56.8	53.7	52	48.7	46.8	45.6	44.3
3	MCR	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
4	CDR	29.41	29.41	29.41	29.41176	29.41176	29.41176	29.41176	29.41176	29.41176
5	HSP-R(L2+L4/2)	75.05	76.8	71.5	68.4	66.7	63.4	61.5	60.3	59
6	HSP (Lesser of L1& L6)	58.1	64.3	69.6	67.1	66.7	63.4	61.5	43.2	32.5
7	LASP-R (L2-(L4/2))	45.5941	47.3941	42.09412	38.99412	37.29412	33.99412	32.09412	30.89412	29.59412
8	LASP (Lesser of L7 and L1)	45.5941	47.3941	42.09412	38.99412	37.29412	33.99412	32.09412	30.89412	29.59412
9	RASP (L6-L8)	12.5058	16.9058	27.5058	28.1058	29.4117	29.4117	29.4117	12.3058	2.90588
10	AI weights	0.0617	0.1344	0.1035	0.1235	0.1321	0.1328	0.1285	0.1039	0.0796
11	AI band (L9*L10)	0.77161	2.27215	2.84685	3.47107	3.88529	3.90588	3.77941	1.27858	0.23130
12	Sum across L11	22.44218								
13	AAI(L12/(30/MCR))	0.763034								

Note. L: Line number;

L1: REAR: Real ear aided response ;
L2: LTASS: Long term average speech spectrum, in dB SPL;
L3: MCR = Measured Compression Ratio measured in the Stage II;
L4: Compressed Dynamic Range (re-scaled dynamic range using the MCR, i.e.,30/MCR);
L5: Higher speech level in the compressed speech dynamic range. This was calculated by adding LTASS with the half of CDR;
L7: Low speech level in the compressed dynamic range. This was calculated by subtracting LTASS with the half of CDR;
L9: Audibility. This was computed by calculating the difference between L6 and L8.
AAI: Aided Audibility Index

The data were then subjected to regression analysis for finding out the best fit equation that could predict the SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ using SFAT and REAR in both the groups. The derived regression was then verified in Stage IV.

3.4. Stage IV: Verification of the regression equation derived

Participants. The equation derived through regression analysis was verified on two separate groups (Group III and Group IV) of test ears of participants, ten ears in each group. The selection criteria used to select Group III and Group IV were the same as that of Group I and Group II respectively. Group III consisted of ten ears of individuals with mild to moderately-severe hearing loss with a mean PTA of 50 dB HL. The participants were in the age range from 24 to 55 years (mean = 43.6 years). This group was included to verify the regression equations derived for Group I. An additional ten ears of individuals with severe hearing loss in the age range of 22 to 55 years (mean = 43.4 years) with average PTA of 74.47 dB HL formed Group IV. This group served as verification group for equations derived for Group II.

Test material and procedure. The test material, aided conditions and testing procedure in the verification groups were same as that mentioned in Stages I, II and III earlier. The regression equations derived were used to predict SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ using SFAT and REAR in the verification groups. The predicted and measured SRS were then statistically compared in the verification groups.

3.5. Assessment of test re-test reliability

The SFAT, REAR and SRS were obtained again on nine ears (18%) out of the 49 ears in Groups I and II. The method, material and procedure were the same as that used for actual experiment. The second trial was done within three months after the first trial after ensuring that there was no significant history. The AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ were computed using the same Excel spread sheet as the first trial.

To summarize, the above procedures at different stages resulted in AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ using SFAT and REAR, and SRS obtained at different compression conditions. These were obtained at input levels of 55, 65, and 85 dB SPL. The AAI computed using SFAT and SRS were then statistically compared across different compression settings. The AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ using SFAT and REAR were assessed for their ability to predict SRS in both the groups.

3.6. Statistical analyses

Statistical Package for Social Sciences (SPSS for windows version) and MATLAB 7.9.0.529 (R2009b) were used for the statistical analyses. The following statistical analyses were carried out:

1. Descriptive statistics was used to know about the distribution of data.
2. Shapiro-Wilk test of normality was done to know if the data were normally distributed.
3. 3-way ANOVA, repeated measures ANOVA and Bonferroni adjusted multiple comparison were used for studying the main effect of compression ratio, compression time constants and presentation levels; the interaction between compression parameters and presentation levels; and for the comparison of SRS and AAI calculated using SFAT across different compression parameters in Group I and Group II.

4. Non-linear regression analysis was used for deriving equations for prediction of SRS using AAI, AAI_{SLD} and $AAI_{SLD,\ HLD}$ which were computed from SFAT and REAR.
5. Paired ‘t’ test and Pearson’s correlation analysis were carried out to compare the measured and predicted SRS in the verification groups.

CHAPTER 4

RESULTS

The study aimed at evaluating the utility of aided audibility index (AAI) and speech recognition scores (SRS) in selection of compression parameters, and the utility of AAI in prediction of SRS. The specific objectives of the present study were -

1. To compute AAI, AAI with speech level distortion (SLD) correction factor, i.e., AAI_{SLD} and AAI with speech level distortion and hearing loss desensitization (HLD) correction factors, i.e., $AAI_{SLD,\ HLD}$, using sound field aided thresholds (SFAT) and real ear aided response (REAR) in the following compression conditions for stimuli presented at 55, 65, and 85 dB SPL, in two groups of listeners (i.e., participants with mild to moderately severe SNHL as Group I and those with severe SNHL as Group II):
    a. For a compression ratio of 2:1
        i. With short time constants
        ii. With long time constants
    b. For a compression ratio of 3:1
        i. With short time constants
        ii. With long time constants

2. To investigate the combination of compression ratios (2:1 vs. 3:1) and time constants (short vs. long) that resulted in better SRS and AAI computed with SFAT by studying the effect of compression ratio and time constants on SRS and AAI across different presentation levels, in both the groups.

3. To derive the equation for predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$, computed using SFAT and REAR, in the above compression conditions at three presentation levels, in both the groups.

4. To verify the equation derived for prediction of SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ using SFAT and REAR, on a different group of participants.

In order to test the objectives of the present study, data were collected from two groups of participants. The statistical analyses were carried out using Statistical Package for Social Sciences (SPSS for windows version) and MATLAB version 7.9.0.529 (r2009b). The AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ were calculated using SFAT and REAR. The ability of AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ using SFAT in selecting the compression parameters; and the ability of AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ with SFAT and with REAR in predicting the SRS across different compression ratios (CR) and time constants (TC) were analyzed. The results for the objectives 1 and 2 are given below under two headings:

4.1. AAI and SRS at three presentation levels across different compression parameters

4.1.1. Effect of compression parameters at different presentation levels on AAI and SRS in Group I

4.1.2. Effect of compression parameters and presentation levels on AAI and SRS in Group II

The objective 3 was to derive the equation for predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$. The results for the objective 3 are given under the following headings.

4.2. Derivation of regression equation for predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with SFAT and REAR.

4.2.1. Derivation of regression equation for predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with SFAT in Group I.

4.2.2. Derivation of regression equation for predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with SFAT in Group II.

4.2.3. Derivation of regression equation for predicting of SRS using AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with REAR in Group I.

4.2.4. Derivation of regression equation for predicting of SRS using AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with REAR in Group II.

The objective 4 was about prediction of SRS. The results for the objective 4 are given under the following headings:

4.3. Prediction of SRS using AAI, AAI_{SLD} and $AAI_{SLD, HLD}$.

Using the derived equation, the SRS was predicted in different conditions. The predicted SRS and the measured SRS were statistically compared to verify the efficacy of the derived equation. The results of this are provided under headings mentioned below.

4.3.1. Comparison of measured SRS and predicted SRS obtained from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed from SFAT in Group III.

4.3.2. Comparison of measured SRS and predicted SRS obtained from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed from SFAT in Group IV.

4.3.3. Comparison of measured SRS and predicted SRS using AAI, AAI_{SLD}, $AAI_{SLD, HLD}$ computed from REAR in Group III.

4.3.4. Comparison of measured SRS and predicted SRS using AAI, AAI_{SLD}, $AAI_{SLD, HLD}$ computed from REAR in Group IV.

4.1. AAI and SRS at presentation levels across different compression parameters

Statistical analysis was done on the SRS and the AAI computed using SFAT in different compression settings of the hearing aid, obtained at three presentation levels, from participants in Group I and Group II. For this, the mean and standard deviation (SD) of AAI were calculated using SPSS statistics. The descriptive analysis of data showed that there were outliers in the data. Hence, the data of five outliers were removed in Group I and six were removed in Group II. Thus, data from 25 ears in Group I and 24 ears in Group II were included for all further statistical analyses in all the sections. Shapiro-Wilk test of normality was carried out and the results showed that data were normally distributed ($p > 0.05$). Therefore, parametric tests were utilized for analyzing the data. The mean and SD of the SRS and AAI for Groups I and II are given in Table 4.1.

In Tables and Figures, the compression conditions at different presentation levels were represented as 2S55, 2S65 and so on. The first character (i.e., 2 or 3) represented the compression ratio of 2:1 or 3:1. The second character (i.e., S or L) represented the time constants, short and long. The last two characters (i.e., 55, 65, and 85) represented the presentation levels.

Table 4.1

Mean and standard deviation (SD) of SRS and AAI computed with SFAT in Group I (N = 25) and Group II (N = 24), at different hearing aid compression conditions

Compression Conditions^	Group I			Group II		
	AAI$^{\#}$	SRS$^{\#\#}$		AAI$^{\#}$	SRS$^{\#\#}$	
	Mean (SD)	Mean (SD)	Percentage	Mean (SD)	Mean (SD)	Percentage
2S55	0.8678 (0.04)	31.16 (9.07)	77.90	0.7899 (0.07)	16.58 (10.14)	41.45
2S65	0.8784 (0.04)	38.04 (3.53)	95.10	0.8248 (0.06)	30.95 (8.50)	77.37
2S85	0.8935 (0.04)	38.52 (2.52)	96.30	0.8589 (0.06)	35.25 (5.26)	88.12
2L55	0.8701 (0.04)	30.08 (9.44)	75.20	0.7970 (0.07)	17.50 (11.43)	43.75
2L65	0.8745 (0.04)	38.24 (3.28)	95.60	0.7970 (0.07)	30.29 (8.37)	75.72
2L85	0.8878 (0.03)	38.60 (2.66)	96.50	0.8088 (0.07)	35.29 (5.29)	88.22
3S55	0.8749 (0.04)	29.28 (73.20)	73.20	0.8269 (0.06)	17.37 (10.79)	43.42
3S65	0.8797 (0.04)	37.80 (4.29)	94.50	0.8347 (0.06)	30.12 (8.07)	75.30
3S85	0.8898 (0.04)	38.40 (3.35)	96.00	0.8597 (0.06)	35.29 (5.17)	88.22
3L55	0.8724 (0.05)	30.52 (9.84)	76.30	0.7878 (0.07)	18.08 (11.02)	45.20
3L65	0.8724 (0.05)	38.28 (2.95)	95.70	0.7878 (0.07)	31.79 (7.13)	79.48
3L85	0.8855 (0.04)	38.60 (2.04)	96.50	0.7985 (0.07)	35.95 (4.70)	89.88

Note. $^{\#}$: Aided Audibility Index; Ranges from 0 to 1;
$^{\#\#}$: Speech Recognition Scores; Maximum possible score being 40;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

In order to find out the main effects of independent variables such as compression ratios, time constants (AT and RT), presentation levels (PL) and groups, and interaction effects between them, a three-way ANOVA, with *groups as independent factor*, [Compression ratio (2) X Time constants (2) X Presentation levels (3) X *Groups (2)*] was done for AAI and SRS separately. The results of the same are provided in the Table 4.2.

Table 4.2

Main effect and interaction between compression parameters (CR and TC), presentation levels and groups for AAI and SRS, on three-way ANOVA

Test variables and groups	AAI	SRS
	F value	F value
CR	F(1, 47) = 0.450	F(1, 47) = 0. 112
TC	F(1, 47) = 40.677***	F(1, 47) = 2.009
PL	F(2, 94) = 97.943***	F(2, 94) = 107.034***
Group	F(1, 47) = 17.24***	F(1, 47) = 21.761***
CR * TC	F(1, 47) = 10.815**	F(1, 47) = 5.898*
CR * PL	F(2, 94) = 46.973***	F(2, 94) =0 0.105
CR * Groups	F(1, 47) = 0.258	F(1, 47) = 2.323
TC * PL	F(2, 94) = 40.914***	F(2, 94) = 0.133
TC * Groups	F(1, 47) = 27.210***	F(1,47) = 0.496
PL * Groups	F(2, 94) = 6.908**	F(2,94) = 13.239***
CR * TC * PL	F(2, 94) = 37.136***	F(2, 94) = 0.725
CR * TC * Groups	F(1, 47) = 7.541*	F(1, 47) = 0.000
CR * PL * Groups	F(2, 94) = 8.500**	F(2, 94) = 1.120
TC * PL * Groups	F(2, 94) = 24.632***	F(2, 94) = 0.283
CR * TC * PL * Groups	F(2, 94) = 20.616***	F(2, 94) = 4.210*

Note. AAI: Aided Audibility Index; SRS: Speech Recognition Scores; CR: Compression Ratio; TC: Time Constants; PL: Presentation Level; $*p < 0.05$; $**p < 0.01$; $***p < 0.001$.

The results of ANOVA revealed that there were significant main effects for all the variables except compression ratio and significant interactions among all the conditions except between compression ratio and groups for AAI (Table 4.2). For SRS, there were significant main effects for presentation levels and groups, and significant interactions among all three variables and groups. The effect size (η_p^2) varied between 0.3 to 0.7 across different variables, which represents moderate to large effect size. Hence, the effect of compression parameters at each presentation levels on AAI and SRS was analyzed separately for each group using repeated measures ANOVA. The group-wise results are given in the following sections.

4.1.1. Effect of compression parameters at different presentation levels on AAI and SRS in Group I. The mean and standard deviation (SD) values of AAI and SRS of Group I are given in the Table 4.3. The Table 4.3 revealed that the compression ratio of 2:1 with short time constants at 85 dB SPL yielded the highest AAI (0.8935) whereas the same condition at 55 dB SPL resulted in the lowest AAI (0.8678). For the analysis of effect of compression parameters only AAI computed with SFAT was considered.

Table 4.3

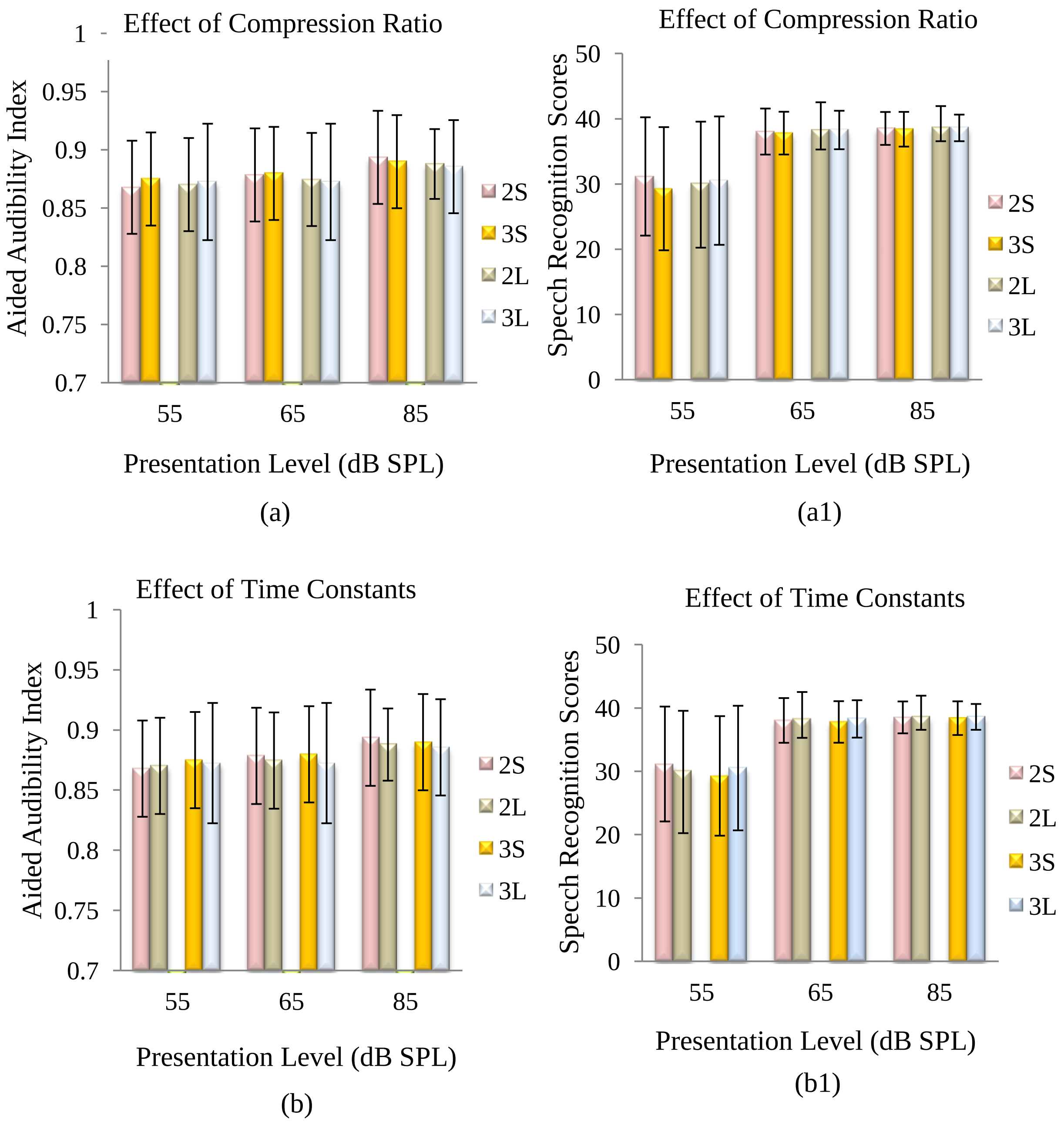
Mean and Standard deviation (SD) of AAI computed with SFAT, and SRS in Group I (N=25)

Compression Conditions^	AAI[#]		SRS[##]		
	Mean	SD	Mean	Percentage	SD
2S55	0.8678	0.04	31.16	77.90	9.07
2S65	0.8784	0.04	38.04	95.10	3.53
2S85	0.8935	0.04	38.52	96.30	2.52
2L55	0.8701	0.04	30.08	75.20	9.44
2L65	0.8745	0.04	38.24	95.60	3.28
2L85	0.8878	0.03	38.60	96.50	2.66
3S55	0.8749	0.04	29.28	73.20	9.48
3S65	0.8797	0.04	37.80	94.50	4.29
3S85	0.8898	0.04	38.40	96.00	3.35
3L55	0.8724	0.05	30.52	76.30	9.84
3L65	0.8724	0.05	38.28	95.70	2.95
3L85	0.8855	0.04	38.60	96.50	2.04

Note. [#]: Aided Audibility Index; Ranges from 0 to 1;
[##]: Speech Recognition Scores; Maximum possible score being 40;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

From Table 4.3, it can also be observed that the compression ratios of 2:1 and 3:1 with long time constants at 85 dB SPL (i.e., 2L85 and 3L85) resulted in the highest SRS (i.e., 38.60) and the compression ratio of 3:1 with short time constants at 55 dB SPL (3S55) resulted in the lowest SRS (i.e., 29.28). In order to highlight the effect of compression ratio and time constants at different presentation levels, the mean and SD of AAI and SRS are given in Figure 4.1.

It can be observed in Figure 4.1 (a) that at 85 dB SPL, the AAI was slightly better for 2:1 when compared to 3:1 compression ratio. There was no difference between the two compression ratios at 65 dB SPL. A compression ratio of 3:1 resulted in slightly higher AAI at the 55 dB SPL. Figure 4.1 (a1) represents a comparison of SRS obtained with the compression ratios of 2:1 and 3:1 for each time constant and presentation level. From Figure 4.1 (a1), it can be noted that the SRS was similar at compression ratios of 2:1 and 3:1, at all presentation levels and time constants except at 55 dB SPL. At 55 dB SPL, slightly higher SRS for 2:1 when compared to 3:1 with short time constants was observed. At 65 and 85 dB SPL, the SRS was similar between 2:1 and 3:1 compression ratios.



(a) (a1)

(b) (b1)

Figure 4.1. Mean and SD (error bars) of (a) AAI and (a1) SRS at different compression ratios (2:1 and 3:1) and presentation levels (55, 65 and 85 dB SPL); Mean and SD of (b) AAI and (b1) SRS at different time constants (short and long) and presentation levels (55, 65 and 85 dB SPL) in Group I. In the figures, 2S is the compression ratio of 2:1 with short time constants; 2L is the compression ratio of 2:1 with long time constants; 3S is the compression ratio of 3:1 with short time constants; 3L is the compression ratio of 3:1 with long time constants; AAI range being 0 to 1; Maximum possible SRS being 40.

The effect of time constants on AAI and SRS is given in the Figure 4.1 (b) and (b1) respectively. The AAI was slightly lower for longer time constants than the shorter time constants at all presentation levels and compression ratios. Figure 4.1 (b1) showed that the longer time constants resulted in slightly higher SRS when compared to shorter constants when the compression ratio was 3:1. Whereas at the compression ratio of 2:1, the SRS was similar across short and long time constants at all the presentation levels.

In order to know if the difference in AAI obtained at different compression conditions were significant, repeated measures ANOVA was carried out. There were four compression conditions, i.e., 2S, 2L, 3S and 3L. Comparison between these conditions were carried out within each presentation level. This analysis of the effect of compression parameters (compression ratios and time constants) on AAI revealed that there was no significant difference among any of the compression conditions at any of the presentation levels at 55 dB SPL, [F(3,72) = 1.711; $p > 0.05$; ; $\eta_p^2 = 0.040$], at 65 dB SPL, [F(3,72) = 1.012; $p > 0.05$; ; $\eta_p^2 = 0.056$], and at 85 dB SPL [F(3,72) = 1.011; $p > 0.05$; ; $\eta_p^2 = 0.040$].

Analysis of the effect of compression on SRS also did not yield a significant difference among any of the compression conditions, at any of the presentation levels [at 55 dB SPL [F(3,72) = 1.711; $p > 0.05$; ; $\eta_p^2 = .067$], at 65 B SPL, [F(3,72) = 0.043; $p > 0.05$; ; $\eta_p^2 = 0.015$], and at 85 B SPL [F(3,72) = 0.161; $p > 0.05$; ; $\eta_p^2 = 0.007$].

4.1.2. Effect of compression parameters and presentation levels on AAI and SRS in Group II. The mean and SD of the AAI and SRS of Group II were computed. The mean and SD of AAI and SRS at different compression ratio, time constants and presentation levels are given in the Table 4.4. It can be seen in the Table 4.4 that AAI across compression ratios is very similar and the longer time constants resulted in lesser AAI. The AAI increased with increase in intensity level. SRS also followed a similar pattern.

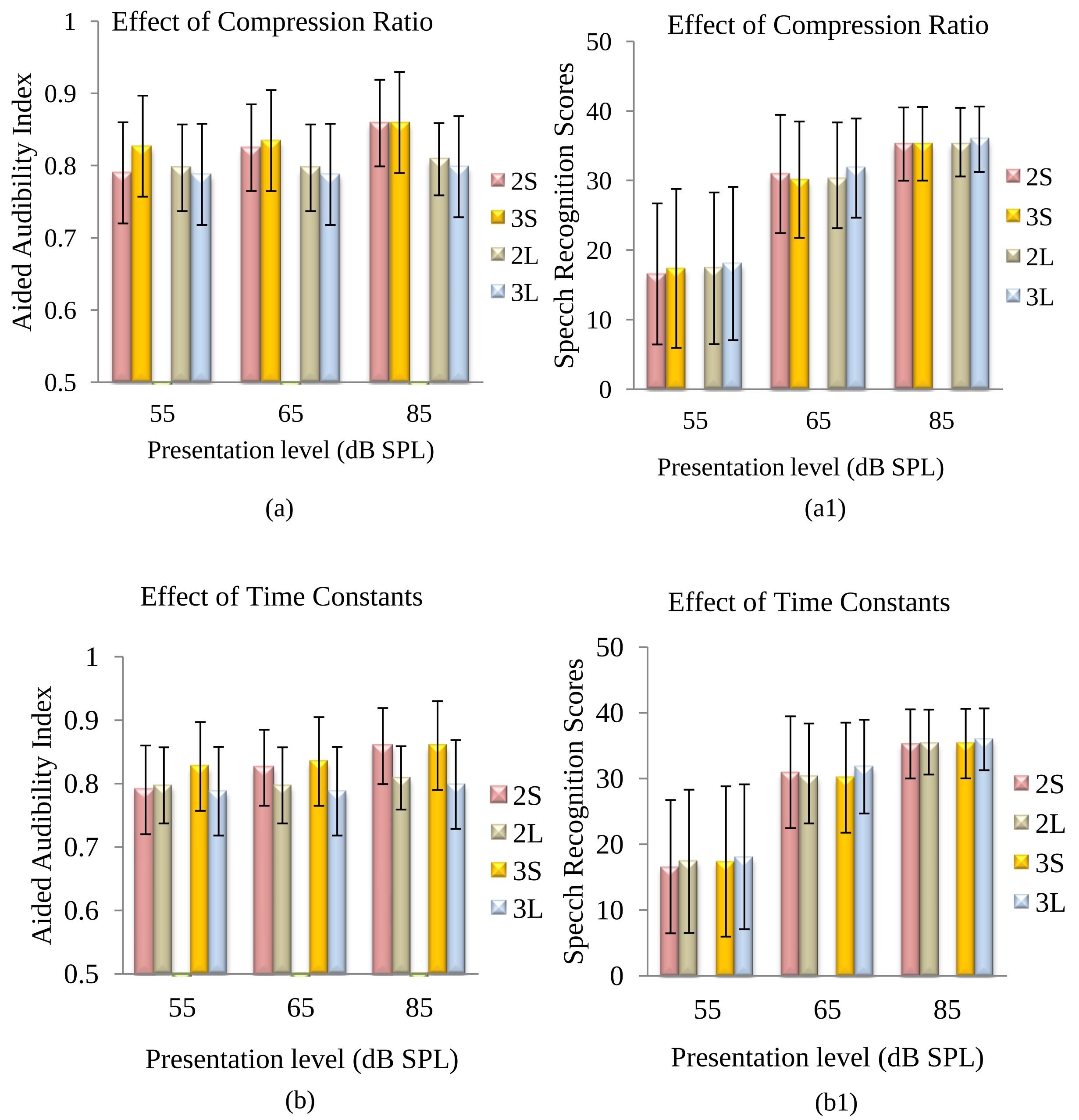
Table 4.4

Mean and Standard deviation (SD) of AAI computed with SFAT, and SRS in Group II (N=24)

Compression Conditions^	AAI[#]		SRS[##]		
	Mean	SD	Mean	Percentage	SD
2S55	0.7899	0.07	16.58	41.45	10.14
2S65	0.8248	0.06	30.95	77.37	8.50
2S85	0.8589	0.06	35.25	88.12	5.26
2L55	0.7970	0.07	17.50	43.75	11.43
2L65	0.7970	0.07	30.29	75.72	8.37
2L85	0.8088	0.07	35.29	88.22	5.29
3S55	0.8269	0.06	17.37	43.42	10.79
3S65	0.8347	0.06	30.12	75.30	8.07
3S85	0.8597	0.05	35.29	88.22	5.17
3L55	0.7878	0.07	18.08	45.20	11.02
3L65	0.7878	0.07	31.79	79.47	7.13
3L85	0.7985	0.07	35.95	89.87	4.70

Note. [#]: Aided Audibility Index; Ranges from 0 to 1;
[##]: Speech Recognition Scores; Maximum possible score being 40;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

The mean and SD of AAI and SRS are given in Figure 4.2 to highlight the effects of compression ratio and time constants on AAI and SRS in Group II. The descriptive analysis of AAI across different compression ratios [Figure 4.2 (a)] revealed that, when the time constants were shorter, 3:1 resulted in higher AAI. However, as the level of presentation increased, this effect reduced. When the time constants were longer, 3:1 resulted in slightly lower AAI compared to 2:1, at all presentation levels. Similarly, there was an effect of compression ratio on SRS at all the presentation levels [Figure 4.2 (a1)]. That is, 3:1 compression ratio resulted in higher SRS when compared to 2:1. A similar pattern was noted at 65 and 85 dB SPL, only when the time constants were longer. For short time constants, there was essentially no difference in SRS between the two compression ratios. In addition, the time constants had an effect on AAI [Figure 4.2 (b)], but not on SRS [Figure 4.2 (b1)]. The longer time constants resulted in poorer AAI. Though there was an effect of time constants on AAI, SRS was similar across time constants.



(a) (a1)

(b) (b1)

Figure 4.2. Mean and SD (error bars) of (a) AAI and (a1) SRS at different compression ratios (2:1 and 3:1) and presentation levels (55, 65 and 85 dB SPL); Mean and SD of (b) AAI and (b1) SRS at different time constants (short and long) and presentation levels (55, 65 and 85 dB SPL) in Group II. In the figures, 2S is the compression ratio of 2:1 with short time constants; 2L is the compression ratio of 2:1 with long time constants; 3S is the compression ratio of 3:1 with short time constants; 3L is the compression ratio of 3:1 with long time constants; AAI range being 0 to 1; Maximum possible SRS being 40.

For analysis of the effect of compression ratio and time constants on AAI and SRS, repeated measures ANOVA was done. There were four compression conditions, i.e., 2S, 2L, 3S and 3L. Comparison between these conditions were carried out within each presentation level. The results revealed a significant effect of compression ratio and time constants on AAI at 55 dB SPL [F(3,69) = 17.556; $p < 0.001$; $\eta_p^2 = 0.433$; power = 1.000], at 65 dB SPL [F(3,69) = 22.425; $p < 0.001$; $\eta_p^2 = 0.494$; power = 1.000]; and, at 85 dB SPL [F(3,69) = 17.556; $p < 0.001$; $\eta_p^2 = 0.721$; power = 1.000]. Bonferonni adjusted multiple comparison was done and the results of the same are presented in Table 4.5.

Table 4.5

Comparison of AAI computed using SFAT across different compression parameters using Bonferonni adjusted multiple comparison in Group II

Presentation level (dB SPL)	Effect of compression ratio			Effect of time constants		
	Condition (A)	Condition (B)	Mean Difference in AAI (A-B)	Condition (A)	Condition (B)	Mean Difference in AAI (A-B)
55	2S	3S	-0.037^{***}	3S	2L	0.030^{**}
					3L	0.039^{***}
65	-	-	-	2S	2L	0.028^{**}
					3L	0.037^{***}
	-	-	-	3S	2L	0.038^{***}
					3L	0.047^{***}
85	-	-	-	2S	2L	0.050^{***}
					3L	0.600^{***}
	-	-	-	3S	2L	0.051^{**}
					3L	0.061^{***}

Note. **: $p < 0.01$;
***: $p < 0.001$;
AAI: Aided Audibility Index
2S,3S: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1; Second character (i.e., S or L) represents time constants, short and long.

The results (Table 4.5) showed that at all the presentation levels, the shorter time constants resulted in significantly higher AAI when compared to longer time constants, irrespective of the compression ratios. In addition, there was a significant difference between 2:1 and 3:1, only when the time constants were shorter and only at 55 dB SPL. These differences had a moderate to good effect size.

A comparison of SRS between short and long time constants in Group II, as depicted in Figure 4.2 (b1), showed that longer time constants resulted in slightly higher SRS for 3:1 compression ratio, except at 55 dB SPL. At 55 dB SPL, long time constant resulted in higher SRS when compared to short time constant, for both 2:1 and 3:1 compression ratios.

Repeated measures ANOVA was carried out in order to know the effect of compression ratio and time constants on SRS. The results did not reveal a significant effect of compression parameters on SRS even in this group at 55 dB SPL [F(3,69) = 9.149; $p > 0.05$; $\eta_p^2 = 0.039$], at 65 dB SPL [F(3,69) = 13.778; $p < 0.001$; $\eta_p^2 = 0.079$], and, at 85 dB SPL [F(3,69) = 1.759; $p > 0.001$; $\eta_p^2 = 0.071$].

The above results reflect the effect of compression ratio and time constants on AAI and SRS, and hence the optimum settings for individuals with mild to moderately-severe hearing loss and severe hearing loss. The summary of the above results are presented in Table 4.6.

Table 4.6

Summary of effect of compression parameters at different presentation levels(PL) on AAI computed using SFAT and SRS

Compression Conditions	PL	Group I		Group II	
		AAI	SRS	AAI	SRS
Compression Ratio	55 dB SPL	No effect	No effect	3:1 > 2:1 for Short TC	No effect
	65 dB SPL	No effect	No effect	No effect	No effect
	85 dB SPL	No effect	No effect	No effect	No effect
Time constants	55 dB SPL	No effect	No effect	Short TC > Long TC	No effect
	65 dB SPL	No effect	No effect	Short TC > Long TC	No effect
	85 dB SPL	No effect	No effect	Short TC > Long TC	No effect

Note. AAI: Aided Audibility Index; SRS: Speech Recognition Scores; CR: Compression Ratio; TC: Time Constants; PL: Presentation levels.

From Table 4.6, it can be noted that for individuals with lesser degree of hearing loss, parameters such as compression ratio, short and long time constants did not have a significant effect on AAI and SRS. However, descriptive analysis showed that the difference in mean values of AAI between the compression conditions was higher than in the difference in mean values of SRS. For individuals with severe degree of hearing loss, AAI was significantly higher for shorter time constants; whereas, SRS was similar across compression conditions.

4.2. Derivation of regression equation for predicting SRS.

The derivation of regression equation for prediction of SRS was done using AAI, AAI_{SLD} (AAI with SLD correction factor) and $AAI_{SLD, HLD}$ (AAI with SLD and HLD correction factors). This was done separately for AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed using SFAT and REAR. The results of this are given below.

4.2.1. Derivation of regression equation for predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with SFAT in the Group I. The mean and standard deviation (SD) of AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ were calculated and are given in Table 4.7. The analysis across different compression settings revealed that AAI, AAI_{SLD} and $AAI_{SLD,\ HLD}$ were similar across different compression ratios and time constants (Table 4.7). The analysis across different presentation levels revealed that AAI was the least at 55 dB SPL and the highest at 85 dB SPL. This pattern was reflected in SRS too. Whereas, AAI_{SLD} and $AAI_{SLD,\ HLD}$ decreased as the level of presentation decreased.

Table 4.7

Mean and standard deviation (SD) of AAI, AAI_{SLD} and $AAI_{SLD,\ HLD}$ computed with SFAT (N=25) and SRS in Group I

Compression Conditions^	$AAI^{\#}$		$AAI_{SLD}^{\#}$		$AAI_{SLD,\ HLD}^{\#}$		$SRS^{\#\#}$	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2S55	0.8678	0.04	0.8163	0.05	0.7109	0.05	31.16	9.07
2S65	0.8784	0.04	0.7996	0.04	0.6950	0.05	38.04	3.53
2S85	0.8935	0.04	0.7668	0.04	0.6638	0.05	38.52	2.52
2L55	0.8701	0.04	0.8221	0.05	0.7149	0.06	30.08	9.44
2L65	0.8745	0.04	0.7996	0.05	0.6954	0.05	38.24	3.28
2L85	0.8878	0.03	0.7677	0.04	0.6675	0.05	38.60	2.66
3S55	0.8749	0.04	0.8152	0.05	0.7120	0.05	29.28	9.48
3S65	0.8797	0.04	0.7983	0.05	0.6978	0.05	37.80	4.29
3S85	0.8898	0.04	0.7747	0.05	0.6739	0.05	38.40	3.35
3L55	0.8724	0.05	0.8156	0.06	0.7146	0.06	30.52	9.84
3L65	0.8724	0.05	0.7953	0.06	0.6970	0.06	38.28	2.95
3L85	0.8855	0.04	0.7734	0.06	0.6748	0.06	38.60	2.04

Note. $^{\#}$: Aided Audibility Index; Ranges from 0 to 1;
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
$^{\#\#}$: Speech Recognition Scores; Maximum possible SRS score being 40;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

A non-linear regression model was fitted to the data for deriving equation or transfer function to predict SRS from AAI, AAI_{SLD} and $AAI_{SLD,\ HLD}$. Literature shows that the relationship between audibility and speech intelligibility is non-linear (Fletcher & Galt, 1950; Humes, 1986; Manjula, 2007; Studebaker & Sherbecoe, 1993;

Wilde & Humes, 1990), hence, the non-linear regression model was fitted to the data. For deriving a suitable equation that could best fit the data of the present study, MATLAB 7.9.0.529 (r2009b) was used. The power equation (equation 4.1, 4.2, 4.3) was found to fit the data based on the R^2using the Curve Fitting Tool (CF Tool) in MATLAB. The power function is a form of non-linear regression. The R^2 is an indicator of the approximation of regression line to the actual measured data. This CF Tool uses method of least squares to fit the data.

$$pSRS = a*(AAI)^b+c \quad \text{... Equation 4.1}$$

$$pSRS = a*(AAI_{SLD})^b+c \quad \text{... Equation 4.2}$$

$$pSRS = a*(AAI_{SLD,\ HLD})^b+c \quad \text{.. Equation 4.3}$$

In the equations 4.1, 4.2, and 4.3, the pSRS is the predicted speech recognition scores; and a, b and c are fitting constants. The fitting constants and the R-squared (R^2) were derived from the power function. Here, it must be noted that the R^2 is one of the metrics that measures goodness of fit, and it ranges from 0 to 1. The R-squared is a measure of how close the data are to the fitted regression line. In general, the fitting model is better when the R^2 is higher. The F-test for regression was also done to see if the regression was significant or not. A significant F-test indicates that the observed R^2 is reliable. Thus, the F-test determines whether the proposed relationship between the response variable and the set of predictors is statistically reliable, and thus is highly useful when the research objective is prediction of a response variable such as SRS. The values of fitting constants, R^2 and F Ratio are given in the Tables 4.8, 4.9 and 4.10 for AAI, AAI_{SLD} and $AAI_{SLD,\ HLD}$, respectively.

Table 4.8

R^2, fitting constants and F ratio of power equation for predicting SRS from AAI computed using SFAT in Group I

Compression Conditions^	R^2	Fitting constants			F Ratio
		a	b	c	
2S55	0.62	2236.31	0.07	-2182.57	252.34***
2S65	0.33	$(-3.885)^{-2}$	-145.48	38.81	1325.08***
2S85	0.29	157.95	48.02	36.78	2528.02***
2L55	0.65	-16.99	-4.62	63.32	232.29***
2L65	0.26	33.69	1.32	10.03	1402.43***
2L85	0.26	11.90	8.02	33.85	2154.39***
3S55	0.75	68.32	4.95	-6.76	313.74***
3S65	0.21	58.63	29.60	35.42	749.46***
3S85	0.20	$(1.874)^7$	189.3	36.82	1001.22***
3L55	0.60	58.80	6.74	5.96	195.25***
3L65	0.43	-1.43	-7.16	42.44	2256.86***
3L85	0.31	9.48	8.18	34.92	3956.26***

Note. ***: $p < 0.001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

The results show that the power model is significant for all the tested conditions, though, the R^2 values were high only at a presentation level of 55 dB SPL, irrespective of the compression ratio and time constants. A significant F-test, even when the R^2 is not very high, indicates that the tested model can be reliably used to predict the dependent variable (Arhin & Noel, 2015; Grace-Martin, 2012). Hence, the power functions provided in equations 4.1, 4.2 and 4.3 can be used to reliably predict SRS from AAI.

Table 4.9

R^2, fitting constants and F Ratio of power equation for predicting SRS from AAI_{SLD} computed using SFAT in Group I

Compression Conditions^	R^2	Fitting constants			F Ratio
		a	b	c	
2S55	0.57	-5.51	-6.16	51.63	220.41***
2S65	0.42	-0.01	-19.66	40.14	1562.84***
2S85	0.35	-3.09	-3.24	46.00	2741.92***
2L55	0.49	-18.98	-3.12	65.87	159.77***
2L65	0.32	-4.17	-3.34	47.28	1531.86***
2L85	0.58	$(-9.67)^{-5}$	-29.72	39.62	3788.46***
3S55	0.57	65.52	4.08	0.12	179.46***
3L55	0.42	69.10	1.95	-16.10	132.77***
3L65	0.39	26.95	1.15	17.54	2098.82***
3L85	0.41	13.61	3.32	32.69	4617.35***

Note. ***: $p < 0.001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

Table 4.10

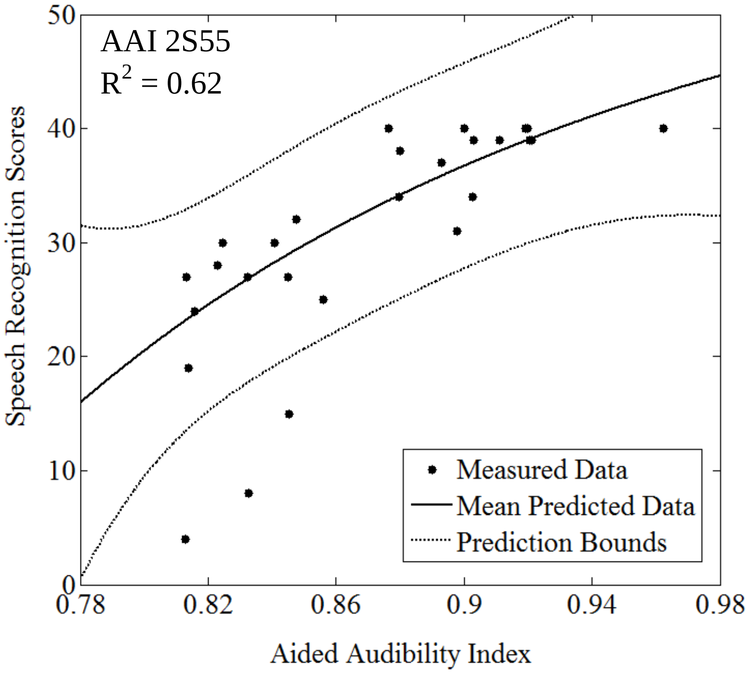
R^2, fitting constants and F ratio of power equation for predicting SRS from $AAI_{SLD,\ HLD}$ computed using SFAT in Group I

Compression Conditions^	R^2	Fitting constants			F Ratio
		a	b	c	
2S55	0.63	-0.69	-8.15	44.58	254.17***
2S65	0.51	0.00	-23.40	39.92	1802.21***
2S85	0.75	$(-5.614)^{-3}$	-57.95	39.6	7119.91***
2L55	0.57	-4.33	-4.50	51.04	189.80***
2L65	0.32	-0.71	-4.99	43.02	1531.28***
2L85	0.49	0.00	-18.42	40.04	3160.81***
3S55	0.79	-1.41	-7.113	47.21	374.67***
3S65	0.26	-0.06	-10.3	40.89	14.93***
3S85	0.27	0.00	-21.05	39.68	1376.14***
3L55	0.49	-52.80	-1.06	106.62	152.26***
3L65	0.66	-0.127	-7.82	41.08	3819.71***
3L85	0.79	-0.005	-12.83	39.97	13042.63***

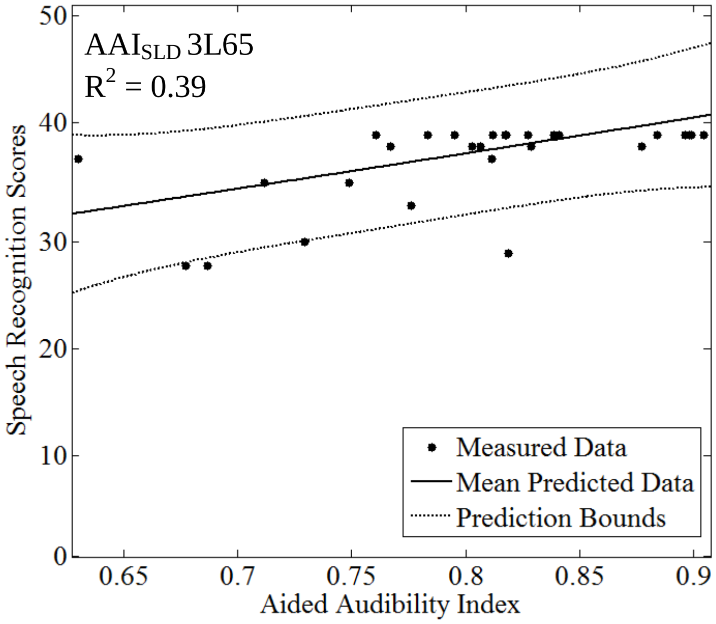
Note. ***: $p < 0.001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

Further, addition of SLD, and both SLD and HLD correction factors resulted in significant power function models in all the conditions. However, inclusion of SLD correction did not improve the R^2 values considerably, whereas addition of both SLD and HLD correction factors did improve the R^2 considerably, only for a very few conditions at higher presentation levels.

The mean predicted data points (the regression curve) obtained using the power equations in two conditions are given in Figure 4.3. The graphs also display 95% prediction bounds.



a)



b)

Figure 4.3. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from a) AAI in 2S55, b) AAI_{SLD} in 3L65 in Group I. The AAI and AAI_{SLD} were computed using SFAT. Here, 2S55 is the compression ratio of 2:1 with short time constants, at presentation level of 55 dB SPL; 3L65 is the compression ratio of 3:1 with long time constants at presentation level of 65 dB SPL.

It could be observed that the most of the measured SRS are within the prediction bounds. The Figure 4.3 represents only two samples. The regression curves for all the other conditions (given in Tables 4.8, 4.9 and 4.10) of SRS predicted using AAI computed with SFAT in Appendix B, AAI_{SLD} in Appendix C, and $AAI_{SLD, HLD}$ in Appendix D.

4.2.2. Derivation of regression equation for predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with SFAT in Group II. The mean and standard deviation (SD) were calculated for AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with SFAT in Group II. The mean and SD of the same are given in the Table 4.11.

Table 4.11

Mean and Standard deviation (SD) of AAI_{SLD} and $AAI_{SLD, HLD}$ computed with SFAT, and SRS in Group II (N=24)

Compression Conditions^	$AAI^{\#}$		$AAI_{SLD}^{\#}$		$AAI_{SLD,HLD}^{\#}$		$SRS^{\#\#}$	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2S55	0.7899	0.07	0.6826	0.07	0.5730	0.07	16.58	10.14
2S65	0.8248	0.06	0.6850	0.06	0.5738	0.06	30.95	8.50
2S85	0.8589	0.06	0.6686	0.05	0.5564	0.05	35.25	5.26
2L55	0.7970	0.07	0.6951	0.07	0.5859	0.07	17.50	11.43
2L65	0.7970	0.07	0.6679	0.06	0.5633	0.06	30.29	8.37
2L85	0.8088	0.07	0.6389	0.06	0.5382	0.06	35.29	5.29
3S55	0.8269	0.06	0.7158	0.06	0.5991	0.06	17.37	10.79
3S65	0.8347	0.06	0.7007	0.06	0.5866	0.06	30.12	8.07
3S85	0.8597	0.05	0.6860	0.05	0.5720	0.04	35.29	5.17
3L55	0.7878	0.07	0.6862	0.07	0.5758	0.07	18.08	11.02
3L65	0.7878	0.07	0.6662	0.07	0.5594	0.07	31.79	7.13
3L85	0.7985	0.07	0.6439	0.06	0.5408	0.06	35.95	4.70

Note. $^{\#}$: Aided Audibility Index; Ranges from 0 to 1;
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
$^{\#\#}$: Speech Recognition Scores; Maximum possible SRS score being 40;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

A similar process of fitting a regression model was followed as that for Group I. The same power model that was appropriate for Group I was found to fit the data. Further analysis showed that the power model was significant for all the tested conditions and only the conditions where the R^2 was higher than 0.2 is given in the tables, as according to Cohen (1988), a R^2 value of higher than 0.2 represents a good fit. Tables 4.12, 4.13 and 4.14 show the R^2 and fitting constants (a, b and c) for predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ respectively.

Table 4.12

R^2, fitting constants and F ratio of power equation for predicting SRS from AAI computed using SFAT in Group II

Compression Condition^	R^2	Fitting constants			F Ratio
		a	b	c	
2S55	0.31	-0.24	-10.40	21.64	31.43***
2L65	0.33	-6.411	-3.244	44.52	146.17***
2L85	0.29	-5.241	-2.917	45.47	462.07***
3S65	0.28	-1.15	-7.56	35.76	141.32***
3S85	0.26	-0.4202	-10.64	38.16	458.34***
3L55	0.32	-1.173	-6.841	26.10	32.41***
3L85	0.27	-0.05358	-12.20	37.82	590.29***

Note. ***: $p < 0.001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

Table 4.13

R^2*, fitting constants and F ratio of power equation for predicting SRS from* AAI_{SLD} *computed using SFAT in Group II*

Compression Condition^	R^2	Fitting constants			F Ratio
		a	b	c	
2S55	0.34	-0.2776	-7.406	23.36	33.44***
2S65	0.27	-6.21	-2.577	48.13	135.83***
2L55	0.26	-5.332	-2.987	34.41	25.91***
2L65	0.43	253.4	0.2216	-201.2	172.13***
2L85	0.35	-20.49	-0.8918	66.15	504.79***
3S55	0.24	-0.208	-8.951	23.30	27.115***
3S65	0.35	-1.24	-5.346	39.59	160.97***
3S85	0.30	-0.04855	-10.18	38.48	488.21***
3L55	0.34	-0.9418	-5.542	27.58	33.47***
3L65	0.43	-0.6125	-5.458	38.77	258.95***
3L85	0.31	-0.04051	-8.363	38.54	622.03***

Note. ***: $p < 0.001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

Table 4.14

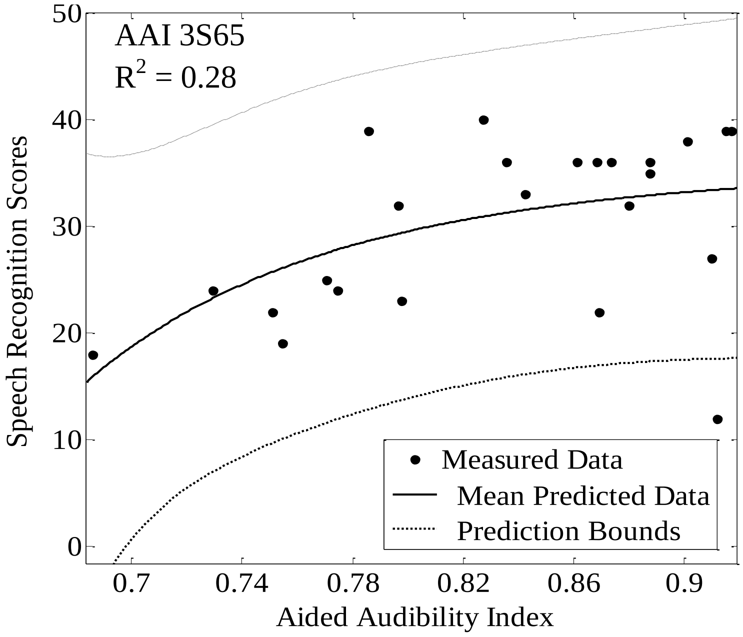
R^2*, fitting constants and F ratio of power equation for predicting SRS from* $AAI_{SLD, HLD}$ *computed using SFAT in Group II*

Compression Condition^	R^2	Fitting constants			F Ratio
		a	b	c	
2S55	0.33	-0.182	-5.857	23.41	32.95***
2S65	0.24	-41.14	-0.6118	89.12	129.89***
2L55	0.28	-0.7562	-4.44	27.33	26.42***
2L65	0.40	-7.079	-1.871	51.89	166.15***
2L85	0.35	-3.289	-1.984	47.07	503.99***
3S55	0.26	-0.02212	-9.507	22.47	28.22***
3S65	0.33	-0.2216	-6.011	37	15.26***
3S85	0.26	-0.01055	-9.4	38.18	461.84***
3L55	0.37	-0.3115	-5.42	26.57	35.32***
3L65	0.40	-0.08136	-6.34	36.69	247.96***
3L85	0.30	-0.001648	-10.01	37.87	608.91***

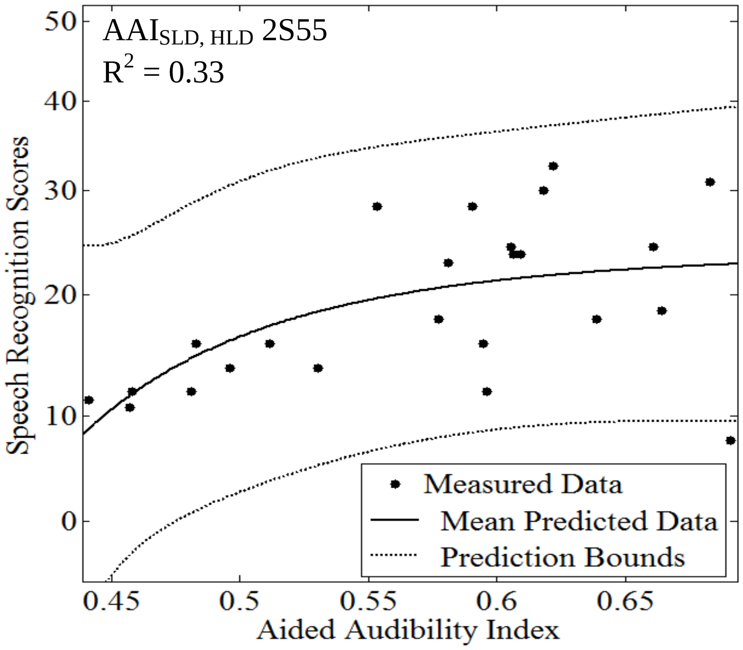
Note. ***: $p < 0.001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

As it can be observed in the Tables 4.12, 4.13 and 4.14, addition of SLD correction factor alone and addition of both HLD and SLD factors resulted in significant regression models and a better R^2 value than without the correction factors. It was also observed that the R^2 did not depend on the compression ratio or time constants. However, R^2 at the lower presentation levels was higher than at higher presentation levels. That is, the ability of prediction of SRS at lower presentation levels is better than at higher presentation levels, in Group II.

The mean of predicted SRS (the regression curve) obtained using the power equations in two conditions in Group II are given in Figure 4.4. The graphs also display 95% prediction bounds.



a)



b)

Figure 4.4. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from a) AAI in 3S65 and b) $AAI_{SLD, HLD}$ in 2S55 in Group II. The AAI and AAI_{SLD} were computed using SFAT. Here, 2S55 is the compression ratio of 2:1 with short time constants, at presentation level of 55 dB SPL; 3S65 is the compression ratio of 3:1 with short time constants at presentation level of 65 dB SPL.

It could be observed that the most of the measured SRS are within the prediction bounds. The Figure 4.4 represents only two samples. The regression curves for all the other conditions (given in Tables 4.12, 4.13 and 4.14) of SRS predicted using AAI computed with SFAT in Appendix E, AAI_{SLD} in Appendix F, and $AAI_{SLD, HLD}$ in Appendix G.

4.2.3. Derivation of regression equation for predicting SRS using AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with REAR in Group I. The mean and standard deviation (SD) of AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ for REAR were obtained in Group I (Table 4.15). For analyzing the ability of AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ to predict the SRS using REAR, non-linear regression model was fit to data. For this, CF Tool in MATLAB 7.9.0.529 (r2009b) was used. This tool uses the method of least squares. The analysis revealed that the same power equations as mentioned earlier (equations 4.1, 4.2, 4.3) were found to fit the data.

Table 4.15

Mean and standard deviation (SD) of SRS, AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed with REAR in Group I

Compression Conditions^	$AAI^{\#}$		$AAI_{SLD}{}^{\#}$		$AAI_{SLD, HLD}{}^{\#}$		$SRS^{\#\#}$	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2S55	0.8074	0.09	0.7500	0.07	0.6161	0.07	31.16	9.07
2S65	0.8760	0.06	0.8001	0.04	0.6597	0.06	38.04	3.53
2S85	0.9771	0.03	0.8538	0.03	0.6502	0.06	38.52	2.52
2L55	0.8096	0.09	0.7623	0.07	0.6253	0.06	30.08	9.44
2L65	0.8669	0.06	0.7941	0.04	0.6508	0.05	38.24	3.28
2L85	0.9699	0.03	0.8542	0.03	0.6604	0.06	38.60	2.66
3S55	0.8212	0.08	0.7680	0.06	0.6264	0.06	29.28	9.48
3S65	0.8729	0.07	0.7979	0.05	0.6484	0.05	37.80	4.29
3S85	0.9698	0.03	0.8622	0.03	0.6642	0.05	38.40	3.35
3L55	0.8171	0.09	0.7643	0.06	0.6252	0.06	30.52	9.84
3L65	0.8664	0.06	0.7944	0.04	0.6434	0.05	38.28	2.95
3L85	0.9658	0.04	0.8610	0.03	0.6633	0.06	38.60	2.04

Note. $^{\#}$: Aided Audibility Index; Ranges from 0 to 1;
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
$^{\#\#}$: Speech Recognition Scores; Maximum possible SRS score being 40;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

The values of fitting constants and R^2 values are given in the Tables 4.16 and 4.17 for AAI_{SLD} and $AAI_{SLD, HLD,}$ respectively. In the tables, only the conditions that resulted in R^2 value of more than 0.2 are given. The AAI without any SLD and HLD correction in all the conditions resulted in R^2 less than 0.2, and hence not listed in the tables. However, addition of HLD and SLD correction resulted in significant non-linear regression models in all the conditions.

Table 4.16

R^2, fitting constants and F ratio of power equation to predict SRS using AAI_{SLD} computed from REAR in Group I

Compression Conditions^	R^2	Fitting constants			F Ratio
		a	b	C	
3L85	0 .33	$(7.114)^{-15}$	-174.1	39	4142.33***

Note. ***: $p < 0.001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

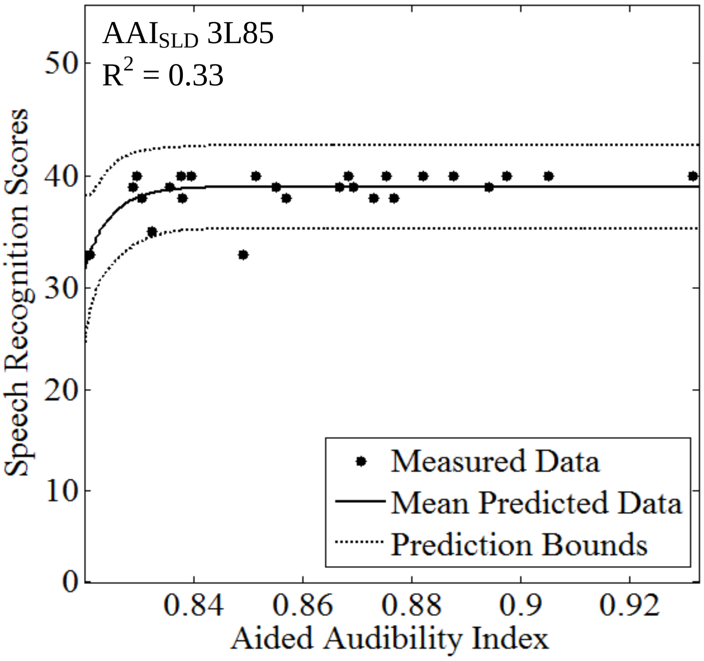
Table 4.17

R^2, fitting constants and F ratio of power equation to predict SRS from $AAI_{SLD,\ HLD}$ computed using REAR in Group I

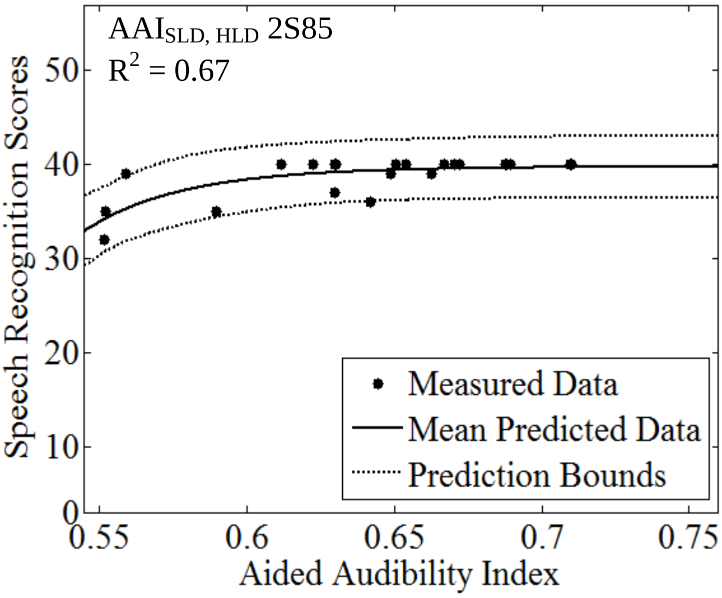
Compression Conditions^	R^2	Fitting constants			F Ratio
		a	b	c	
2S55	0.24	75.08	3.038	11.8	121.92***
2S85	0.67	$(-0.3269)^{-5}$	-16.4	39.79	5376.74***
2L55	0.28	76.51	1.901	-2.405	103.89***
2L65	0.38	-0.005889	-13.19	40.37	1668.02***
2L85	0.78	$(-4.538)^{-8}$	-31.85	39.49	7787.5***
3S55	0.35	223.5	0.4469	-154.2	117.40***
3S65	0.22	$(-1.354)^{-14}$	-63.58	38.76	878.97***
3S85	0.63	$(-9.77)^{-5}$	-19.62	39.66	2805.68***
3L55	0.37	-17.81	-1.932	72.92	120.51***
3L65	0.39	-0.2642	-5.902	41.95	2110.07***
3L85	0.73	-0.01818	-9.997	40.25	10281.64***

Note. ***: $p < .001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

The mean predicted data points (the regression curve) obtained using the power equations in two conditions in Group I are given in Figure 4.5. The graphs also display 95% prediction bounds.



a)



b)

Figure 4.5. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from a) AAI$_{SLD}$ in 3L85 and b) AAI$_{SLD, HLD}$ in 2S85 in Group I. The AAI$_{SLD}$ and AAI$_{SLD, HLD}$ were computed using REAR. Here, 2S85 is the compression ratio of 2:1 with short time constants, at presentation level of 85 dB SPL; 3L85 is the compression ratio of 3:1 with long time constants at presentation level of 85 dB SPL.

The Figure 4.5 represents only two samples. The regression curves for all the other conditions (given in Tables 4.16 and 4.17) are given in Appendix H for Group I.

4.2.4. Derivation of regression equation for predicting of SRS using AAI, $\mathbf{AAI_{SLD}}$ and $\mathbf{AAI_{SLD,\,HLD}}$ computed with REAR, in Group II. The mean and standard deviation (SD) of AAI, AAI_{SLD} and $AAI_{SLD,\,HLD}$ computed using real ear aided response (in dB SPLs) were calculated for Group II. The mean and SD of the same are given in the Table 4.18.

Table 4.18

Mean and standard deviation (SD) of SRS, AAI, AAI_{SLD} and $AAI_{SLD,\,HLD}$ computed with REAR in Group II

Compression Conditions^	$AAI^{\#}$		$AAI_{SLD}{}^{\#}$		$AAI_{SLD,\,HLD}{}^{\#}$		$SRS^{\#\#}$	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2S55	0.8951	0.09	0.8725	0.06	0.6007	0.03	16.58	10.14
2S65	0.9091	0.09	0.8834	0.08	0.5747	0.04	30.95	8.50
2S85	0.9385	0.08	0.7855	0.02	0.5292	0.04	35.25	5.26
2L55	0.9509	0.03	0.8161	0.02	0.6063	0.03	17.50	11.43
2L65	0.9780	0.02	0.8080	0.02	0.5833	0.04	30.29	8.37
2L85	0.9351	0.08	0.7911	0.02	0.5394	0.05	35.29	5.29
3S55	0.9517	0.03	0.8220	0.02	0.6059	0.03	17.37	10.79
3S65	0.9794	0.02	0.8161	0.02	0.5850	0.04	30.12	8.07
3S85	0.9399	0.07	0.8041	0.02	0.5472	0.04	35.29	5.17
3L55	0.9518	0.03	0.8199	0.02	0.5973	0.04	18.08	11.02
3L65	0.9746	0.02	0.8113	0.02	0.5818	0.04	31.79	7.13
3L85	0.9418	0.06	0.8063	0.02	0.5502	0.04	35.95	4.70

Note. $^{\#}$: Aided Audibility Index; Ranges from 0 to 1;
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
$^{\#\#}$: Speech Recognition Scores; Maximum possible SRS score being 40;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

For analyzing the ability of AAI, AAI_{SLD} and $AAI_{SLD,\,HLD}$ to predict the SRS using REAR, a non-linear regression model was fitted to data using a similar procedure as given in the Sections 4.2.1 and 4.2.2. The analysis revealed that the power equation (Equations 4.1, 4.2, 4.3) fitted these data as well.

The values of fitting constants and R^2 for AAI and $AAI_{SLD, HLD}$ are given in the Tables 4.19 and 4.20 respectively. In the tables, only those conditions that resulted in $R^2$of more than 0.2 (Cohen, 1988) are included. The R^2 was less than 0.2 in all the conditions of AAI and AAI_{SLD}, except in 3S55 condition. Prediction of SRS from $AAI_{SLD, HLD}$ resulted in significant regression model in all the conditions that are presented in the Tables 4.19 and 4.20.

Table 4.19

R^2, fitting constants and F ratio of power equation to predict SRS using from AAI computed with REAR in Group II

Compression Conditions^	R^2	Fitting constants			F Ratio
		a	b	c	
3S55	0.24	-47.68	3.76	57.21	26.92***

Note. ***: $p < 0.001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

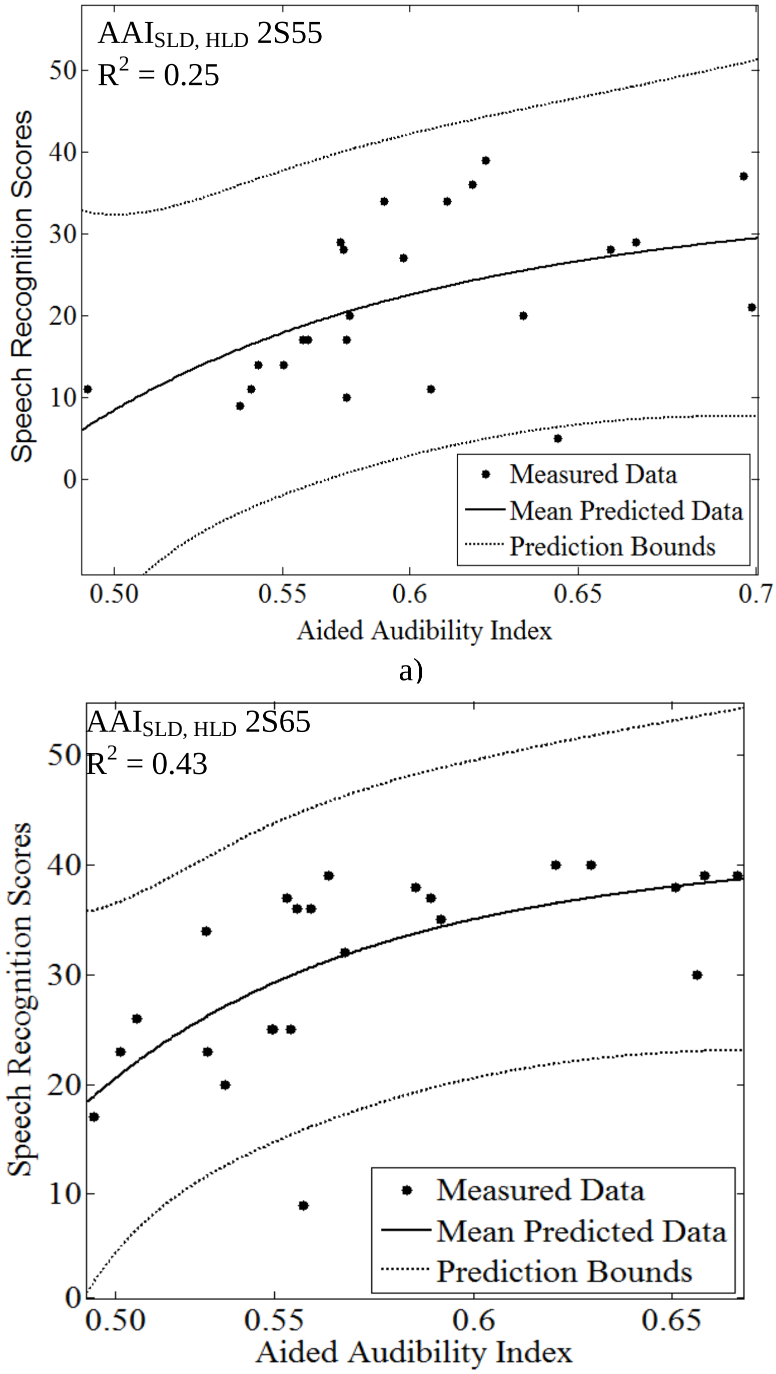
Table 4.20

R^2, fitting constants and F ratio of power equation to predict SRS using $AAI_{SLD, HLD}$ computed with REAR in Group II

Compression Conditions^	R^2	Fitting constants			F Ratio
		a	b	c	
2S55	0.25	-0.6327	-5.918	30.51	28.54***
2S65	0.43	-0.2099	-6.871	42.06	175.62***
2S85	0.21	-2.4400	-2.461	47.28	417.11***
2L55	0.23	-0.1207	-8.698	28.24	24.29***
2L65	0.34	-1.7950	-3.969	46.39	148.18***
2L85	0.35	-1.993	-2.837	47.32	503.22***
3S65	0.32	-0.7291	-5.261	43.33	153.84***
3S85	0.28	-0.009109	-9.71	39.54	471.100***
3L65	0.20	-14.78	-1.377	63.23	183.55***
3L85	0.34	$(-1.722)^{-6}$	-21.74	38.22	693.40***

Note. ***: $p < 0.001$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

The mean of predicted SRS (the regression curve) obtained using the power equations in two conditions are given in Figure 4.6 for Group II. The graphs also display 95% prediction bounds. The Figure 4.6 represents two examples of regression curves for predicting SRS from AA, AAI_{SLD} and $AAI_{SLD, HLD}$. The regression curves for all the other conditions (given in Tables 4.19 and 4.20) are given in Appendix I for Group II.



a)

b)

Figure 4.6. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from a) AAI$_{SLD, HLD}$ in 2S55 and b) AAI$_{SLD, HLD}$ in 2S65 in Group II. The AAI$_{SLD}$ and AAI$_{SLD, HLD}$ were computed using REAR. Here, 2S55 is the compression ratio of 2:1 with short time constants, at presentation level of 55 dB SPL; 2S65 is the compression ratio of 2:1 with short time constants, at presentation level of 65 dB SPL.

In order to statistically assess the usefulness of the derived regression model in predicting SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$, the agreement and the difference between the predicted and the measured SRS were assessed. The agreement between the predicted SRS (pSRS) and the measured SRS (mSRS) was assessed by Pearson’s correlation. Paired t-test was used to know if there was any significant difference between mSRS and pSRS.

Comparison of pSRS and mSRS was done for evaluating the efficacy of the non-linear power model that was used to predict the SRS. The prediction equation was verified by predicting the SRS (pSRS), on two separate groups of participants with mild to moderately-severe degree of hearing loss (Group III) and severe degree of hearing loss (Group IV). The pSRS was compared with the mSRS. This was done for verifying the regression equations.

4.3.1. Comparison of measured SRS and predicted SRS obtained from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed using SFAT in Group III. In group III, the pSRS and mSRS were compared by performing correlation analysis. Before performing Pearson’s correlation analysis, the SRS were transformed into rationalized arcsine unit (rau) for comparison of the measured and predicted SRS. In the current study, the modified rationalized arcsine transformation formula given by Studebaker, McDaniel, and Sherbecoe (1995) was used. Transformation of SRS into rau makes the data fulfill the assumptions of the statistical procedures and converts the non-linear relationship between variables into a linear relationship. Thus making the scores more suitable for parametric statistical analysis (Thornton & Raffin, 1978; Studebaker, 1985). The rationalized arcsine transform provides values that closely match their corresponding percentage scores (within 1%) between about 16 percent and 84 percent. Beyond that range, scores in rau steadily diverge from the actual value of percentages. The exact limits of the rau scale depend on the number of test items; however, they never exceed -23 rau to 123 rau.

Thus, conversion into rau made the SRS appropriate for parametric statistical measures (Sherbecoe & Studebaker; 2004; Studebaker, 1985; Studebaker, Gray, & Branch, 1999; Studebaker et al., 1995). The mean and SD of the measured and predicted SRS, in rau, are given in the Table 4.21.

Table 4.21

Mean and SD of measured SRS (mSRS) and predicted SRS (pSRS) in rau obtained from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed using SFAT in Group III

Compression Conditions^	mSRS		pSRS					
			AAI		AAI_{SLD}		$AAI_{SLD, HLD}$	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
2S55	54.13	38.79	71.71	19.60	58.45	28.75	61.81	30.92
2S65	82.68	28.77	103.99	04.33	99.38	20.17	105.36	00.00
2S85	99.95	17.37	109.65	09.75	101.02	10.44	101.30	08.68
2L55	108.76	09.89	74.41	18.41	67.54	27.50	68.94	27.45
2L65	52.08	45.05	102.17	08.89	99.40	14.04	101.44	13.16
2L85	84.69	25.68	106.93	09.39	100.13	19.40	115.71	00.00
3S55	100.35	17.19	65.70	11.53	66.83	19.50	65.27	28.95
3S65	112.55	06.65	95.00	04.57	▨	▨	96.27	10.49
3S85	51.20	38.84	107.03	09.59	▨	▨	105.36	00.00
3L55	85.97	26.82	78.32	17.05	75.86	16.82	75.98	18.72
3L65	102.96	16.42	105.30	07.72	104.30	10.79	105.28	10.34
3L85	109.49	08.35	107.37	06.14	103.72	06.93	105.30	07.72

Note. AAI: Aided Audibility Index; Ranges from 0 to 1;
mSRS: Measured speech recognition scores;
pSRS: Predicted speech recognition scores.
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
▨ Conditions that had $R^2 < 0.2$ are shaded and they were not considered for predicting SRS.

Tables 4.22, 4.23 and 4.24 reveal the results of Pearson's correlation between the mSRS and pSRS derived from AAI, AAI_{SLD}, and $AAI_{SLD, HLD}$ respectively. The results showed that the correlation was moderate in most of the conditions when the mSRS was compared with pSRS derived from AAI. The correlation was weak in many conditions when the SLD and the HLD correction factors were added to AAI (Tables 4.23 and 4.24).

Table 4.22

Correlation between mSRS (in rau) and pSRS (in rau) obtained from AAI calculated for SFAT obtained in different compression conditions in Group III

mSRS / pSRS	Compression Conditions^											
	2S55	2S65	2S85	2L55	2L65	2L85	3S55	3S65	3S85	3L55	3L65	3L85
2S55	0.28											
2S65		0.48										
2S85			0.25									
2L55				0.53								
2L65					0.65*							
2L85						-0.05						
3S55							0.42					
3S65								0.41				
3S85									0.77**			
3L55										0.49		
3L65											0.65*	
3L85												0.47

Note. *: $p < 0.05$;
**: $p < 0.01$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
mSRS: Measured speech recognition scores
pSRS: Predicted speech recognition scores

Table 4.23

Correlation between mSRS (in rau) and pSRS (in rau) obtained from AAI_{SLD} calculated for SFAT obtained in different compression conditions in Group III

mSRS / pSRS	Compression Conditions^									
	2S55	2S65	2S85	2L55	2L65	2L85	3S55	3L55	3L65	3L85
2S55	0.35									
2S65		0.68*								
2S85			0.24							
2L55				0.34						
2L65					0.46					
2L85						-0.008				
3S55							0.26			
3L55								0.39		
3L65									0.77**	
3L85										0.42

Note. *: $p < 0.05$;

**: $p < 0.01$;

^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

mSRS: Measured speech recognition scores

pSRS: Predicted speech recognition scores

Table 4.24

Correlation between mSRS (in rau) and pSRS (in rau) obtained from AAI$_{SLD, HLD}$ calculated for SFAT obtained in different compression conditions in Group III

mSRS / pSRS	Compression Conditions^											
	2S55	2S65	2S85	2L55	2L65	2L85	3S55	3S65	3S85	3L55	3L65	3L85
2S55	0.43											
2S65		0.00										
2S85			0.11									
2L55				0.50								
2L65					0.81*							
2L85						0.00						
3S55							0.47					
3S65								0.63				
3S85									0.00			
3L55										0.48		
3L65											0.79**	
3L85												0.50

Note. *: $p < 0.05$;
**: $p < 0.01$;
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels;
mSRS: Measured speech recognition scores;
pSRS: Predicted speech recognition scores.

In order to assess the significance of difference between the mSRS and pSRS paired 't' test was carried out. The results revealed that the difference was not significant between the predicted SRS and the measured SRS in all the compression conditions, except for SRS predicted from AAI and AAI$_{SLD, HLD}$ in 3S55 condition. The results of this are given in the Table 4.25.

Table 4.25

Difference between mSRS (in rau) and pSRS (in rau) predicted by AAI, AAI_{SLD} and $AAI_{SLD,\,HLD}$ calculated using SFAT in different compression conditions in Group III, on paired 't' test

Compression Conditions^	mSRS and pSRS predicted from								
	AAI			AAI_{SLD}			$AAI_{SLD,HLD}$		
	t	df	*p*	t	df	*p*	t	df	*p*
2S55	1.156	9	0.278	2.345	9	0.044	2.064	9	0.069
2S65	0.808	9	0.440	0.120	9	0.907	0.983	9	0.351
2S85	0.233	9	0.821	1.952	9	0.083	1.903	9	0.090
2L55	1.463	9	0.178	1.775	9	0.110	1.870	9	0.094
2L65	0.434	9	0.674	0.183	9	0.858	0.339	9	0.742
2L85	1.509	9	0.166	1.909	9	0.089	1.500	9	0.168
3S55	2.632	9	0.027*	2.097	9	0.065	2.271	9	0.049*
3S65	1.661	9	0.131				1.649	9	0.133
3S85	1.276	9	0.234				1.566	9	0.152
3L55	1.591	9	0.146	1.757	9	0.113	1.837	9	0.099
3L65	0.061	9	0.953	0.061	9	0.953	0.475	9	0.646
3L85	2.279	9	0.059	2.279	9	0.049	1.815	9	0.103

Note. AAI: Aided Audibility Index; Ranges from 0 to 1;
mSRS: Measured speech recognition scores;
pSRS: Predicted speech recognition scores.
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
▨ Conditions that had $R^2 < 0.2$ are shaded and they were not considered for predicting SRS.

4.3.2. Comparison of measured SRS and predicted SRS obtained from AAI, AAI_{SLD} and $AAI_{SLD,\,HLD}$ computed using SFAT in Group IV. Comparison of pSRS and mSRS was done for ensuring the efficacy of the non-linear power model that was used to predict the SRS. The SRS was predicted using the data obtained from a separate group of ten individuals with severe hearing loss in the verification group. This was done for AAI, AAI_{SLD} and $AAI_{SLD,\,HLD}$ obtained for sound field thresholds. Similar to Group I, the SRS was converted to rau. The mean and SD of the measured and predicted SRS, in rau, are given in Table 4.26.

Table 4.26

Mean and SD of mSRS (in rau) and pSRS (in rau) obtained from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ calculated from SFAT in Group IV

Compression Conditions^	mSRS (in rau)		pSRS (in rau) predicted from					
	Mean	SD	AAI		AAI_{SLD}		$AAI_{SLD,HLD}$	
			Mean	SD	Mean	SD	Mean	SD
2S55	39.88	23.24	29.29	22.72	36.54	13.64	34.28	17.89
2S65	72.58	17.40			64.86	21.72	65.81	18.55
2S85	91.20	12.93						
2L55	47.43	24.42			37.04	11.77	36.93	12.97
2l65	72.36	22.43	59.48	26.46	62.32	22.39	59.80	27.58
2L85	94.73	19.72	74.29	25.33	79.73	16.76	82.39	12.73
3S55	39.51	29.82			39.15	11.51	35.29	19.75
3S65	71.51	19.49	67.98	13.13	68.59	16.07	70.77	12.36
3S85	91.09	20.46	82.07	17.15	87.14	11.52	83.65	16.95
3L55	43.51	27.06	35.01	21.11	37.43	19.98	38.24	19.49
3L65	75.11	27.92			63.11	34.67	63.45	33.86
3L85	93.55	17.55	86.44	12.74	84.81	17.93	87.41	11.31

Note. AAI: Aided Audibility Index; Ranges from 0 to 1;
mSRS: Measured speech recognition scores;
pSRS: Predicted speech recognition scores.
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
▨ Conditions that had $R^2 < 0.2$ are shaded and they were not considered for predicting SRS.

As it can be seen, the predicted SRS (in rau) from $AAI_{SLD, HLD}$ are closer to the measured SRS (in rau). As was done in Group I, Pearson's correlation test was carried out to assess the agreement between the measured and predicted SRS. The results showed a weak to moderate agreement between the measured and predicted scores as shown in Tables 4.27, 4.28 and 4.29, on Pearson's correlation test. Inclusion of SLD and HLD correction factors improved the correlation between the mSRS and pSRS in many of the aided conditions.

Table 4.27

Correlation between mSRS (in rau) and pSRS (in rau) obtained from AAI calculated from SFAT in different compression conditions in Group IV

mSRS / pSRS	Compression Conditions^						
	2S55	2L65	2L85	3S65	3S85	3L55	3L85
2S55	0.567						
2L65		0.226					
2L85			-0.024				
3S65				0.296			
3S85					0.336		
3L55						0.530	
3L85							0.117

Note. ^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
mSRS: Measured speech recognition scores
pSRS: Predicted speech recognition scores

Table 4.28

Correlation between mSRS (in rau) and pSRS (in rau) obtained from AAI$_{SLD}$ calculated from SFAT in different compression conditions, in Group IV

mSRS / pSRS	Compression Conditions^										
	2S55	2S65	2L55	2L65	2L85	3S55	3S65	3S85	3L55	3L65	3L85
2S55	0.375										
2S65		0.582									
2L55			0.252								
2L65				0.211							
2L85					0.053						
3S55						0.364					
3S65							0.180				
3S85								0.470			
3L55									0.466		
3L65										0.377	
3L85											0.115

Note. ^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
mSRS: Measured speech recognition scores
pSRS: Predicted speech recognition scores

Table 4.29

Correlation between mSRS (in rau) and pSRS (in rau) obtained from $AAI_{SLD, HLD}$ *calculated from SFAT in different compression conditions in Group IV*

mSRS pSRS	Compression Conditions^										
	2S55	2S65	2L55	2L65	2L85	3S55	3S65	3S85	3L55	3L65	3L85
2S55	0.436										
2S65		0.420									
2L55			0.298								
2L65				0.228							
2L85					-0.011						
3S55						0.508					
3S65							0.201				
3S85								0.306			
3L55									0.530		
3L65										0.346	
3L85											0.171

Note. ^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1; Second character (i.e., S or L) represents time constants, short and long; Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

mSRS: Measured speech recognition scores

pSRS: Predicted speech recognition scores

The paired-t test was carried out to assess the difference between the mSRS and pSRS. The results of this did not reveal a significant difference between the predicted and measured SRS in all the conditions indicating that there was no difference between the mSRS and pSRS. The results of this are given in Table 4.30.

Table 4.30

Difference between mSRS (in rau) and pSRS (in rau) obtained from AAI and $AAI_{SLD, HLD}$ *computed using SFAT in different compression conditions, in Group IV on paired 't' test*

Compression Conditions^	mSRS and pSRS predicted from								
	AAI			AAI_{SLD}			$AAI_{SLD,HLD}$		
	t	df	*p*	t	df	*p*	t	df	*p*
2S55	1.566	9	0.152	0.477	9	0.645	0.794	9	0.448
2S65				1.335	9	0.215	1.104	9	0.298
2S85									
2L55				1.352	9	0.209	1.384	9	0.200
2L65	1.332	9	0.215	1.128	9	0.288	1.267	9	0.237
2L85	1.990	9	0.078	1.882	9	0.093	1.654	9	0.132
3S55				0.040	9	0.969	0.511	9	0.622
3S65	0.568	9	0.584	0.412	9	0.690	0.122	9	0.906
3S85	1.306	9	0.224	0.687	9	0.509	1.059	9	0.317
3L55	1.123	9	0.291	0.767	9	0.463	0.708	9	0.497
3L65				1.040	9	0.325	1.033	9	0.328
3L85	1.101	9	0.300	1.171	9	0.272	1.012	9	0.338

Note. AAI: Aided Audibility Index; Ranges from 0 to 1;
mSRS: Measured speech recognition scores;
pSRS: Predicted speech recognition scores.
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
▨ Conditions that had $R^2 < 0.2$ are shaded and they were not considered for predicting SRS.

4.3.3. Comparison of measured SRS and predicted SRS using AAI, AAI_{SLD}, $AAI_{SLD, HLD}$ computed from REAR, in Group III. Comparison of the predicted SRS (pSRS) and the measured SRS (mSRS) was done for ensuring the efficacy of the non-linear power model that was used to predict the SRS. The SRS was predicted using the data obtained from ten individuals in a separate group used for the verification of the equation. This was done for AAI_{SLD} and $AAI_{SLD, HLD}$ obtained using real ear aided response in dB SPL. The mean and SD of the measured and predicted SRS are given in the Table 4.31. The SRS predicted from AAI is not given in Table 4.31 as the R^2 was less than 0.2 in all the compression conditions. It could be observed in Table 4.31 that the measured and predicted SRS were very similar.

Table 4.31

Mean and SD of mSRS (in rau) and pSRS (in rau) obtained from AAI_{SLD} *and* $AAI_{SLD, HLD}$ *calculated for REAR in different compression conditions in Group III*

Compression Conditions^	mSRS (in rau)		pSRS (in rau)			
	Mean	SD	AAI_{SLD}		$AAI_{SLD, HLD}$	
			Mean	SD	Mean	SD
2S55	82.68	28.77			74.00	12.73
2S85	108.76	09.89			99.70	10.95
2L55	84.69	25.68			68.47	14.21
2L65	100.35	17.19			94.55	13.72
2L85	112.55	06.65			101.95	07.36
3S55	85.97	26.82			59.55	24.04
3S65	102.96	16.42			98.38	11.50
3S85	109.49	08.35			100.70	09.56
3L55	91.37	29.65			61.49	36.23
3L65	104.14	12.48			93.14	13.83
3L85	110.34	09.58	105.85	03.86	99.66	7.75

Note. AAI: Aided Audibility Index; Ranges from 0 to 1;
mSRS: Measured speech recognition scores;
pSRS: Predicted speech recognition scores.
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
▨ Conditions that had $R^2 < 0.2$ are shaded and they were not considered for predicting SRS.

In order to assess the usefulness of AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ in predicting SRS using REAR, the agreement and the difference between the predicted and the measured SRS were assessed statistically. Pearson’s correlation was used to assess the agreement between the two. The results of this are given in Table 4.32. The correlation was weak in most of the conditions.

Table 4.32

Correlation between mSRS (in rau) and pSRS (in rau) obtained from $AAI_{SLD, HLD}$ *calculated from REAR in different compression conditions in Group III*

mSRS pSRS	Compression Conditions^										
	2S55	2S85	2L55	2L65	2L85	3S55	3S65	3S85	3L55	3L65	3L85
2S55	0.06										
2S85		0.24									
2L55			-0.00								
2L65				0.003							
2L85					0.25						
3S55						-0.04					
3S65							-0.05				
3S85								0.71*			
3L55									-0.15		
3L65										-0.29	
3L85											0.21

Note. *: $p < 0.05$
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
mSRS: Measured speech recognition scores
pSRS: Predicted speech recognition scores

The paired-t test carried out to assess the difference between the two scores, i.e., measured and predicted, revealed that there was no significant difference between the pSRS and mSRS in all the conditions, except for compression ratio of 3:1 at 55 and 85 dB SPL with short time constants (3S55 and 3S85). The results of paired t-test are given in Table 4.33. The results showed no significant agreement between the measured and predicted scores in most of the conditions.

Table 4.33

Difference between mSRS (in rau) and pSRS (in rau) predicted by $AAI_{SLD, HLD}$ *calculated using REAR in different compression conditions, on paired t-test in Group III*

Compression Conditions^	$AAI_{SLD, HLD}$		
	t	df	*p*
2S55	0.891	9	0.396
2S65	2.866	9	0.019*
2S85	2.226	9	0.053
2L55	1.731	9	0.117
2L65	0.834	9	0.426
2L85	3.888	9	0.004
3S55	2.280	9	0.049*
3S65	0.705	9	0.499
3S85	4.053	9	0.003*
3L55	1.883	9	0.092
3L65	1.642	9	0.135
3L85	1.250	9	0.243

Note. AAI: Aided Audibility Index; Ranges from 0 to 1;
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
*: $p < 0.05$
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.

4.3.4. Comparison of measured SRS and predicted SRS using AAI, AAI_{SLD}, and $AAI_{SLD, HLD}$ computed from REAR, in Group IV. The mean and SD of predicted SRS and measured SRS, in rau, using AAI and $AAI_{SLD, HLD}$ computed from REAR in Group IV are given in the Table 4.34. The mean of predicted SRS from AAI_{SLD} is not given in Table 4.34, as all the conditions in AAI_{SLD} had R^2 less than 0.2. As it can be seen from Table 4.34, the mean of predicted SRS in rau is closer to mean of measured SRS, as the presentation level increased.

Table 4.34

Mean and SD of mSRS (in rau) and pSRS (in rau) obtained from AAI and $AAI_{SLD, HLD}$ calculated from REAR in different compression conditions in Group IV

Compression Conditions^	mSRS		pSRS			
	Mean	SD	AAI		$AAI_{SLD,HLD}$	
			Mean	SD	Mean	SD
2S55	39.88	23.24			26.28	25.81
2S65	72.58	17.40			68.00	22.86
2S85	91.20	12.93			83.79	14.32
2L55	47.43	24.42			25.45	23.80
2L65	72.36	22.43			59.81	29.67
2L85	94.73	19.72			82.64	15.45
3S55	39.51	29.82	44.30	13.23		
3S65	71.51	19.49			71.77	16.55
3S85	91.09	20.46			87.11	14.33
3L55	43.51	27.06				
3L65	75.11	27.92			75.11	13.42
3L85	93.55	17.55			91.63	11.33

Note. AAI: Aided Audibility Index; Ranges from 0 to 1;
mSRS: Measured speech recognition scores;
pSRS: Predicted speech recognition scores.
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
▨ Conditions that had $R^2 < 0.2$ are shaded and they were not considered for predicting SRS.

The Pearson's correlation between the SRS predicted by $AAI_{SLD, HLD}$ and measured SRS for Group IV is given in the Table 4.35. The results indicated that there was a positive correlation in all the given conditions. However, the degree of the correlation varied from weak to moderate level. The conditions with the compression ratio of 2:1 had higher correlation.

Table 4.35

Correlation between mSRS (in rau) and pSRS (in rau) obtained from AAI calculated from REAR in different compression conditions in Group IV

mSRS / pSRS	Compression Conditions^									
	2S55	2S65	2S85	2L55	2L65	2L85	3S65	3S85	3L65	3L85
2S55	0.568									
2S65		0.607								
2S85			0.393							
2L55				0.526						
2L65					0.264					
2L85						0.158				
3S65							0.259			
3S85								0.387		
3L65									0.268	
3L85										0.331

Note. ^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
mSRS: Measured speech recognition scores
pSRS: Predicted speech recognition scores

Table 4.36

Difference between mSRS (in rau) and pSRS (in rau)obtained from AAI and $AAI_{SLD, HLD}$ *computed using REAR, on paired 't' test for different compression conditions in Group IV*

Compression Conditions^	mSRS and pSRS predicted by					
	AAI			$AAI_{SLD, HLD}$		
	t	df	p	t	df	P
2S55				1.877	9	0.093
2S65				0.782	9	0.454
2S85				1.556	9	0.154
2L55				2.958	9	0.016*
2L65				1.236	9	0.248
2L85				1.658	9	0.132
3S55	0.432	9	0.676			
3S65				0.027	9	0.979
3S85				0.631	9	0.544
3L55						
3L65				0.000	9	1.000
3L85				0.334	9	0.746

Note. mSRS: Measured speech recognition scores;
pSRS: Predicted speech recognition scores.
AAI: Aided Audibility Index; Ranges from 0 to 1;
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
*: $p < 0.05$
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
Conditions that had $R^2 < 0.2$ are shaded and they were not considered for predicting SRS.

The results of paired t-test (Table 4.36) revealed that there was no significant difference between the predicted and measured SRS in all the conditions, except for compression ratio of 2:1 at 55 dB SPL with short time constants (2L55) (p<0.05).

4.4. Assessment of test re-test reliability

The SRS, AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ between the two trials carried out on 18% out of the 49 ears in Groups I and II were compared using Cronbach's alpha. The results of the Cronbach's alpha are given in Table 4.37. The results showed that the data had good internal consistency or reliability in majority of the conditions.

Table 4.37

Cronbach's alpha for test re-test reliability of different measures

Compression Conditions^	AAI	AAI_{SLD}	$AAI_{SLD, HLD}$	SRS
2S55	0.628	0.710	0.845	0.801
2S65	0.900	0.900	0.939	0.815
2S85	0.867	0.897	0.949	0.938
2L55	0.550	0.669	0.835	0.898
2L65	0.252	0.488	0.834	0.886
2L85	0.843	0.860	0.935	0.753
3S55	0.477	0.682	0.883	0.896
3S65	0.726	0.842	0.917	0.884
3S85	0.726	0.700	0.889	0.709
3L55	0.733	0.863	0.905	0.825
3L65	0.641	0.869	0.890	0.880
3L85	0.818	0.896	0.919	0.738

Note, AAI: Aided Audibility Index; Ranges from 0 to 1;
SLD: Speech Level Distortion correction factor
HLD: Hearing Loss Desensitization correction factor
SRS: Speech Recognition Scores
^: First character (i.e., 2 or 3) represents the compression ratio of 2:1 or 3:1;
Second character (i.e., S or L) represents time constants, short and long;
Last two characters (i.e., 55, 65, and 85) represent the presentation levels.
Conditions that had R2< 0.2 are shaded and they were not considered for predicting SRS.

The summary of the results of regression analysis and the comparison of predicted and measured SRS are presented in a table format (Table 4.38). The table summarizes the results for both the groups.

Table 4.38

Summary of results of prediction of SRS from AAI, AAI_{SLD}, and $AAI_{SLD, HLD}$ in both the groups

Prediction of SRS	Group I	Group II
	Prediction using SFAT	
Prediction of SRS from AAI	- Good Prediction	- Poor Prediction
Prediction of SRS from AAI_{SLD}	- Good prediction - Prediction from AAI = Prediction from AAI_{SLD}	- Prediction from AAI_{SLD} > Prediction from AAI
Prediction of SRS from $AAI_{SLD, HLD}$	- Good prediction - Prediction from AAI = Prediction from AAI_{SLD}, $AAI_{SLD, HLD}$	- Prediction from $AAI_{SLD, HLD}$> Prediction from AAI & AAI_{SLD}
	Prediction using REAR	
Prediction of SRS from AAI	- Average prediction - Prediction using SFAT > Prediction from REAR	- Poor prediction
Prediction of SRS from AAI_{SLD}	- Average prediction - Prediction using SFAT > Prediction from REAR	- Poor prediction
Prediction of SRS from $AAI_{SLD, HLD}$	- Average prediction - Prediction from AAI < Prediction from AAI_{SLD}< Prediction from $AAI_{SLD, HLD}$ - Prediction using SFAT > Prediction from REAR	- Average prediction - Prediction from AAI and AAI_{SLD}< Prediction from $AAI_{SLD, HLD}$ - Prediction using SFAT > Prediction from REAR

The summary of the results of regression analysis of AAI and SRS showed that the AAI obtained from sound filed thresholds could be used for prediction of SRS; whereas, AAI computed from REAR was not a good predictor of SRS in Group I. Addition of correction factors such as SLD and HLD was not required in this group. Whereas, addition of correction factors such as SLD and HLD, as in AAI_{SLD} and $AAI_{SLD, HLD}$, improved the prediction of SRS in the group with severe hearing loss.

CHAPTER 5

DISCUSSION

The primary objective of the present study was to evaluate the utility of aided audibility index (AAI) and speech recognition scores (SRS) in selection of suitable compression ratio and compression time constants using AAI computed with sound field aided thresholds (SFAT), and SRS in two groups of individuals. The Group I contained ears of individuals with mild to moderately-severe sensorineural hearing loss and Group II contained ears of individuals with severe sensorineural hearing loss. The second objective was to derive an equation for predicting the SRS from AAI, AAI with speech level distortion (SLD) correction factor, i.e., AAI_{SLD} and AAI with SLD and hearing loss desensitization (HLD) correction factors, i.e., $AAI_{SLD, HLD}$ computed using SFAT and real ear aided response (REAR), with compression ratios of 2:1 and 3:1, and short (attack time = 2 ms and release time = 40 ms) and long (attack time = 20 ms and release time = 640 ms) time constants at three presentation levels, in Group I and Group II. Another objective of the study was to verify the derived equation for prediction of SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed using SFAT and REAR, on two different groups (Group III and Group IV) of participants. Statistical analyses were carried out to analyze the effect of compression parameters on AAI and SRS in Groups I and II; and to derive an equation to predict SRS from AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ computed using SFAT and REAR. The results of the study are discussed in the following sections.

5.1. Effect of compression parameters on AAI and SRS in Group I

Two compression parameters were considered in the study, compression ratio and release time. The statistical analysis showed that the AAI was similar across different compression parameters in the Group I, though descriptive analysis revealed differences in AAI across compression conditions (Table 4.1). That is, changing the compression ratio from 2:1 to 3:1 and time constants from short to long did not make a difference in the AAI.

These results in Group I could be because of the measured compression ratio (MCR) obtained in different compression conditions. Higher MCR is usually associated with lower dynamic range of speech. The MCR is used to estimate the audibility of speech peaks for an individual (Souza & Turner, 1999; Stelmachowicz et al., 1994). In the current study, the MCR for longer time constants was slightly lesser (around 1.1:1 at 65 dB SPL input level irrespective of compression ratio) when compared to that of shorter time constants (around 1.2:1 at 65 dB SPL input level), irrespective of compression ratio setting on the hearing aid. This pattern was observed for all the presentation levels.

These results are similar to that observed by Henning and Bentler (2008). They found that the MCR to be 1.4:1 and 2:1 for the nominal compression ratio (NCR, the compression ratio that is set in the computer) of 2:1 and 4:1 respectively, for a four channel hearing aid with the release time of 32 ms. However, the MCR was obtained only at 65 dB SPL in their study. Henning and Bentler further reported that for both the NCRs, i.e., of 2:1 and 4:1, the MCR became closer to NCR as the release time decreased. However, the effect of release time was more prominent for the NCR of 4:1 only. The small difference in the MCR between the short and long time constants, in the current study, than that reported by Henning and Bentler, could be due to the fact that compression ratios chosen in the current study were very close to each other (i.e., 2:1 and 3:1). In addition, the MCR for 2:1 and 3:1 did not differ much. The above results imply that though there was an effect of release time on MCR, it was very small, and hence, the AAI was similar across time constants and compression ratios.

The SRS did not differ statistically across different compression parameters. Boike and Souza (2000) found that there was no effect of compression ratio on speech recognition in quiet. The reasons cited for AAI might also contribute to similar SRS across compression ratios and time constants. That is, the effect of time constants, as reflected in MCR, is so small that its effect is not revealed on the SRS. Another reason could be that the sentences were presented in quiet in the present study. Boike and Souza (2000) found that the compression ratio affected the speech recognition in noise in individuals with mild to moderate sensorineural hearing loss. In noise, the compression ratio has been reported to affect the output as a negative effect of compression is to amplify noise, if any, present during gaps in speech signal (Dillon, 1996; Moore et al., 1999). This results in masking effect and at higher compression ratios, the masking effect could have been greater resulting in poorer performance at higher compression ratios (Boike & Souza, 2000). Hence*, the null hypothesis 1.4.1a (given in Chapter 1) is accepted, i.e., there is no effect of compression ratio and time constants on SRS and AAI in individuals with mild to moderately-severe hearing loss*.

The selection of compression ratio of 2:1 vs. 3:1, and short vs. long time constants does not make any change in the sentence perception in quiet or in AAI in individuals with mild to moderately-severe with hearing loss. Hence, in quiet, any of the settings included in this study could be selected in the individuals with lesser degree of hearing loss.

Nevertheless, the AAI and SRS depended on the presentation levels across different compression settings. The AAI increased as the presentation level increased. Souza and Turner (1999) have also reported an increase in AAI with increase in the intensity level. This could be because, though the compression amplification provides more gain for soft sounds and lesser gain for louder sounds, the overall output was still higher for the higher input levels, resulting in higher audibility of the signal.

The above study revealed a lesser AAI compared to that seen in the present study, irrespective of the presentation level. The reason for this could be the difference in the compression settings and the stimuli used. They had used compression threshold of 45 dB SPL, whereas the present study used a compression threshold of 55 dB SPL. Higher knee-point has been reported to result in lesser reduction in the dynamic range of speech (Henning & Bentler, 2008). Further, the attack time and release time (i.e., time constants) used in the earlier study was much shorter than the present study. Reports show that as the time constants and compression threshold reduce, the dynamic range of speech also reduces (Henning & Bentler, 2008). Reduction of the dynamic range results in lesser audibility and thus lower AAI. In addition, they had used VCV syllables whereas in the present study sentences were used. Sentences have higher amplitude distribution than VCV syllable (Verschuure et al., 1996). These differences might have resulted in differences in the AAI between the two studies.

The results also showed that the SRS increased with increase in the input level. A similar trend was reported by Souza and Turner (1999). This is due to the fact that compression amplification makes the loud signals comfortable and less distorted (Dillon, 2001). Hence, at higher levels, the sentence recognition scores improved.

At 65 and 85 dB SPL, the SRS obtained in their study was much lower than that obtained in the present study. Souza and Turner had used VCV syllables, whereas, in the present study sentences were used. Higher scores in the present study could be due to higher redundancy for sentences (Miller, Heise, & Lichten, 1951) which was used as the test material.

In the present study, the SRS ranged between 73% to 78% at 55 dB SPL, which are lower than that obtained at a presentation level of 65 or 85 dB SPL. Souza and Turner (1999) have also reported comparable SRS at a presentation level of 55 dB SPL. This indicates that, though sufficient gain was given for lower intensity level signals, there are important speech components which are inaudible that even contextual cues or redundancy in the sentence could not improve the scores.

The above findings suggest that intensity level is a factor that affects AAI as well as speech intelligibility. In the routine hearing aid evaluation, speech intelligibility is usually measured at only one intensity level. The results of the present study suggest that the hearing aid testing protocols need to be revised to include at least three input levels. Since the number of clients is more, readily available information on the compression parameters appropriate for different degrees of hearing loss would be useful. The information on the compression parameters helpful at different presentation levels would be useful information for the manufacturer who can incorporate this into the adaptive algorithm of the hearing aids.

5.2. Effect of compression parameters on AAI and SRS in Group II

Unlike the compression ratio, in the Group II, the AAI was influenced by the time constants. That is, at all the presentation levels, the shorter time constants resulted in a significantly higher AAI when compared to longer time constants. This could be due to the fact that the shorter release time decreases the difference in intensity between peaks and valleys in speech. This reduction could have improved the speech audibility (Jenstad & Souza, 2005). Whereas, the AAI did not differ between the compression ratios (2:1 and 3:1) even in Group II. There was no difference between SRS across the compression ratios and time constants. Similar results have also been reported in the literature, that is, no change in the speech recognition in quiet was observed with change in the time constants (Dreschler, 1989; Jerlvall & Lindblad, 1978; Moore & Glasberg, 1986; Schweitzer & Causey, 1977) or compression ratio (Boike & Souza, 2000; Fikret-Pasa, 1994). This could be due to the fact that sentences were presented in quiet, as explained in the Section 4.1. Further, the effect size of difference between AAI for different time constants was good. Hence, it could be stated that *the null hypothesis 1.4.1b (given in Chapter 1) is partly accepted in individuals with severe hearing loss, i.e., there is no effect of compression ratio on AAI and SRS; however, there is an effect of time constants on AAI alone*.

In Group II, the AAI values ranged between 0.78 and 0.85. This indicates that 78% to 85% of signals are audible irrespective of the compression condition. This implies that the non-linear hearing aid provided good audibility to individuals even with severe hearing loss. Souza and Bishop (1999) reported an AAI of 0.68 and 0.85 at 70 and 85 dB SPL presentation levels respectively, for a single channel compression hearing aid with a compression ratio of 2:1 and short time constants (attack time = 3 ms; release time = 25 ms). These results are comparable with the AAI with short time constants at higher presentation level. At moderate presentation levels in the present study, the AAI (0.78) was higher when compared to that of the previous study. This could be because of the compression settings used. In the earlier study, shorter time (attack time = 3 ms; release time = 25 ms) constants and lower compression thresholds (45 dB SPL) were used. As mentioned earlier, these settings result in reduced dynamic range of speech (Henning & Bentler, 2008) which in turn leads to lower AAI.

The AAI and SRS were higher in all the conditions in Group I when compared to Group II. Souza and Bishop (1999) also reported similar results. These results could be because the individuals with severe hearing loss have much more loss of audibility and spectral resolution than that in individuals with mild to moderate degree of hearing loss (Rosen, 1989; Van Tasell, Soli, Kirby, & Widin, 1987; Moore, 1996). Even, the SRS was higher in Group I when compared to Group II. Hence, it could be said that the shorter time constants is preferable in the individuals with severe hearing loss. The compression ratio could be either 2:1 or 3:1.

The AAI and SRS in the Group II had a similar trend as in the Group I, that is, AAI and SRS increased with increase in intensity. Souza and Bishop (1999) have shown that the AAI and SRS increased with increase in the intensity level even in the group with severe hearing loss. These results support the results of the present study. The SRS was also significantly different between all presentation levels. As the level increased the SRS increased. The output of hearing aid increased with increase in intensity level, hence, there was an increase in the audibility with increase in intensity and hence, the SRS also improved.

Another observation in the present study was that the improvement seen with increase in AAI with the increase in the input level was more with severe degree of hearing loss (0.01 to 0.07 increase) when compared to that of mild to moderately-severe group (0.01 to 0.02 increase), though the overall benefit was lesser. The SRS also varied from 41 to 45% at 55 dB SPL, 75 to 79% at 65 dB SPL, 88 to 90% at 85 dB SPL in Group II. There was a great amount of improvement in SRS as the input level increased, i.e., 73 to 77 % at 55 dB SPL, 93 to 95 % at 65, to 96% at 85 dB SPL. This indicates that there is a higher rate of improvement as the level increased, in Group II. Souza and Bishop (1999) also observed a similar trend in the group with severe hearing loss on the sentence recognition task.

The reason for this could be that the outer hair cells, that are responsible for perception of soft sounds, are damaged in the mild to moderate hearing damage. Hence, the inner hair cells get stimulated once the input level reaches a moderate level (Schum, 2016). This does not happen in individuals with severe hearing loss individuals wherein most of the inner hair cells are also damaged. Hence, the sounds may be distorted even with amplification (Moore, 1996). This distortion, along with the inaudibility of soft consonants at the softer input level might have resulted in poor sentence perception. As the level increased, the audibility of the sounds improved resulting in a sudden increase in the performance; however due to the distortion, the scores are poorer compared to mild to moderate hearing loss.

5.3. Prediction of SRS using AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ with SFAT in Group I

Regression analysis for arriving at the equation that could best fit the data revealed that a power equation using the least squares method could fit the data. There are studies in literature that have also used power equations to predict speech intelligibility (Fletcher & Galt, 1950; Humes, 1986; Manjula, 2007; Studebaker & Sherbecoe, 1993; Wilde & Humes, 1990). The results of the present study showed that the power model was highly significant for all the tested conditions, though the R^2 values were high only at 55 dB SPL level of presentation, irrespective of the compression ratio and time constants, when compared to the other levels of input. A significant F-test, even when the R^2 is not very high, indicates that the tested model can be used reliably to predict the dependent variable, i.e., speech recognition (Arhin & Noel, 2015; Grace- Martin, 2012). Hence, the power function given in the present study can be used reliably to predict SRS from AAI.

In addition, the difference between the measured and predicted scores was comparable and there was a moderate level of agreement between the two in most of the conditions. Hence, it can be inferred from the present study that the AAI can predict the SRS. There are many studies that have reported similar results in individuals with mild to moderate hearing loss (Kamm, Dirks & Bell, 1985; Manjula, 2007; Souza & Turner, 1999).

In the current study, though the addition of SLD and HLD correction resulted in the better R^2 values, especially at higher presentation levels, the SRS predicted from AAI was more closer to the mSRS in majority of the conditions than that obtained from AAI_{SLD} and $AAI_{SLD, HLD}$. Hence, *the null hypothesis 1.4.2a is rejected. That is, the AAI,* AAI_{SLD} *and* $AAI_{SLD, HLD}$ *computed using SFAT can be used to predict the speech* *recognition scores for different compression settings in individuals with mild to moderately-severe hearing loss*. These results are similar to that observed for non-linear compression hearing aids (Ching et al., 1998; Ching et al., 2001; Magnusson et al., 2001) and linear hearing aids (Manjula, 2007) in lesser degree of hearing loss. This implies that the SLD and HLD correction factors were not necessary for predicting SRS in a compression hearing aid for individuals with mild to moderately-severe hearing loss.

5.4. Prediction of SRS using AAI, AAI$_{SLD}$ and AAI$_{SLD, HLD}$ with SFAT in Group II

In individuals with severe sensorineural hearing loss (Group II) also, the power equation could fit the data, though this was true only for a few aided conditions. These results are consistent with the results of many other studies (Ching et al., 1998; Ching et al., 2001; Davies-Venn et al., 2009; Manjula, 2001; Souza & Bishop, 1999). These authors reported that providing high amount of amplification does not always improve intelligibility. They also reported that the ability of listeners with severe hearing loss to extract the cues and thus the speech intelligibility does not improve much at higher gain, especially, at the frequencies where the hearing loss is severe. These researchers have recommended the use of SLD and HLD correction as it improved the predictive ability in individuals with severe hearing loss. The results of the present study support these results.

In the current study, addition of SLD and HLD correction factors resulted in better pSRS in individuals with severe hearing loss. Hence, *the null hypothesis 1.4.2b is partly rejected, i.e., the AAI (computed using SFAT) only with SLD and HLD corrections are significant predictors of SRS, in individuals with severe hearing loss*.

The results of the current study support the fact that the factors other than audibility, such as speech level distortion and hearing loss desensitization affect the prediction of speech intelligibility in individuals with severe degree of hearing loss (Ching et al., 1998; Ching et al., 2001; Davies-Venn et al., 2009; Manjula, 2007). Hence, addition of SLD and HLD factors improve correlation between AAI and speech intelligibility in individuals with severe hearing loss. Hence, *the null hypothesis 1.4.2b is partly accepted. That is, the AAI and* AAI_{SLD} *are not effective predictors of SRS; whereas* $AAI_{SLD,\ HLD}$ *computed using SFAT can be used to predict the speech recognition scores for different compression settings in individuals with severe hearing loss.*

5.5. Prediction of SRS using AAI, AAI_{SLD} and $AAI_{SLD,\ HLD}$ with REAR

The prediction of SRS from AAI, AAI_{SLD} and $AAI_{SLD,\ HLD}$ computed using REAR was not significant in many of the aided conditions in both the groups. Hence, *the null hypotheses 1.4.3a and 1.4.3b are accepted, i.e., the AAI,* AAI_{SLD} *and* $AAI_{SLD,\ HLD}$ *computed using REAR are not the significant predictors of speech recognition scores for different compression settings in individuals with mild to moderately-severe hearing loss, and severe hearing loss*. These results contradict the results of Dillon (1993). His study revealed that SII computed using real ear SPL could predict speech scores for linear hearing aid in listeners with mild to moderate hearing loss. The differences in the results between two studies could be because of many procedural differences. First, the hearing aid used was a linear hearing aid in the earlier study. The SPL in the ear canal varies with presentation level when a non-linear hearing aid is used. Hence, the results reported by Dillon could not be directly compared with results of non-linear hearing aids. The second difference is that Dillon had averaged the SPL across different frequencies and used the averaged value for the analysis. Whereas, the SPL at different frequencies was considered for the analysis in the present study. The SPL in the ear canal varies drastically across frequencies and hence, averaging the SPL across frequencies may be inappropriate.

In the present study, the reason for the poor predictive ability in using AAI computed using REAR could be because of the very nature of the real ear measures. That is, the REAR involves measurement of real ear SPL and this does not represent the processing in the inner ear or at higher auditory system in any way. Hence, the REAR may not have the ability to predict the recognition of speech in compression system. The prediction was slightly better from $AAI_{SLD, HLD}$ when compared to AAI and $AAI_{SLD.}$ Yet, it could be inferred that AAI computed using REAR may not be as good as the AAI computed using SFAT for prediction of SRS.

It is clear from the above discussion that the compression parameters did not have any significant effect on AAI and SRS in individuals with lesser degree of hearing loss. In the present study, the compression ratios were limited to 2:1 and 3:1. Future research on AAI could focus on compression ratios that are spaced apart. In addition, performance with the speech material in the presence of noise could be addressed. A wide range of compression parameters and settings could be chosen and be evaluated using AAI. Whereas, there was an effect of time constants in individuals with severe hearing loss. Further, prediction of speech recognition scores from aided audibility index was better in individuals with lesser degree of hearing loss than with that in individuals with severe degree of hearing loss.

CHAPTER 6

SUMMARY AND CONCLUSIONS

The present study aimed at evaluating the utility of aided audibility index (AAI) and speech recognition scores (SRS) in selection of compression parameters; and the efficiency of AAI in prediction of SRS. The objectives of the present study were to evaluate the effect of compression ratio and time constants on AAI (calculated using sound field aided thresholds) and SRS at presentation levels of 55, 65, and 85 dB SPL presentation levels. The objective was also to study the ability of AAI (computed with sound field aided thresholds - SFAT, and real ear aided response - REAR) in predicting the speech recognition scores (SRS) by deriving regression equation. Further, the ability of the regression equation to predict the SRS was verified on separate group of individuals. Two groups of participants were considered, Group I comprised of 25 ears with mild to moderately- severe sensorineural hearing loss of participants whose age ranged from 18 to 55 years; and the Group II comprised of 24 ears with severe sensorineural hearing loss of participants whose age ranged from 18 to 56 years.

The method included four stages. Stage I involved measurement of REAR, SFAT, and aided SRS in the aided conditions that included different combinations of compression ratios and compression time constants at three input levels, in the two groups. Stage II comprised of measurement of the hearing aid output and calculation of measured compression ratio (MCR). In Stage III, an excel sheet format for computing AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ was generated. Then, derivation of regression equation to predict aided SRS using Aided Audibility Index AAI, AAI_{SLD} and $AAI_{SLD, HLD}$ was done. This equation was used to predict SRS in two separate groups (Group III with mild to moderately severe hearing loss and Group IV with severe hearing loss) of ten individuals in each group. Stage IV involved comparison of the predicted and measured SRS in these groups.

The results revealed that, though there was no statistical difference in AAI and SRS across different compression settings that were included in the present study, in Group I, there were differences in mean AAI across compression settings than in SRS. The AAI and SRS improved with increase in presentation level. On the other hand in Group II, at all the presentation levels, shorter time constants resulted in significantly higher AAI when compared to longer time constants, irrespective of the compression ratios. There was no significant effect of compression parameters at any of the presentation levels on SRS even in this group. In addition, there was an effect of level on AAI and SRS in this group as well, higher presentation level resulting in higher AAI and SRS. Thus, it can be construed that selecting either of the compression ratios, 2:1 or 3:1, does not make a difference. This is true even for the time constants in the Group I.

In Group II, time constants have to be selected with caution. The intensity level is a factor that affects AAI as well as speech intelligibility. In the routine hearing aid evaluation, speech intelligibility is usually measured at only one intensity level, ie., at conversation level which is 45 dB HL. The results of the present study suggest that the hearing aid testing protocols need to be revised to include more input levels.

The results of regression analysis of AAI and SRS showed that the AAI obtained from sound field aided thresholds could be used for prediction of SRS whereas AAI computed from REAR was not a good predictor of SRS in Group I. Addition of correction factors such as SLD and HLD was not required in Group I.

Whereas, addition of correction factors such as SLD and HLD, as in AAI_{SLD} and $AAI_{SLD, HLD}$, improved the prediction of SRS in the group with severe hearing loss. This implies that the SLD and HLD correction factors were not necessary for predicting SRS through a compression hearing aid for individuals with mild to moderately-severe hearing loss.

It can be concluded that the time constants have to be set with caution for individuals with severe hearing loss; whereas, for individuals with mild to moderately-severe hearing loss, selection of time constants and compression ratio does not have to be stringent for quiet situation. Thus, the AAI can be more useful than SRS in selection of compression parameters. In addition, the results of the present study suggest that the hearing aid testing protocols need to be revised to include more input levels. Aided audibility index is also useful in predicting the speech recognition in compression hearing aids, especially for lesser degree of hearing loss; whereas, in individuals with severe hearing loss, addition of speech level distortion and hearing loss desensitization factors is recommended.

5.1. Implications of the study

The following are the implications of the study:

1. AAI reflects the difference between compression parameters better than the sentence recognition. Hence, AAI is an useful measure for differentiating the compression parameters.
2. The results of the present study will help in fine tuning of non-linear hearing aids for different degrees of hearing loss considered in the study.

3. The results of the study support the literature that the AAI will be useful in predicting the speech recognition in compression hearing aids just by having the aided thresholds.

4. This makes the hearing aid fitting easier clinically, as rough estimate of the speech intelligibility can be obtained even in the absence of speech material in a particular language. Hence, making it more useful for-

    a) children, as most of the young children do not have adequate vocabulary for formal speech tests. This, however, has to be systematically studied in children, before any conclusion is drawn.

    b) adults who are non-verbal.

5.2. Future directions

1. Future research on AAI could focus on compression ratios that are spaced apart.

2. Performance with the speech material in the presence of noise could be assessed.

3. A wide range compression parameters and settings could be chosen and be evaluated using AAI.

4. Performance at different presentation levels with linear and non-linear hearing aids can be compared.

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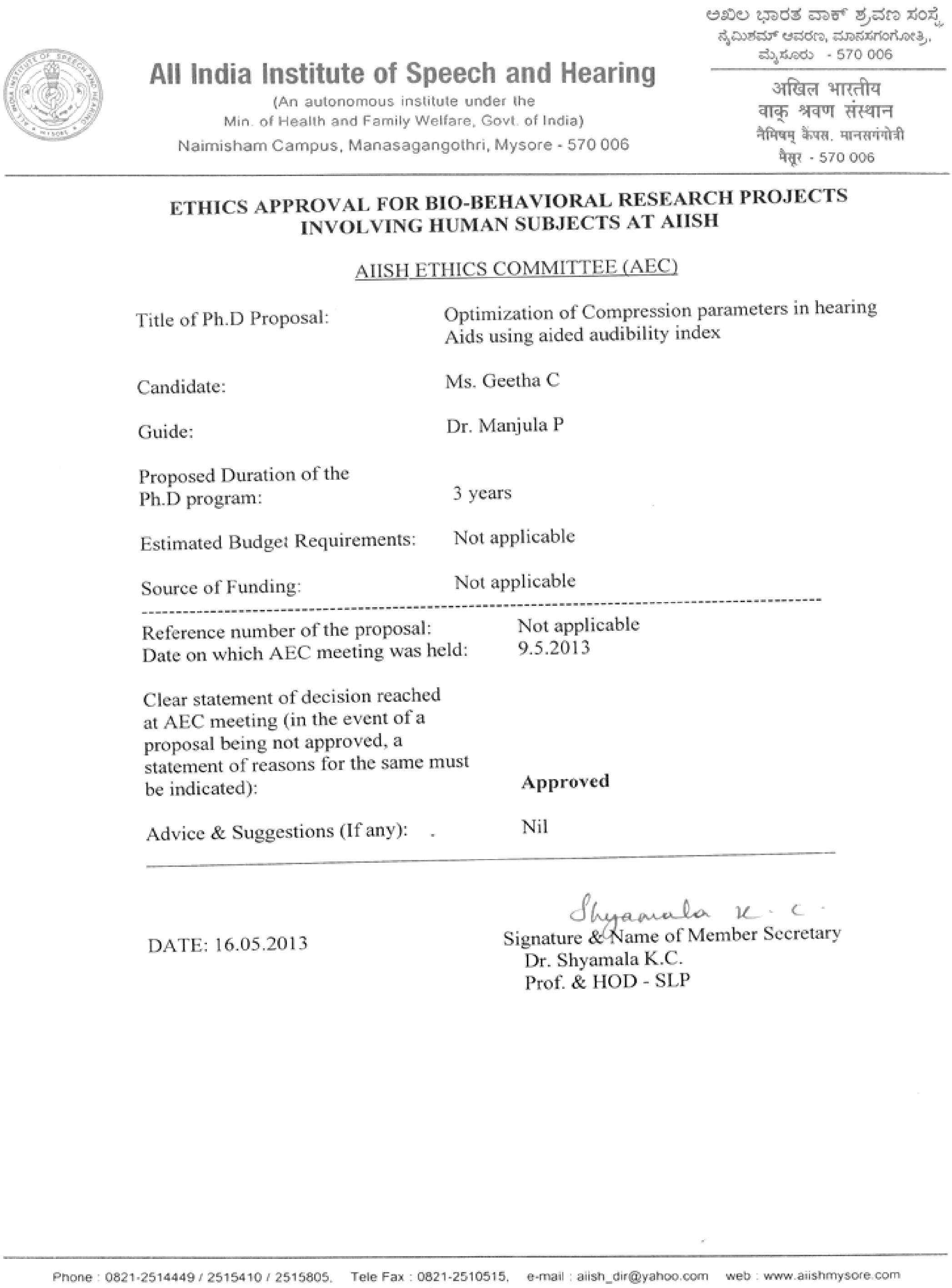
APPENDIX A



ಅಖಿಲ ಭಾರತ ವಾಕ್ ಶ್ರವಣ ಸಂಸ್ಥೆ
ನೈಮಿಶಮ್ ಆವರಣ, ಮಾನಸಗಂಗೋತ್ರಿ,
ಮೈಸೂರು - 570 006

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वाक् श्रवण संस्थान
नैमिषम् कैंपस, मानसगंगोत्री
मैसूर - 570 006

ETHICS APPROVAL FOR BIO-BEHAVIORAL RESEARCH PROJECTS INVOLVING HUMAN SUBJECTS AT AIISH

AIISH ETHICS COMMITTEE (AEC)

Title of Ph.D Proposal:	Optimization of Compression parameters in hearing Aids using aided audibility index
Candidate:	Ms. Geetha C
Guide:	Dr. Manjula P
Proposed Duration of the Ph.D program:	3 years
Estimated Budget Requirements:	Not applicable
Source of Funding:	Not applicable

Reference number of the proposal:	Not applicable
Date on which AEC meeting was held:	9.5.2013
Clear statement of decision reached at AEC meeting (in the event of a proposal being not approved, a statement of reasons for the same must be indicated):	**Approved**
Advice & Suggestions (If any):	Nil

DATE: 16.05.2013

Shyamala K.C.
Signature & Name of Member Secretary
Dr. Shyamala K.C.
Prof. & HOD - SLP

Phone : 0821-2514449 / 2515410 / 2515805, Tele Fax : 0821-2510515, e-mail : aiish_dir@yahoo.com web : www.aiishmysore.com

APPENDIX B

Measured and predicted speech recognition scores from AAI computed using SFAT in Group I

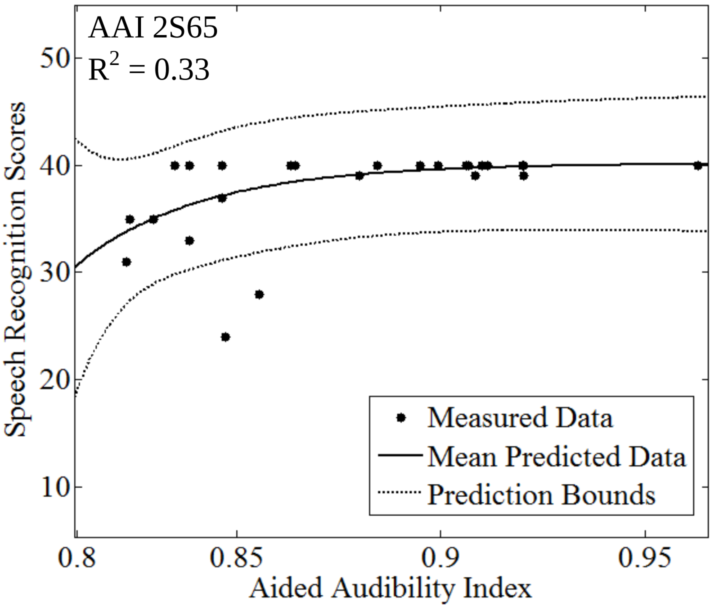

Figure 1. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 2S65 in Group I. The AAI was computed using SFAT. Here, 2S65 is the compression ratio of 2:1 with short time constants, at presentation level of 65 dB SPL.

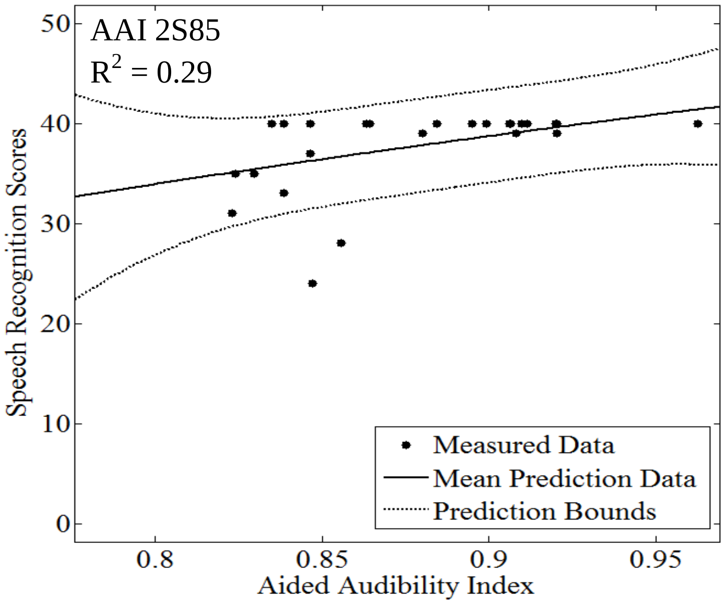

Figure 2. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 2S85 in Group I. The AAI was computed using SFAT. Here, 2S85 is the compression ratio of 2:1 with short time constants, at presentation level of 85 dB SPL.

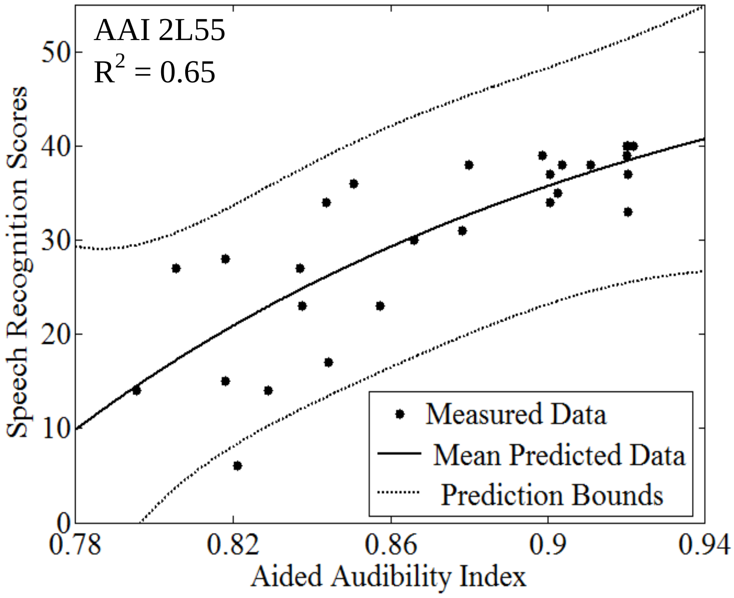

Figure 3. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 2L55 in Group I. The AAI was computed using SFAT. Here, 2L55 is the compression ratio of 2:1 with long time constants, at presentation level of 55 dB SPL.

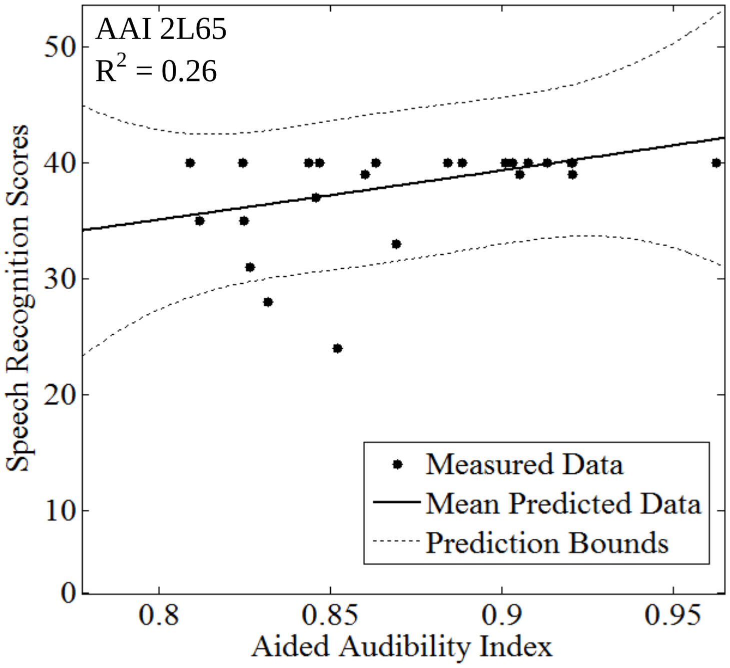

Figure 4. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 2L65 in Group I. The AAI was computed using SFAT. Here, 2L65 is the compression ratio of 2:1 with long time constants, at presentation level of 65 dB SPL.

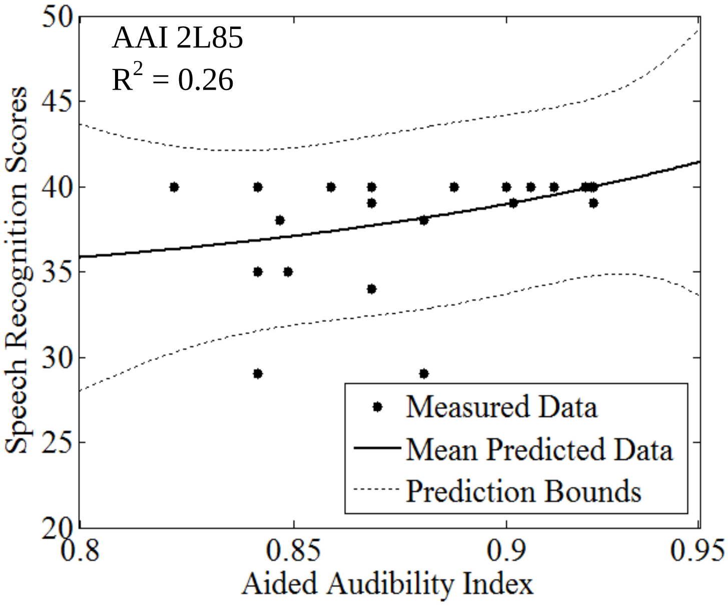

Figure 5. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 2L85 in Group I. The AAI was computed using SFAT. Here, 2L85 is the compression ratio of 2:1 with long time constants, at presentation level of 85 dB SPL.

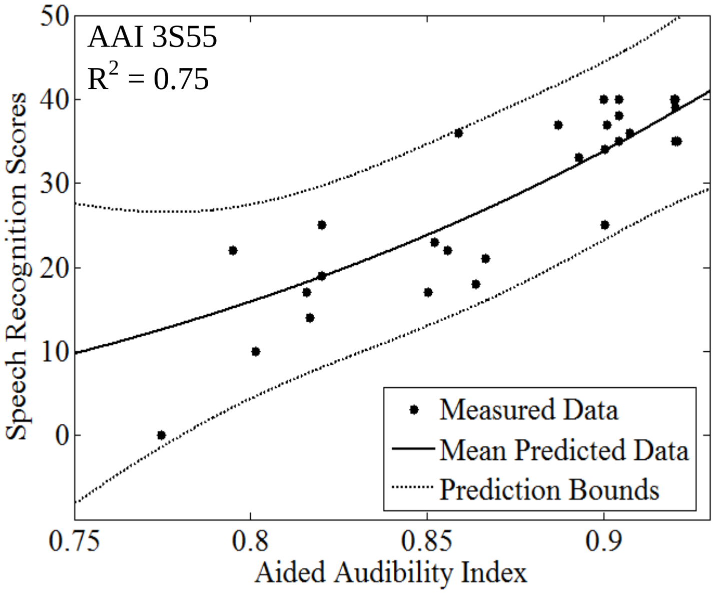

Figure 6. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 3S55 in Group I. The AAI was computed using SFAT. Here, 3S55 is the compression ratio of 3:1 with short time constants, at presentation level of 55 dB SPL.

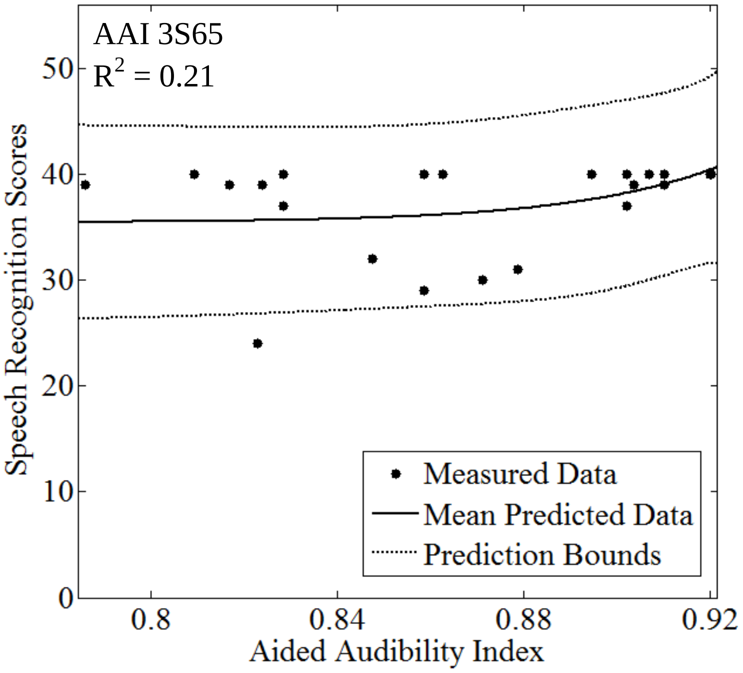

Figure 7. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 3S65 in Group I. The AAI was computed using SFAT. Here, 3S65 is the compression ratio of 3:1 with short time constants, at presentation level of 65 dB SPL.

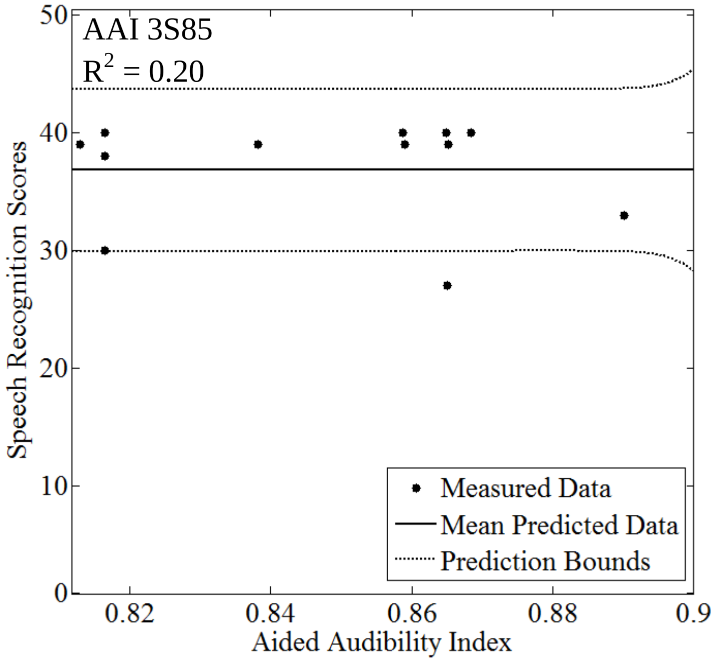

Figure 8. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 3S85 in Group I. The AAI was computed using SFAT. Here, 3S85 is the compression ratio of 3:1 with short time constants, at presentation level of 85 dB SPL.

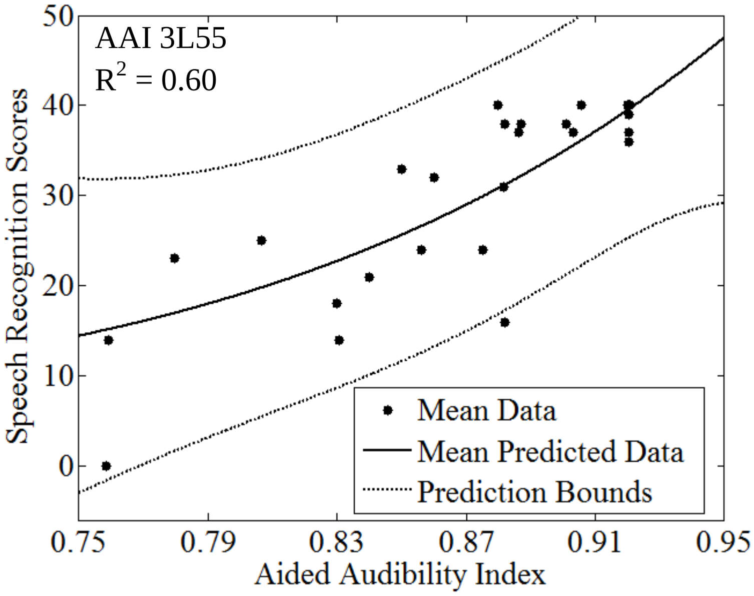

Figure 9. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 3L55 in Group I. The AAI was computed using SFAT. Here, 3L55 is the compression ratio of 3:1 with long time constants, at presentation level of 55 dB SPL.

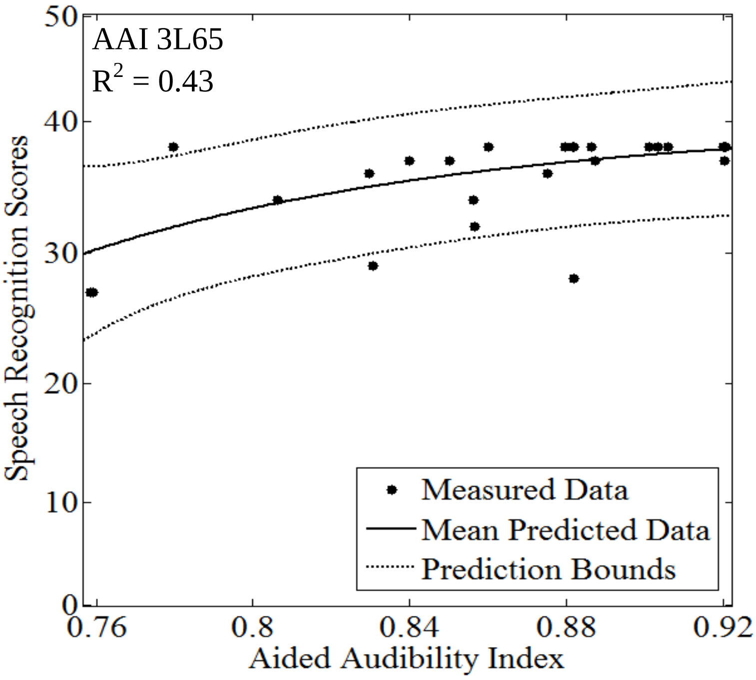

Figure 10. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 3L65 in Group I. The AAI was computed using SFAT. Here, 3L65 is the compression ratio of 3:1 with long time constants, at presentation level of 65 dB SPL.

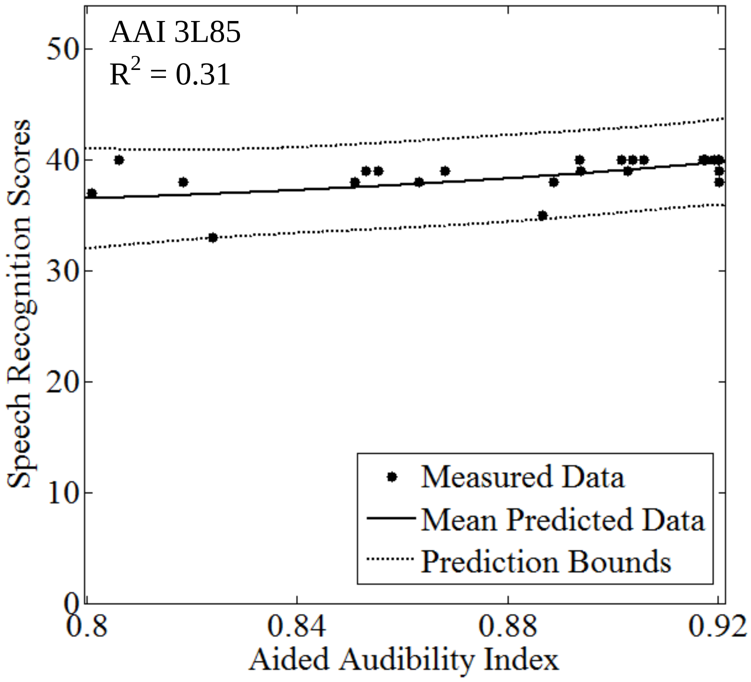

Figure 11. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 3L85 in Group I. The AAI was computed using SFAT. Here, 3L85 is the compression ratio of 3:1 with long time constants, at presentation level of 85 dB SPL.

APPENDIX C

Measured and predicted speech recognition scores from $\mathrm{AAI}_{\mathrm{SLD}}$ computed using SFAT in Group I

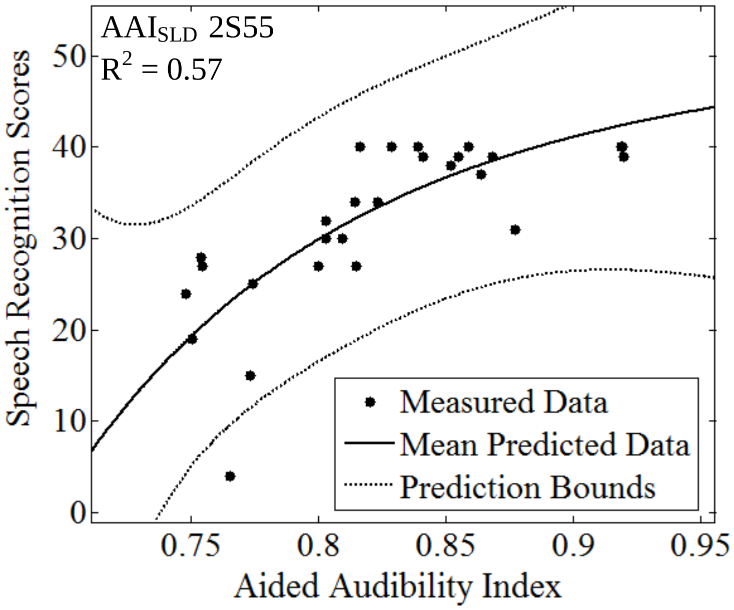

Figure 1. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $\mathrm{AAI}_{\mathrm{SLD}}$ in 2S55 in Group I. The $\mathrm{AAI}_{\mathrm{SLD}}$ was computed using SFAT. Here, 2S55 is the compression ratio of 2:1 with short time constants, at presentation level of 55 dB SPL.

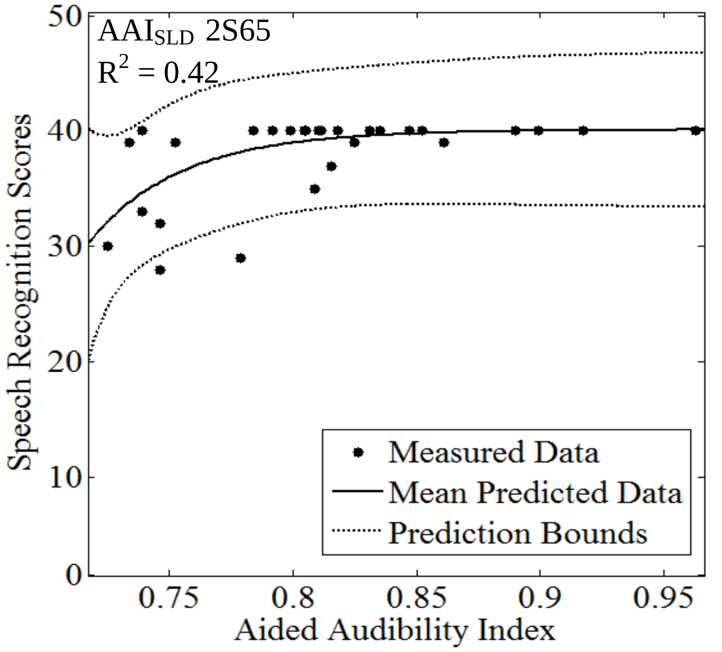

Figure 2. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $\mathrm{AAI}_{\mathrm{SLD}}$ in 2S65 in Group I. The $\mathrm{AAI}_{\mathrm{SLD}}$ was computed using SFAT. Here, 2S65 is the compression ratio of 2:1 with short time constants, at presentation level of 65 dB SPL.

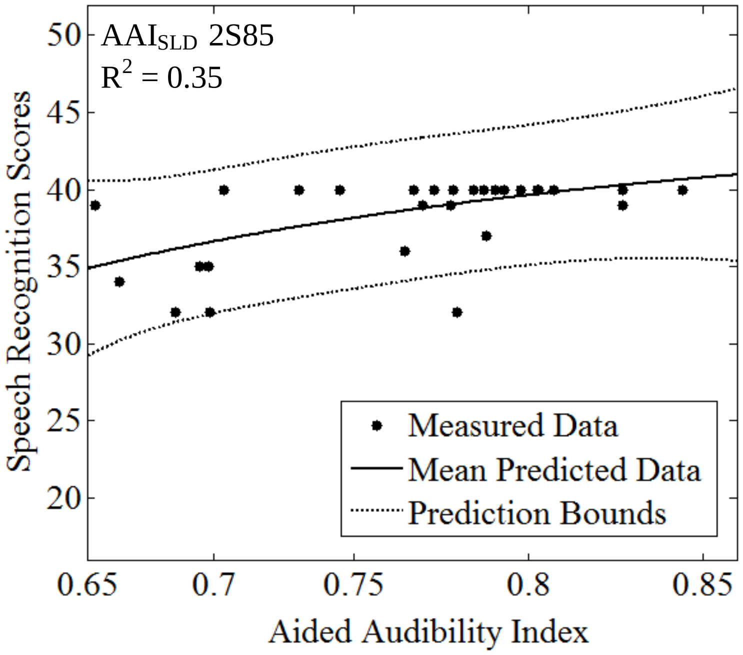

Figure 3. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 2S85 in Group I. The AAI$_{SLD}$ was computed using SFAT. Here, 2S85 is the compression ratio of 2:1 with short time constants, at presentation level of 85 dB SPL.

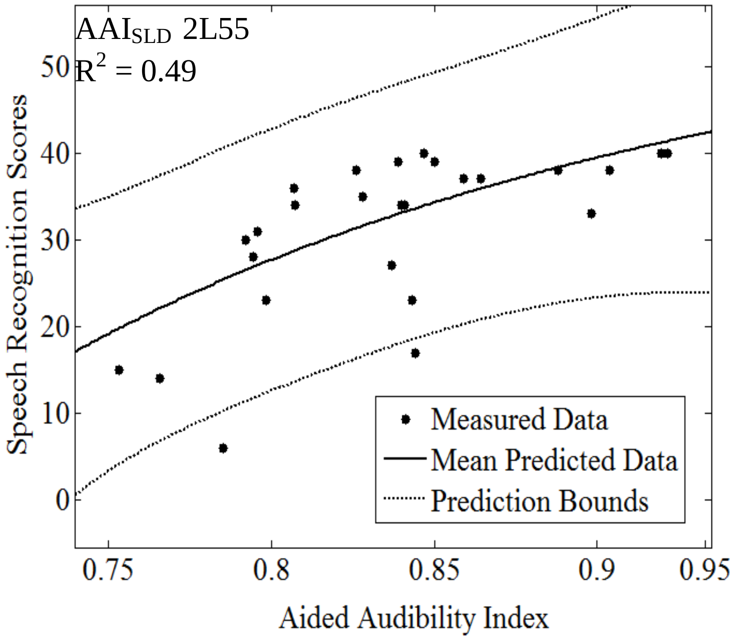

Figure 4. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 2L55 in Group I. The AAI$_{SLD}$ was computed using SFAT. Here, 2L55 is the compression ratio of 2:1 with long time constants, at presentation level of 55 dB SPL.

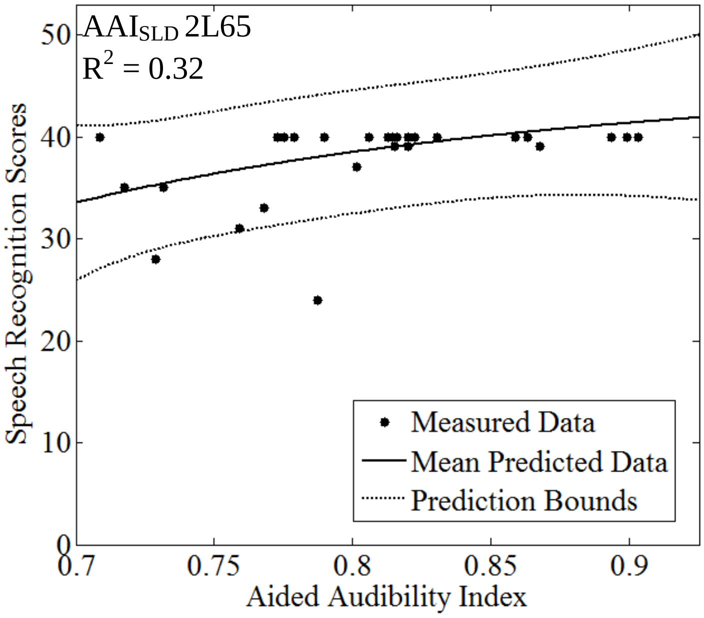

Figure 5. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 2L65 in Group I. The AAI$_{SLD}$ was computed using SFAT. Here, 2L65 is the compression ratio of 2:1 with long time constants, at presentation level of 65 dB SPL.

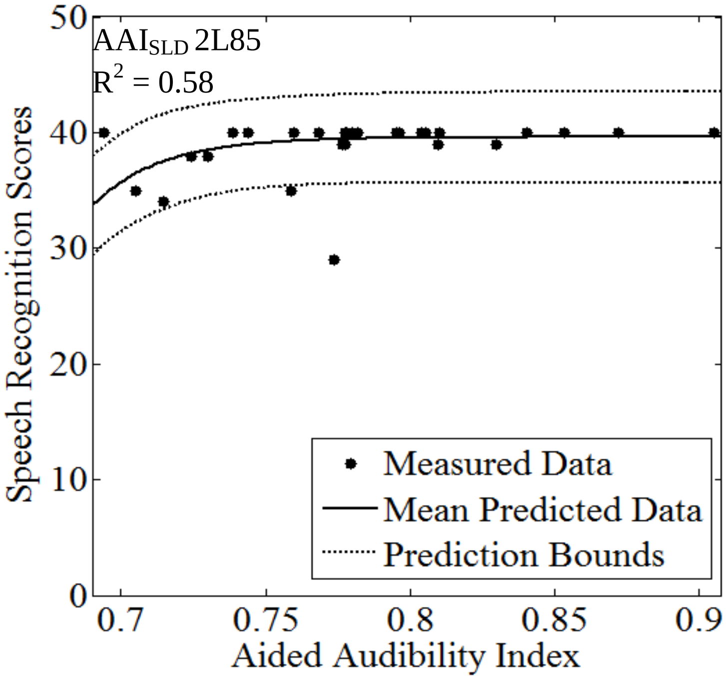

Figure 6. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 2L85 in Group I. The AAI$_{SLD}$ was computed using SFAT. Here, 2L85 is the compression ratio of 2:1 with long time constants, at presentation level of 85 dB SPL.

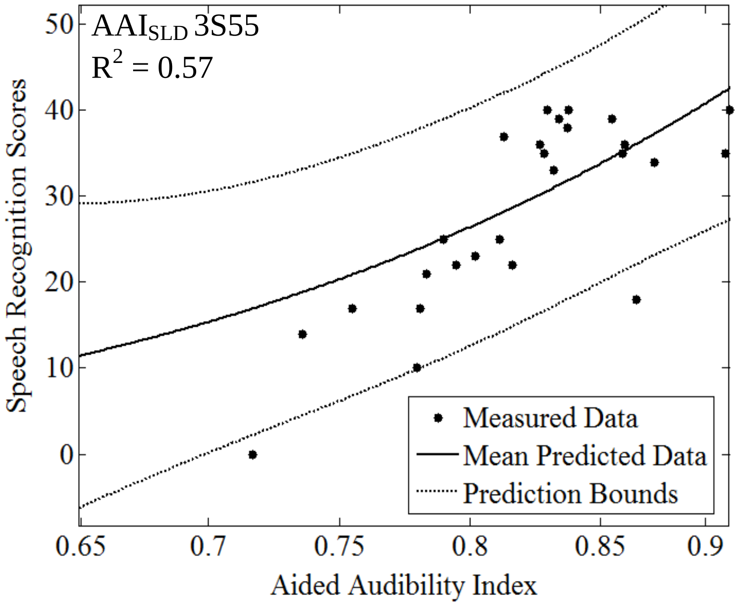

Figure 7. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 3S55 in Group I. The AAI$_{SLD}$ was computed using SFAT. Here, 3S55 is the compression ratio of 3:1 with short time constants, at presentation level of 55 dB SPL.

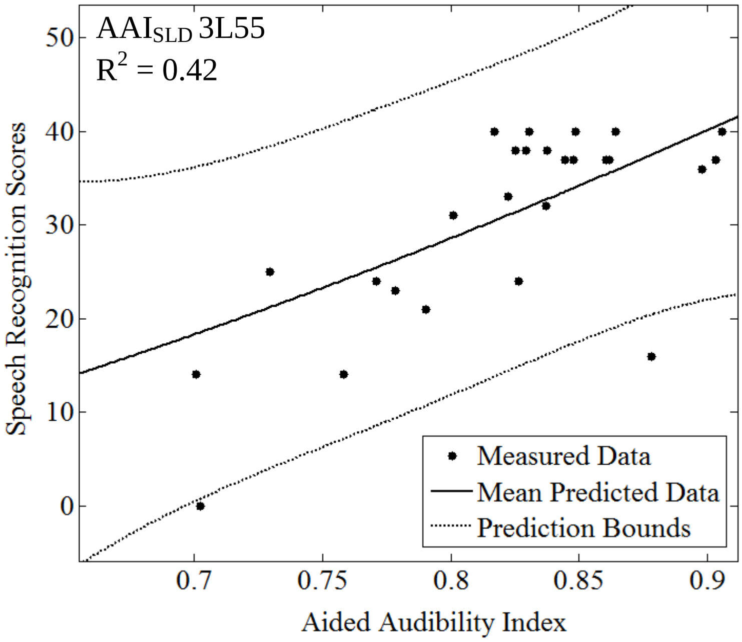

Figure 8. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 3L55 in Group I. The AAI$_{SLD}$ was computed using SFAT. Here, 3L55 is the compression ratio of 3:1 with long time constants, at presentation level of 55 dB SPL.

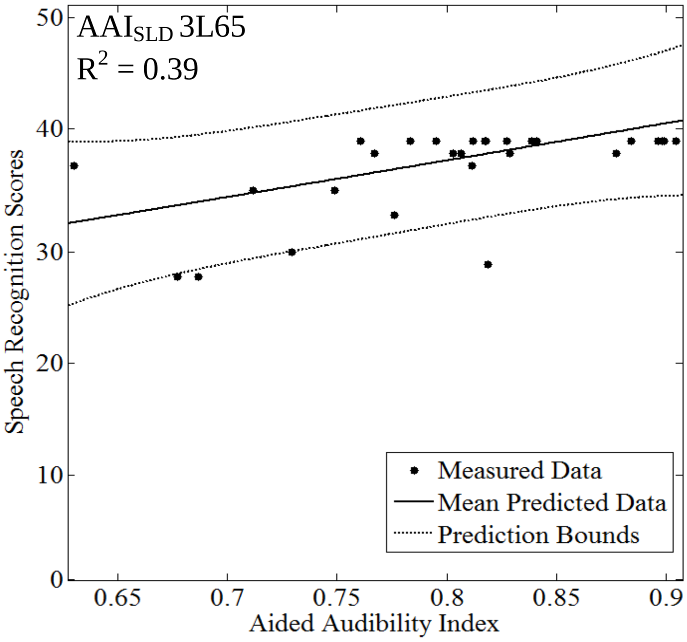

Figure 9. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 3L65 in Group I. The AAI$_{SLD}$ was computed using SFAT. Here, 3L65 is the compression ratio of 3:1 with long time constants, at presentation level of 65 dB SPL.

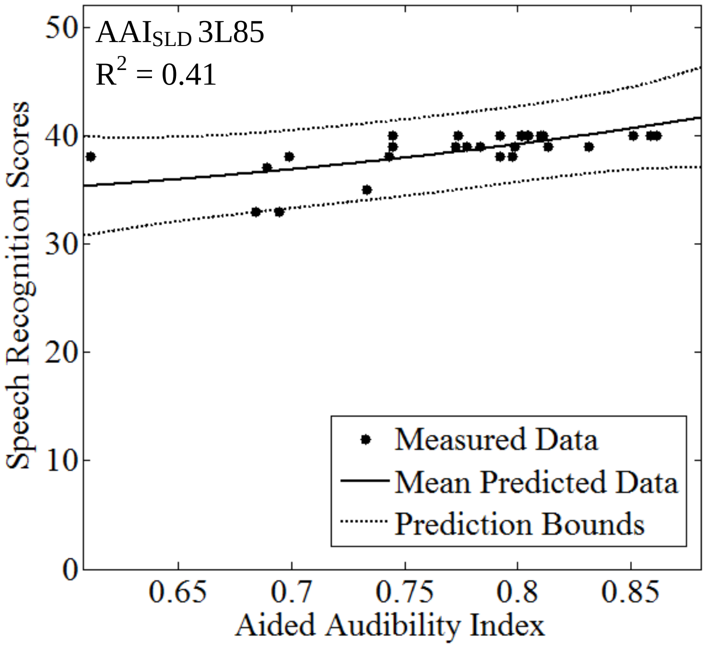

Figure 10. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 3L85 in Group I. The AAI$_{SLD}$ was computed using SFAT. Here, 3L85 is the compression ratio of 3:1 with long time constants, at presentation level of 55 dB SPL.

APPENDIX D

Measured and predicted speech recognition scores from $AAI_{SLD, HLD}$ computed using SFAT in Group I

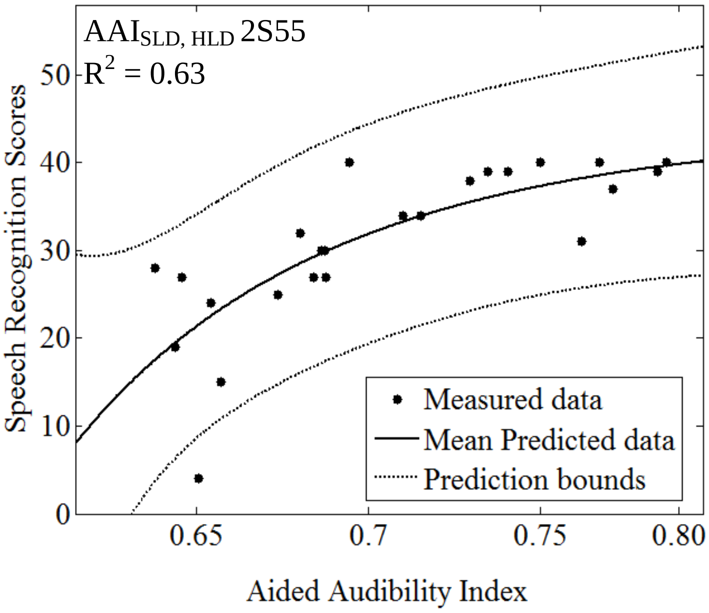

Figure 1. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 2S55 in Group I. The $AAI_{SLD, HLD}$ was computed using SFAT. Here, 2S55 is the compression ratio of 2:1 with short time constants, at presentation level of 55 dB SPL.

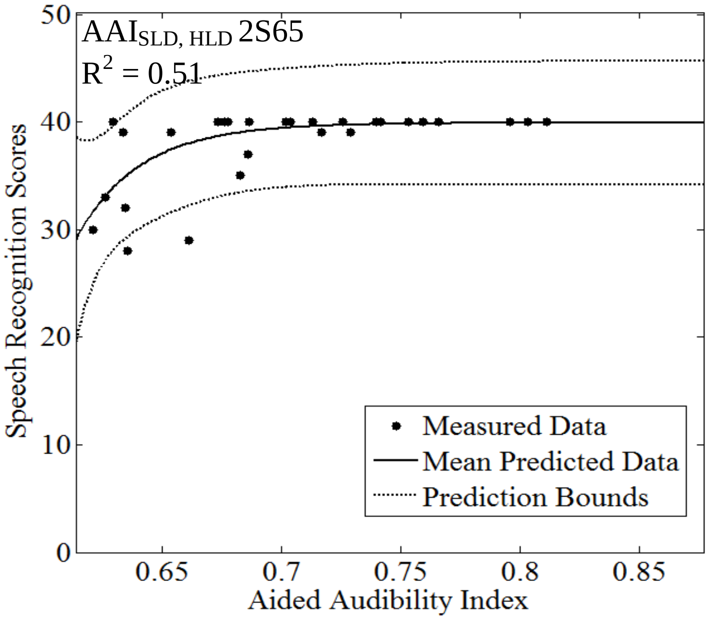

Figure 2. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) for SRS predicted from $AAI_{SLD, HLD}$ in 2S65 in Group I. The $AAI_{SLD, HLD}$ was computed using SFAT. Here, 2S65 is the compression ratio of 2:1 with short time constants, at presentation level of 65 dB SPL.

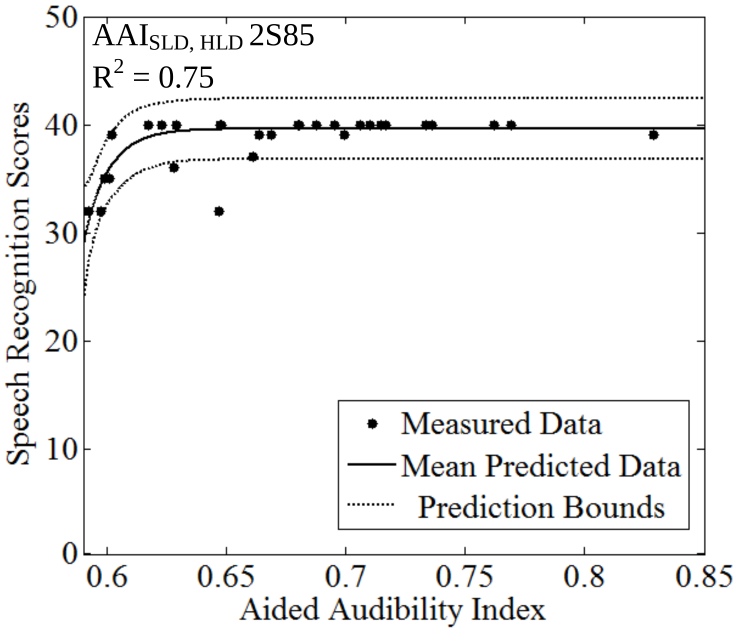

Figure 3. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) for SRS predicted from AAI$_{SLD, HLD}$ in 2S85 in Group I. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 2S85 is the compression ratio of 2:1 with short time constants, at presentation level of 85 dB SPL.

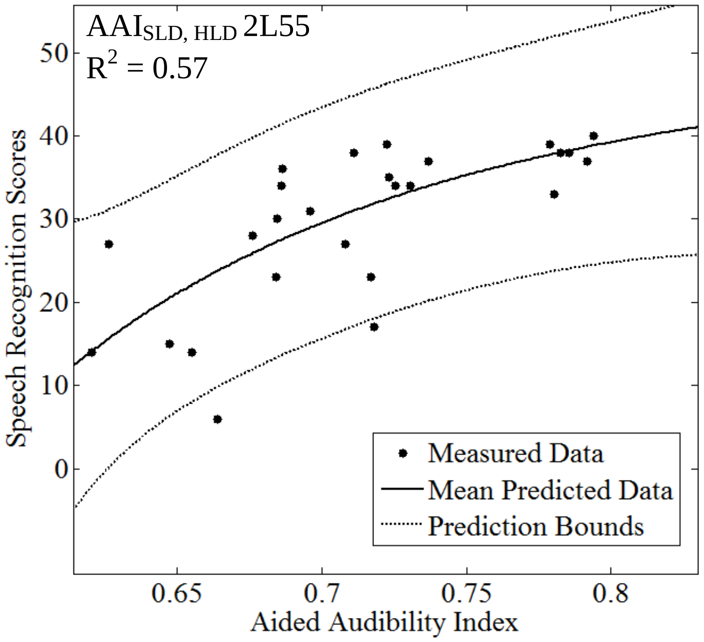

Figure 4. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 2L55 in Group I. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 2L55 is the compression ratio of 2:1 with long time constants, at presentation level of 55 dB SPL.

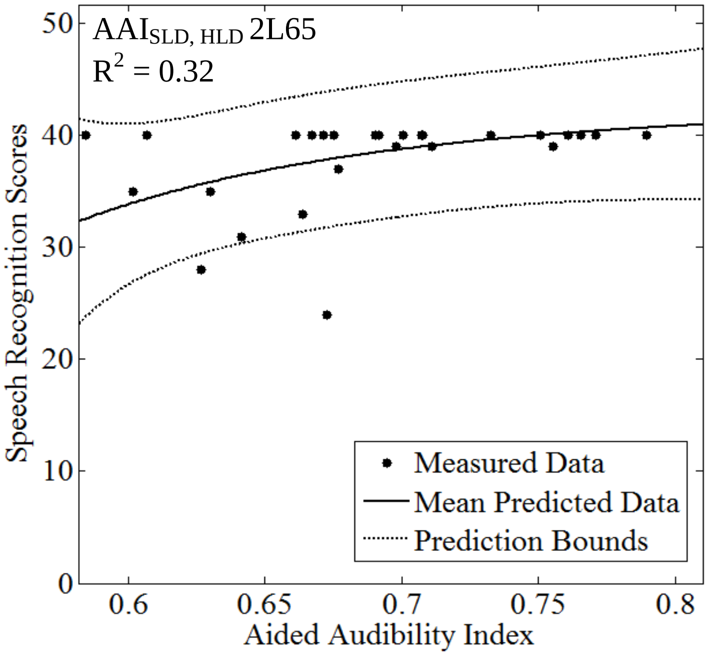

Figure 5. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) for SRS predicted from AAI$_{SLD, HLD}$ in 2L65 in Group I. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 2L65 is the compression ratio of 2:1 with long time constants, at presentation level of 65 dB SPL.

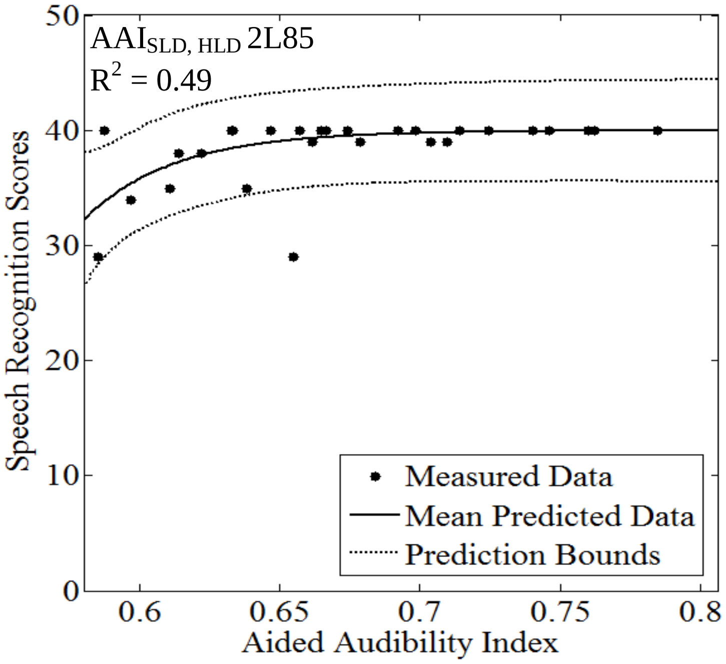

Figure 6. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) for SRS predicted from AAI$_{SLD, HLD}$ in 2L85 in Group I. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 2L85 is the compression ratio of 2:1 with long time constants, at presentation level of 85 dB SPL.

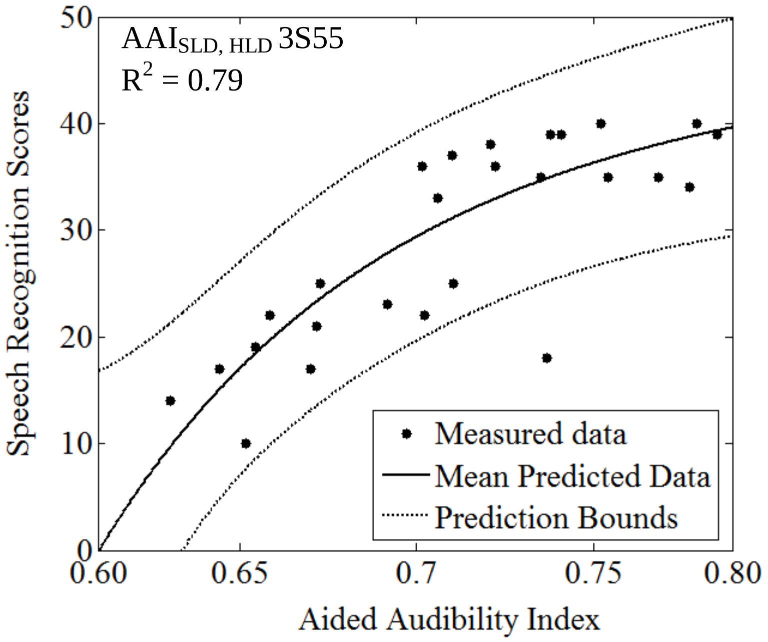

Figure 7. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) for SRS predicted from AAI$_{SLD, HLD}$ in 3S55 in Group I. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 3S55 is the compression ratio of 3:1 with short time constants, at presentation level of 55 dB SPL.

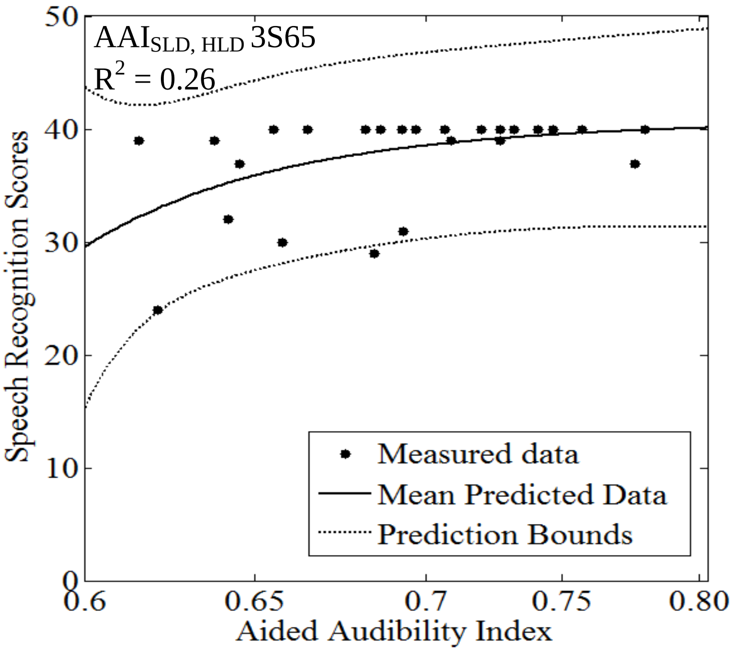

Figure 8. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) for SRS predicted from AAI$_{SLD, HLD}$ in 3S65 in Group I. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 3S65 is the compression ratio of 3:1 with short time constants, at presentation level of 65 dB SPL.

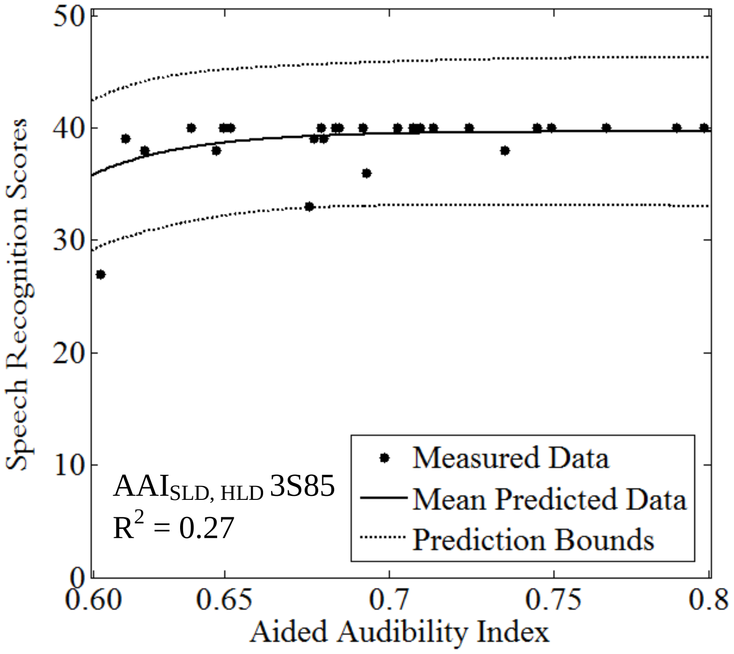

Figure 9. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $\mathrm{AAI}_{\mathrm{SLD,\ HLD}}$ in 3S85 in Group I. The $\mathrm{AAI}_{\mathrm{SLD,\ HLD}}$ was computed using SFAT. Here, 3S85 is the compression ratio of 3:1 with short time constants, at presentation level of 85 dB SPL.

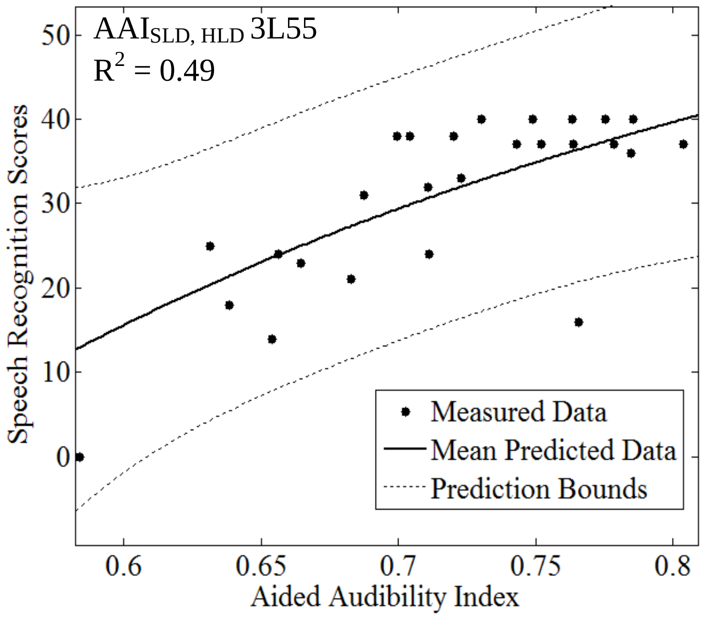

Figure 10. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $\mathrm{AAI}_{\mathrm{SLD,\ HLD}}$ in 3L55 in Group I. The $\mathrm{AAI}_{\mathrm{SLD,\ HLD}}$ was computed using SFAT. Here, 3L55 is the compression ratio of 3:1 with long time constants, at presentation level of 55 dB SPL.

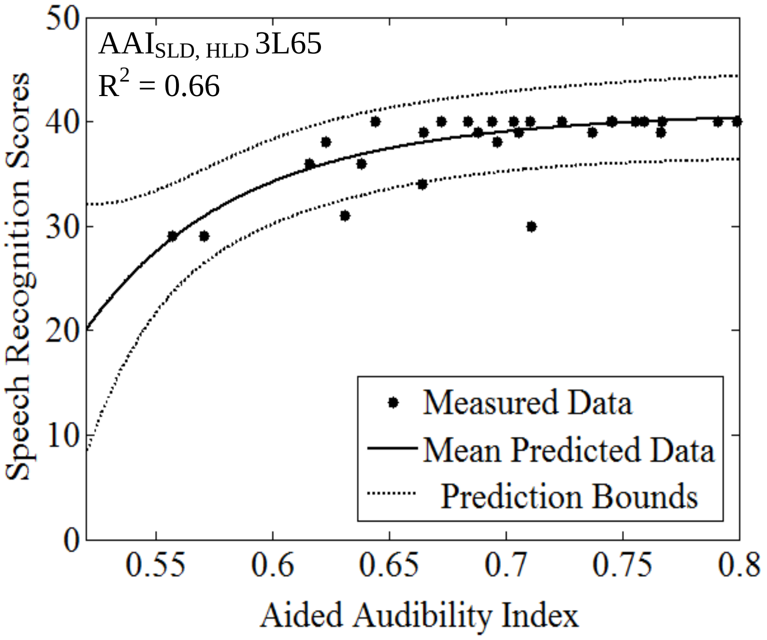

Figure 11. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 3L65 in Group I. The $AAI_{SLD, HLD}$ was computed using SFAT. Here, 3L65 is the compression ratio of 3:1 with long time constants, at presentation level of 65 dB SPL.

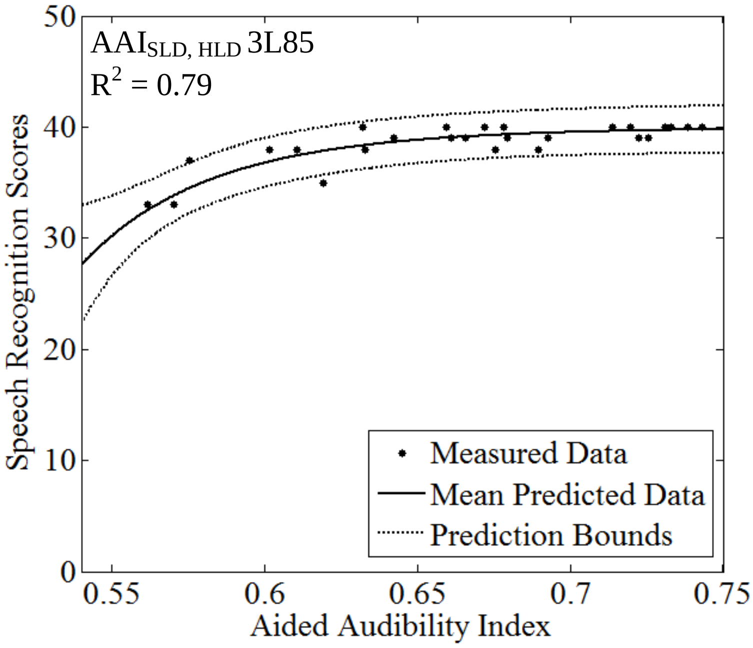

Figure 12. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 3L85 in Group I. The $AAI_{SLD, HLD}$ was computed using SFAT. Here, 3L85 is the compression ratio of 3:1 with long time constants, at presentation level of 85 dB SPL.

APPENDIX E

Measured and predicted speech recognition scores from AAI computed using SFAT in Group II

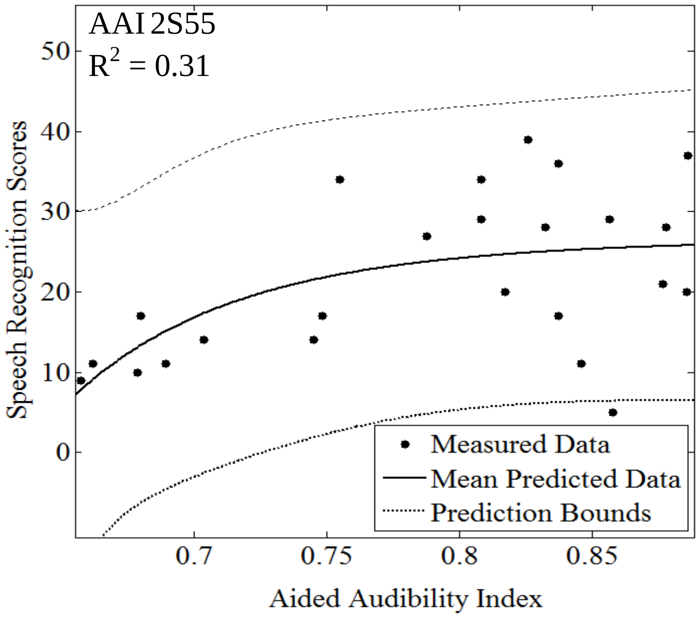

Figure 1. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 2S55 in Group II. The AAI was computed using SFAT. Here, 2S55 is the compression ratio of 2:1 with short time constants, at presentation level of 55 dB SPL

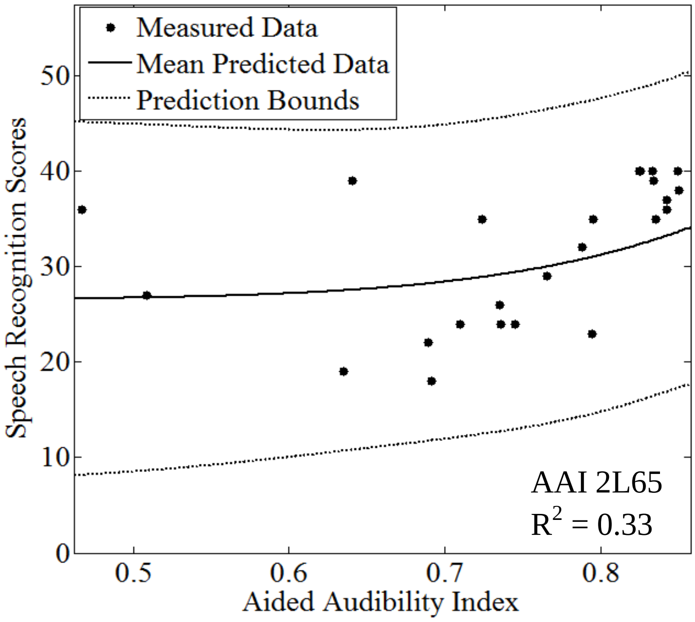

Figure 2. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 2S65 in Group II. The AAI was computed using SFAT. Here, 2S65 is the compression ratio of 2:1 with short time constants, at presentation level of 65 dB SPL.

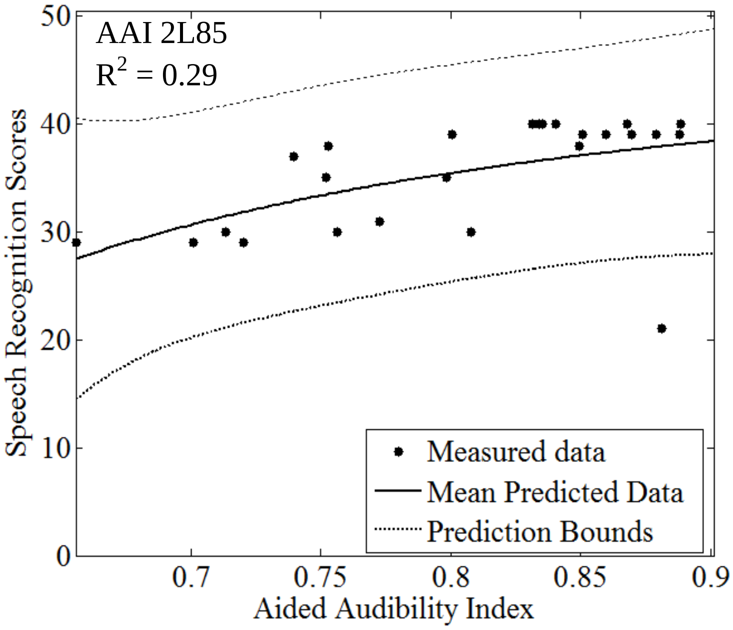

Figure 3. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 2L85 in Group II. The AAI was computed using SFAT. Here, 2L85 is the compression ratio of 2:1 with long time constants, at presentation level of 85 dB SPL.

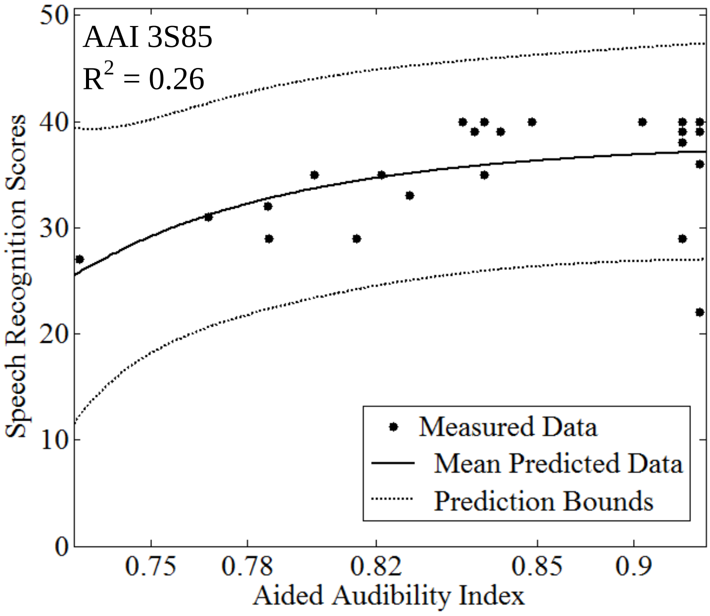

Figure 4. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 3S85 in Group II. The AAI was computed using SFAT. Here, 3S85 is the compression ratio of 3:1 with short time constants, at presentation level of 85 dB SPL.

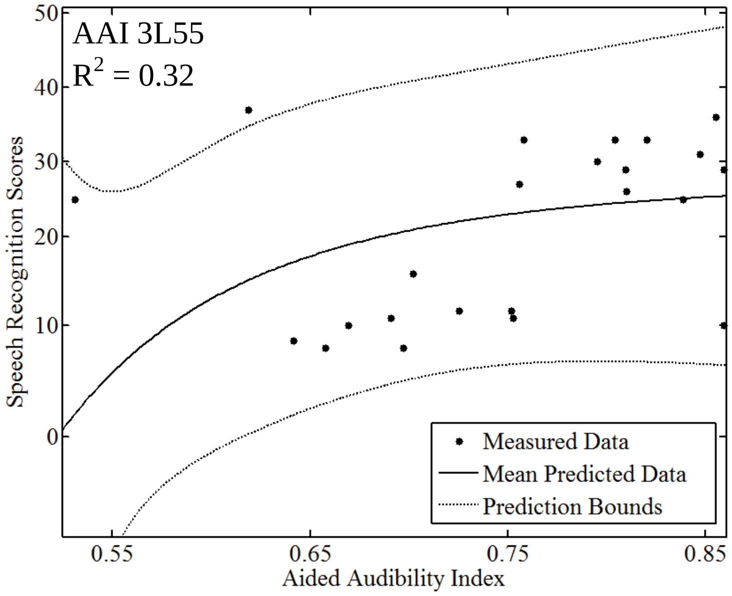

Figure 5. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 3L55 in Group II. The AAI was computed using SFAT. Here, 3L55 is the compression ratio of 3:1 with long time constants, at presentation level of 55 dB SPL.

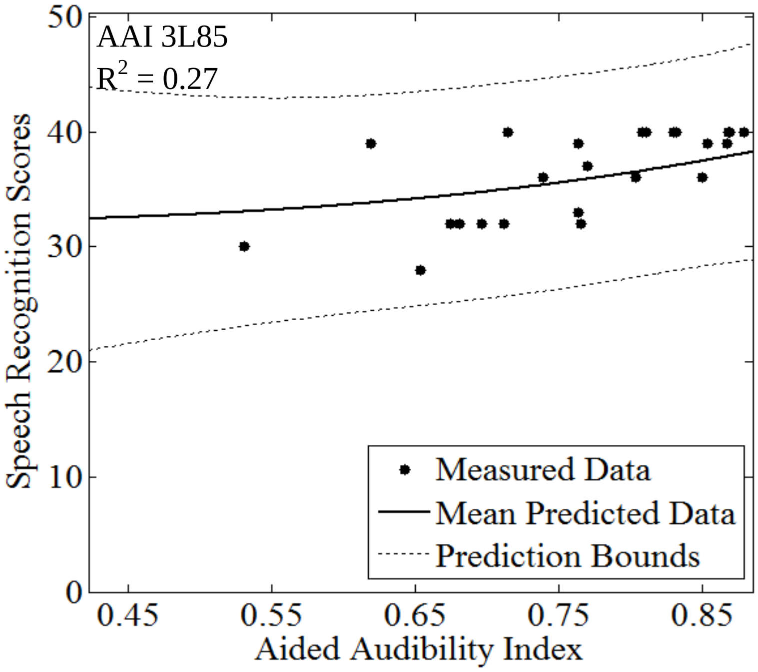

Figure 6. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI in 3L85 in Group II. The AAI was computed using SFAT. Here, 3L85 is the compression ratio of 3:1 with long time constants, at presentation level of 85 dB SPL.

APPENDIX F

Measured and predicted speech recognition scores from AAI_{SLD} computed using SFAT in Group II

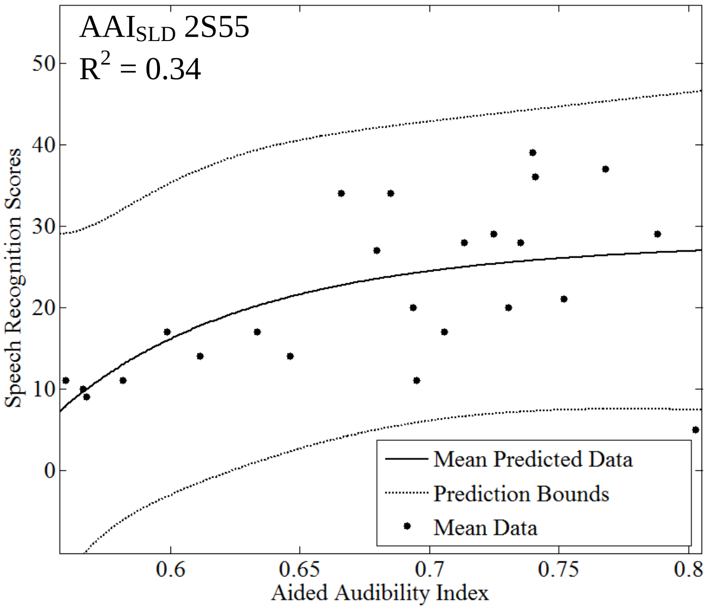

Figure 1. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) for SRS predicted from AAI_{SLD} in 2S55 in Group II. The AAI_{SLD} was computed using SFAT. In the figure, 2S55 is the compression ratio of 2:1 with short time constants, at presentation level of 55 dB SPL.

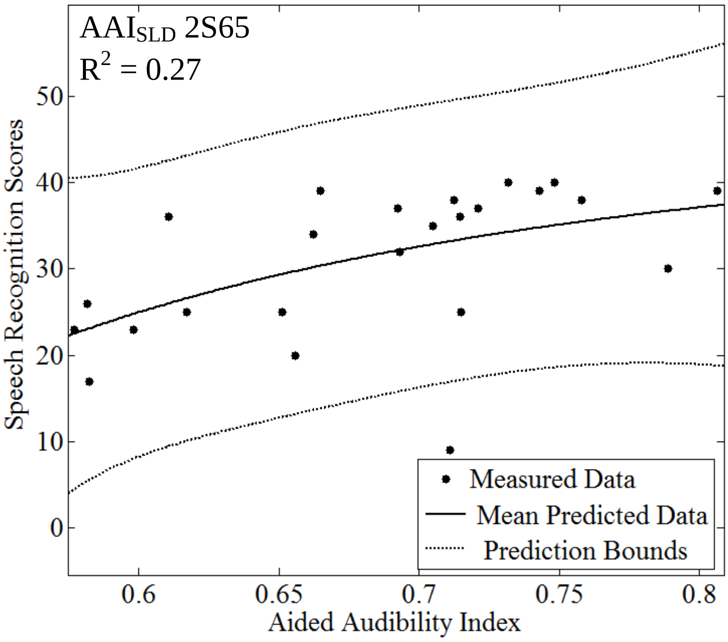

Figure 2. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI_{SLD} in 2S65 in Group II. The AAI_{SLD} was computed using SFAT. Here, 2S65 is the compression ratio of 2:1 with short time constants, at presentation level of 65 dB SPL.

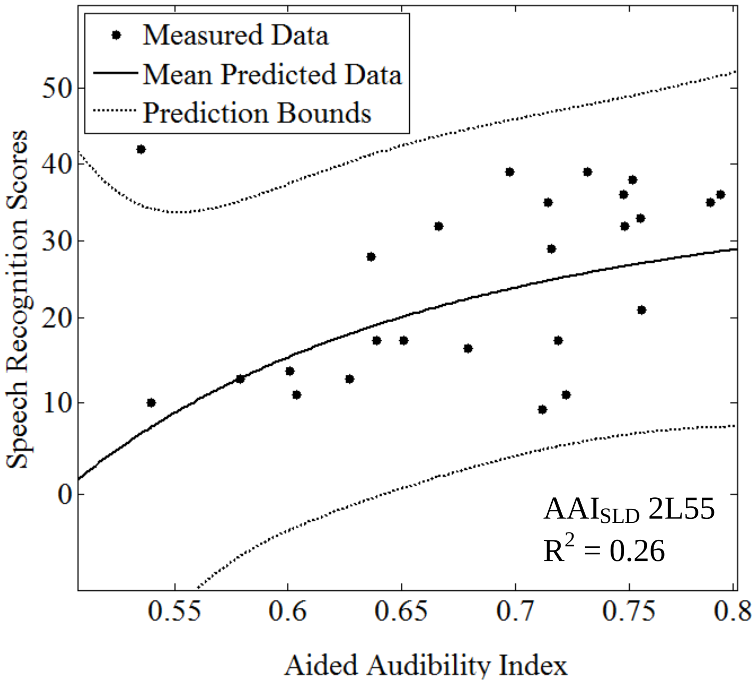

Figure 3. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 2L55 in Group II. The AAI$_{SLD}$ was computed using SFAT. Here, 2L55 is the compression ratio of 2:1 with long time constants, at presentation level of 55 dB SPL.

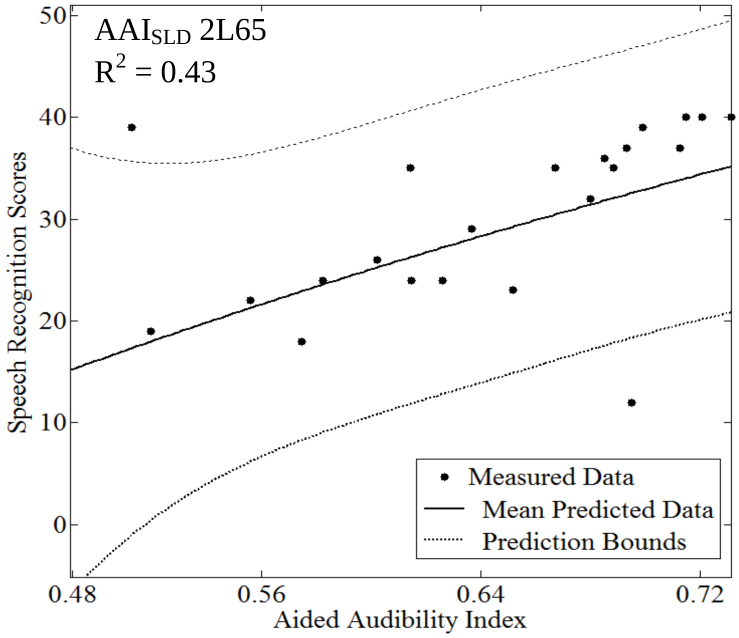

Figure 4. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 2L65 in Group II. The AAI$_{SLD}$ was computed using SFAT. Here, 2L65 is the compression ratio of 2:1 with long time constants, at presentation level of 65 dB SPL.

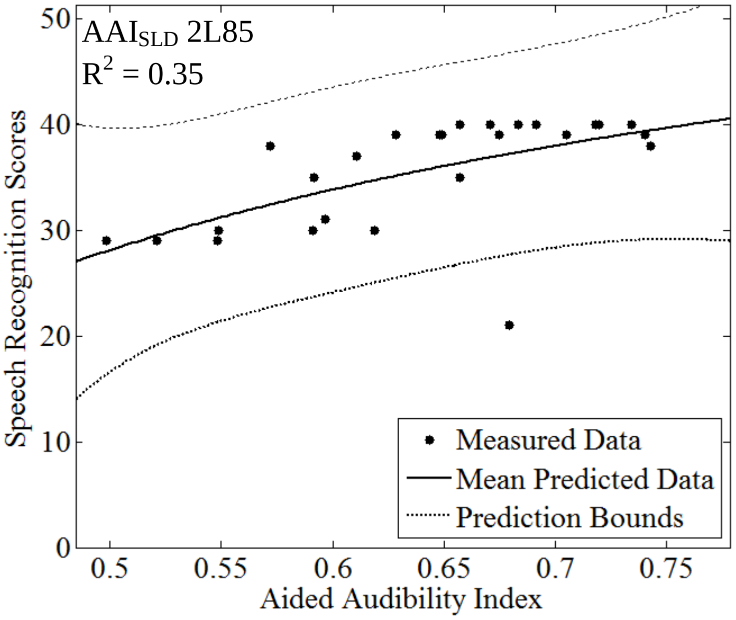

Figure 5. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 2L85 in Group II. The AAI$_{SLD}$ was computed using SFAT. Here, 2L85 is the compression ratio of 2:1 with long time constants, at presentation level of 85 dB SPL.

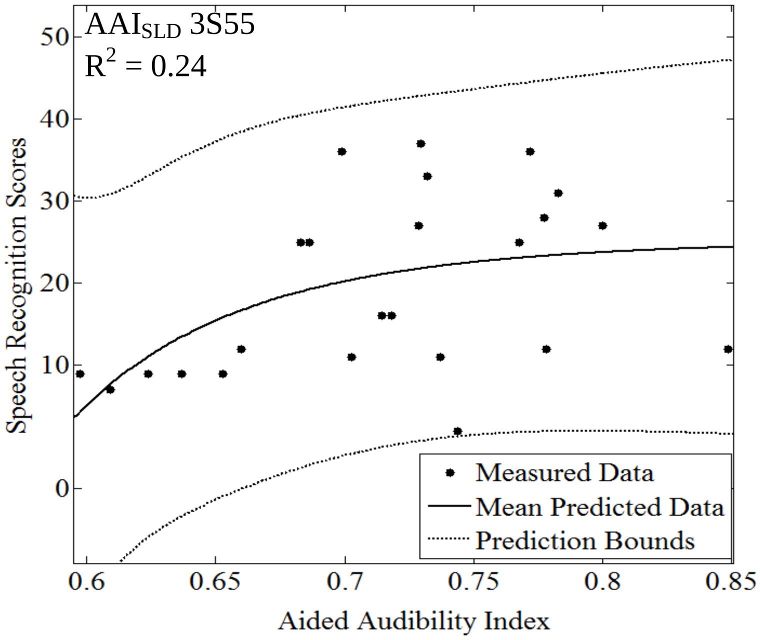

Figure 6. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 3S55 in Group II. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 3S55 is the compression ratio of 3:1 with short time constants, at presentation level of 55 dB SPL.

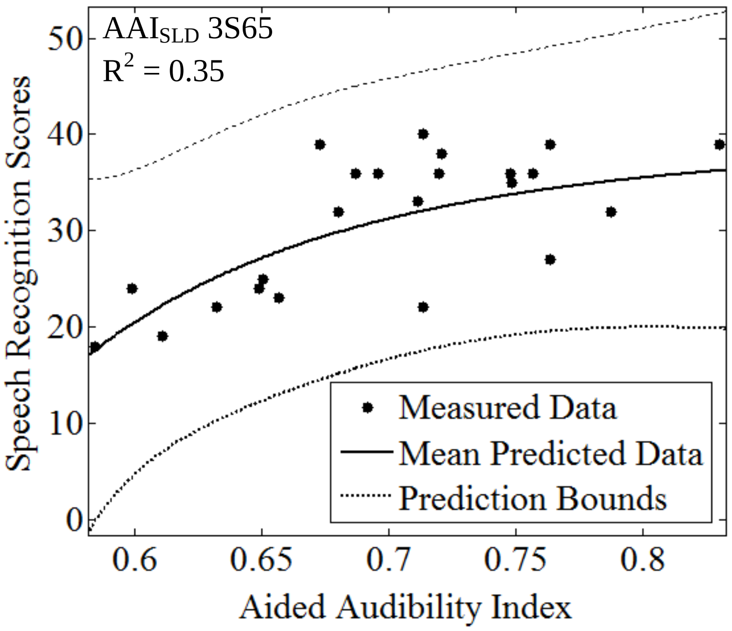

Figure 7. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 3S65 in Group II. The AAI$_{SLD}$ was computed using SFAT. Here, 3S65 is the compression ratio of 3:1 with short time constants, at presentation level of 65 dB SPL.

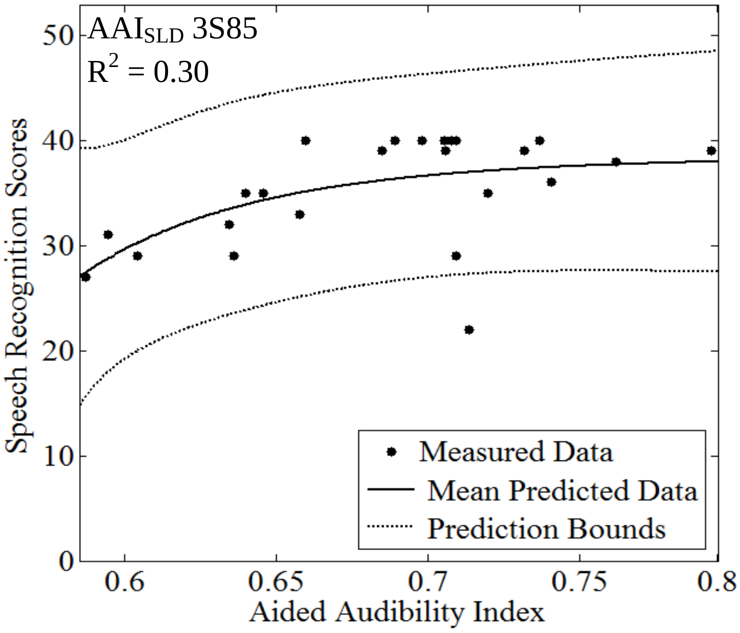

Figure 8. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 3S85 in Group II. The AAI$_{SLD}$ was computed using SFAT. Here, 3S85 is the compression ratio of 3:1 with short time constants, at presentation level of 85 dB SPL.

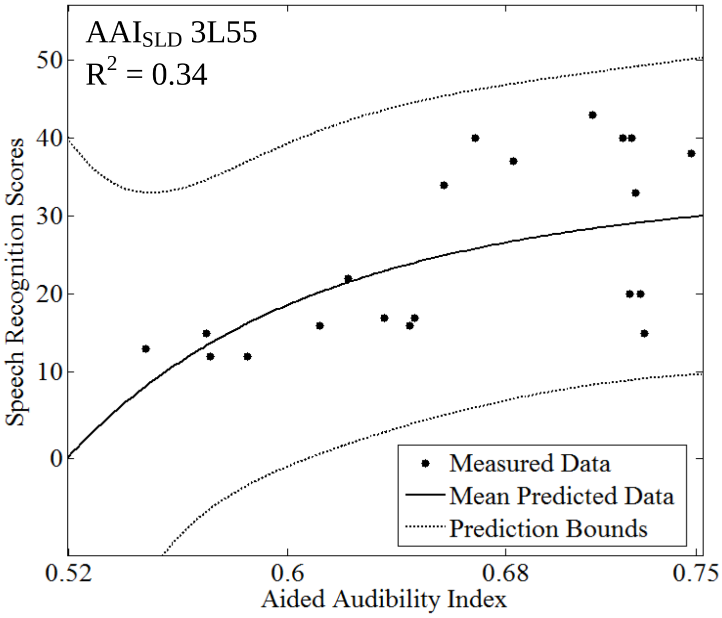

Figure 9. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 3L55 in Group II. The AAI$_{SLD}$ was computed using SFAT. Here, 3L55 is the compression ratio of 3:1 with long time constants, at presentation level of 55 dB SPL.

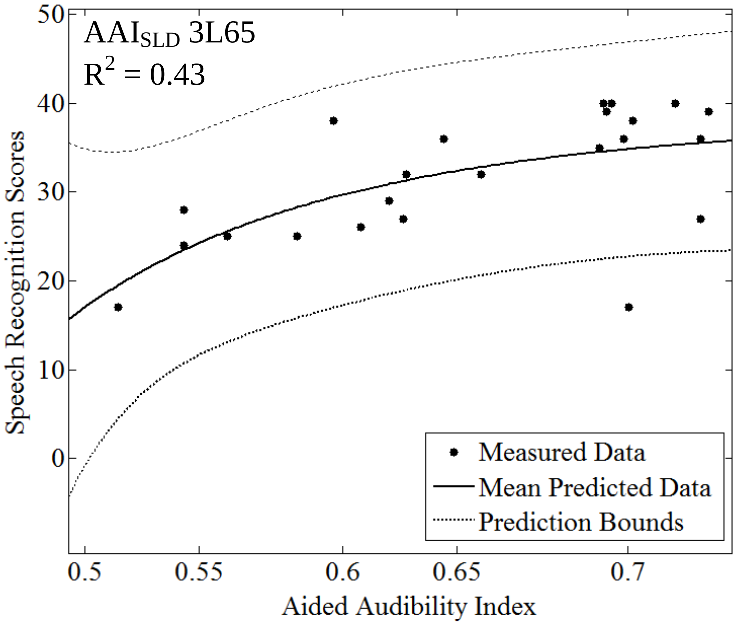

Figure 10. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD}$ in 3L65 in Group II. The AAI$_{SLD}$ was computed using SFAT. Here, 3L65 is the compression ratio of 3:1 with long time constants, at presentation level of 65 dB SPL.

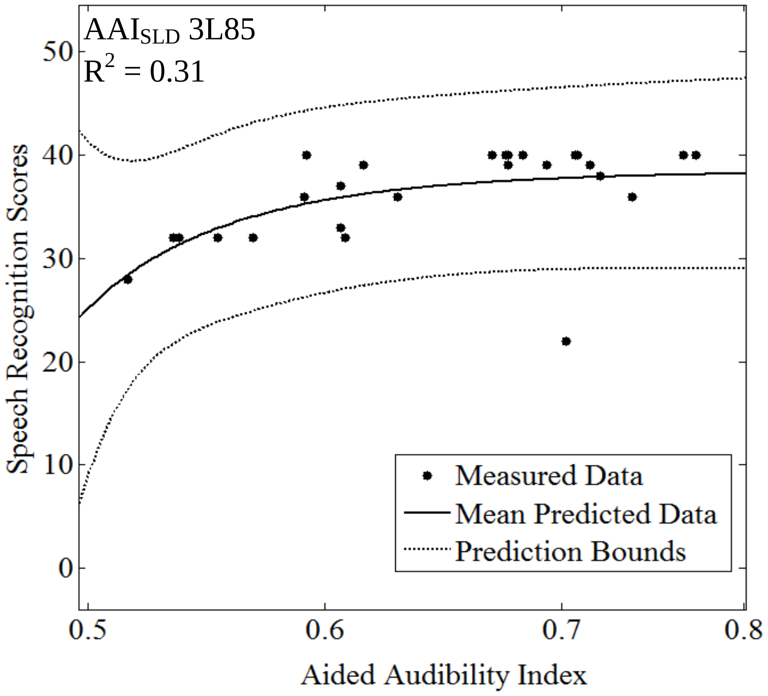

Figure 11. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI_{SLD} in 3L85 in Group II. The AAI_{SLD} was computed using SFAT. Here, 3L85 is the compression ratio of 3:1 with long time constants, at presentation level of 85 dB SPL.

APPENDIX G

Measured and predicted speech recognition scores from $AAI_{SLD, HLD}$ computed using SFAT in Group II

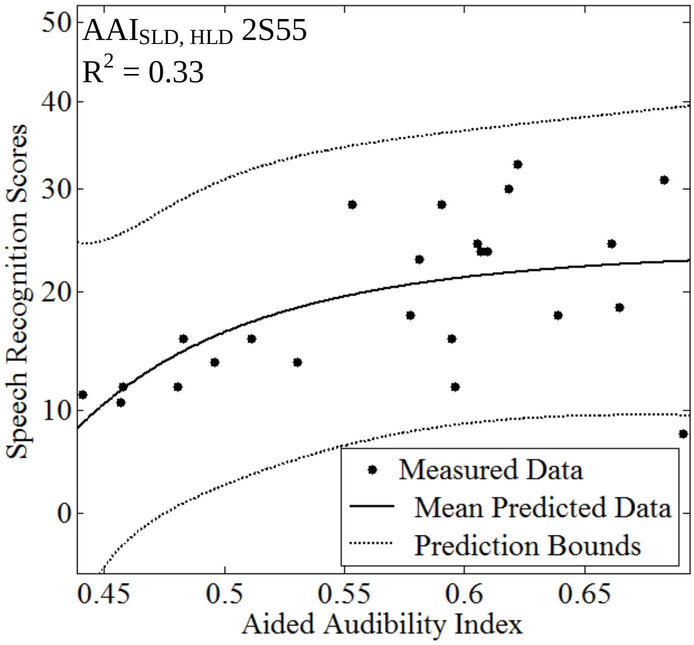

Figure 1. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 2S55 in Group II. The $AAI_{SLD, HLD}$ was computed using SFAT. Here, 2S55 is the compression ratio of 2:1 with short time constants, at presentation level of 55 dB SPL.

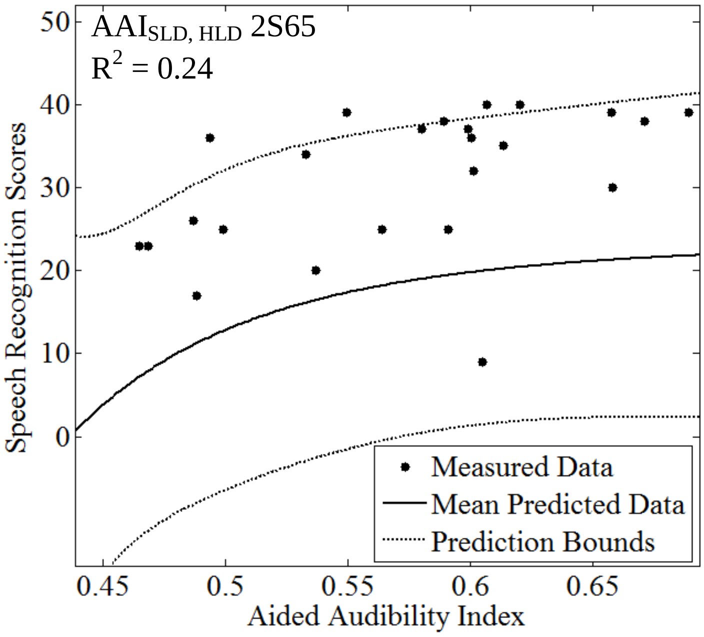

Figure 2. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 2S65 in Group II. The $AAI_{SLD, HLD}$ was computed using SFAT. Here, 2S65 is the compression ratio of 2:1 with short time constants, at presentation level of 65 dB SPL.

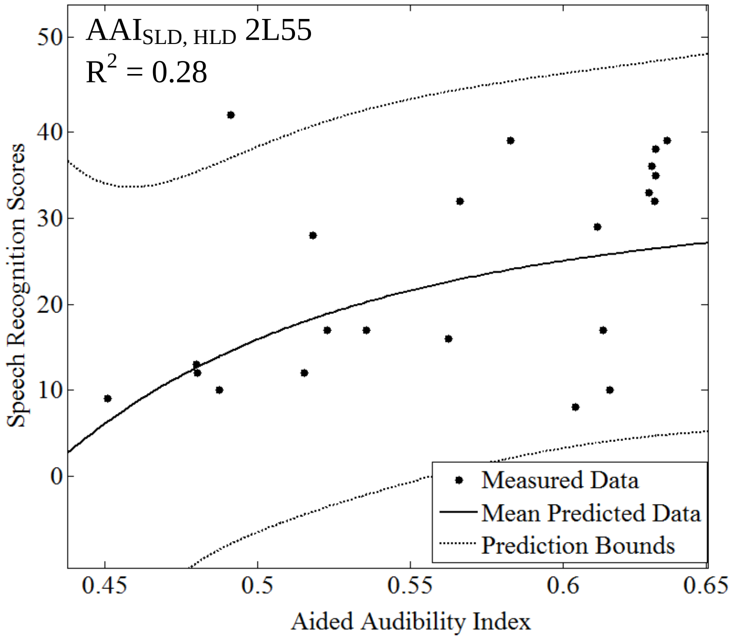

Figure 3. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 2L55 in Group II. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 2L55 is the compression ratio of 2:1 with long time constants, at presentation level of 55 dB SPL.

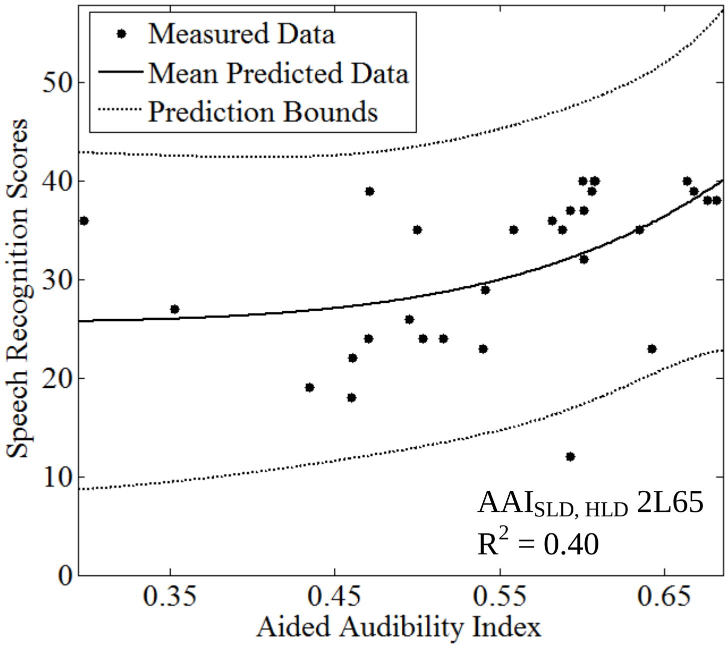

Figure 4. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 2L65 in Group II. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 2L65 is the compression ratio of 2:1 with long time constants, at presentation level of 65 dB SPL.

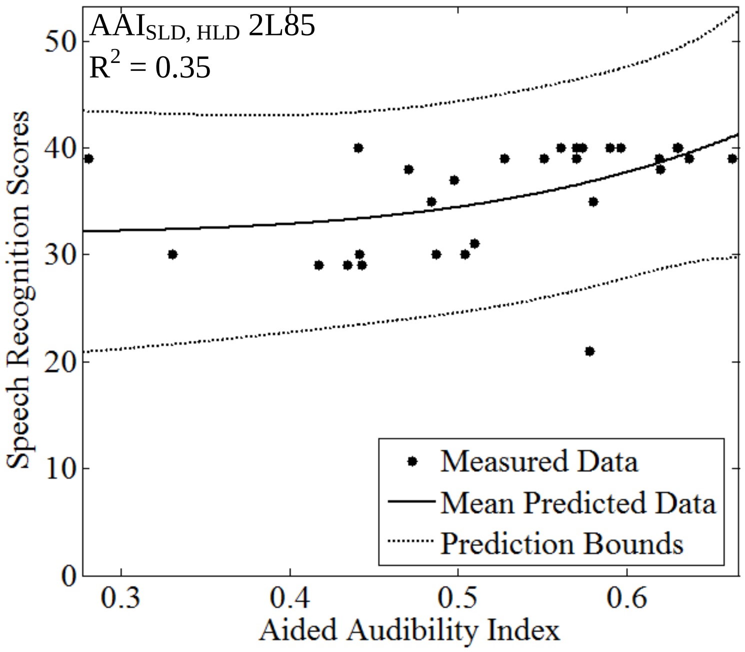

Figure 5. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 2L85 in Group II. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 2L85 is the compression ratio of 2:1 with long time constants, at presentation level of 85 dB SPL.

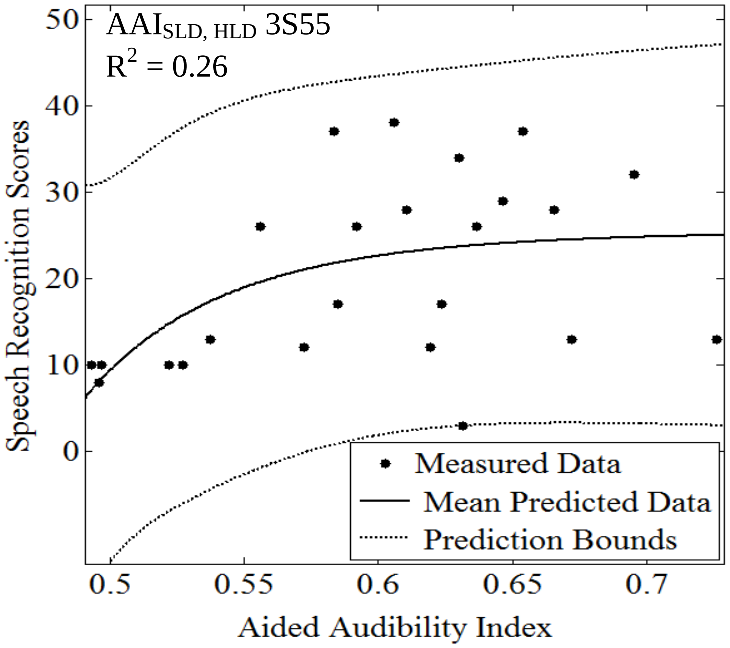

Figure 6. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 3S55 in Group II. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 3S55 is the compression ratio of 3:1 with short time constants, at presentation level of 55 dB SPL.

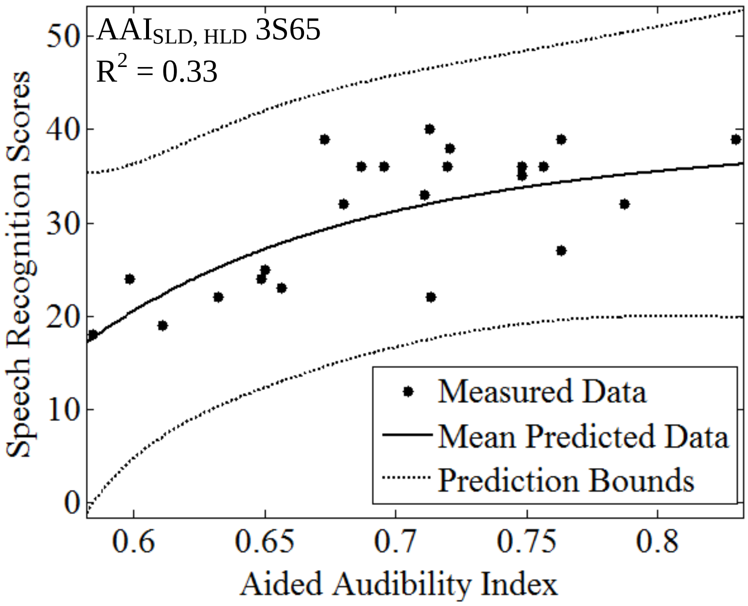

Figure 7. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD,\ HLD}$ in 3S65 in Group II. The $AAI_{SLD,\ HLD}$ was computed using SFAT. Here, 3S65 is the compression ratio of 3:1 with short time constants, at presentation level of 65 dB SPL.

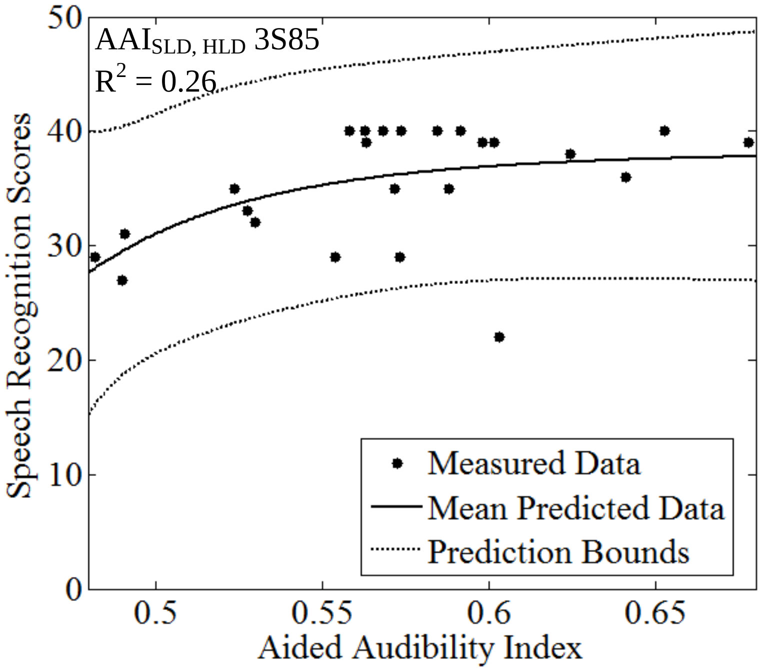

Figure 8. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD,\ HLD}$ in 3S85 in Group II. The $AAI_{SLD,\ HLD}$ was computed using SFAT. Here, 3S85 is the compression ratio of 3:1 with short time constants, at presentation level of 85 dB SPL.

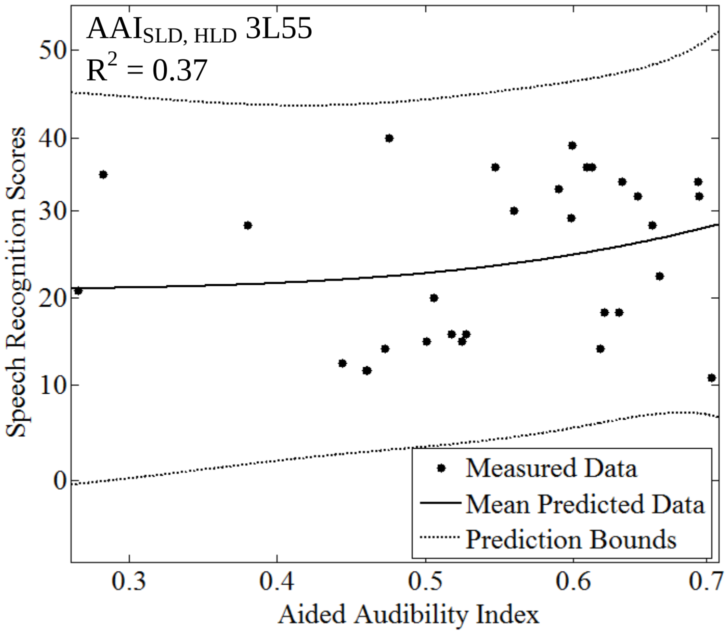

Figure 9. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD,\ HLD}$ in 3L55 in Group II. The $AAI_{SLD,\ HLD}$ was computed using SFAT. Here, 3L55 is the compression ratio of 3:1 with long time constants, at presentation level of 55 dB SPL.

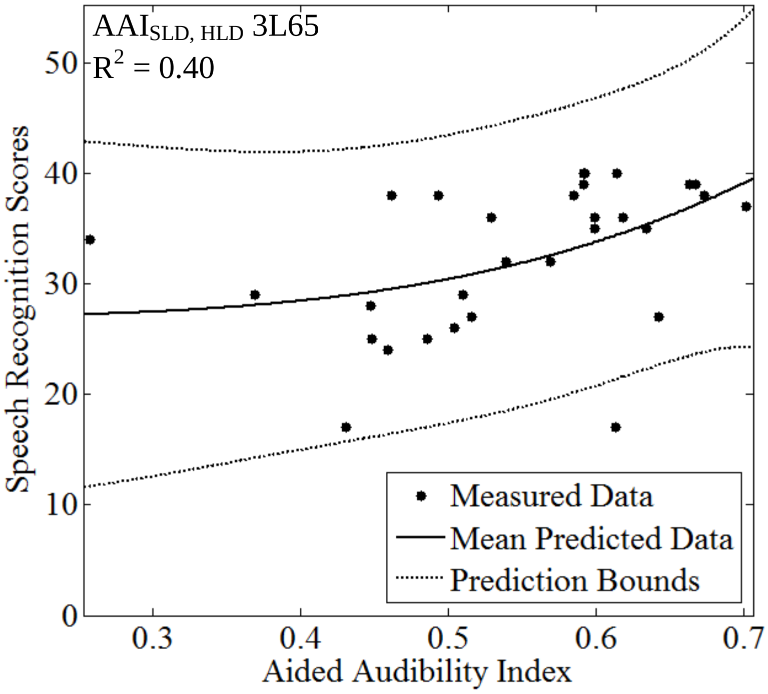

Figure 10. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD,\ HLD}$ in 3L65 in Group II. The $AAI_{SLD,\ HLD}$ was computed using SFAT. Here, 3L65 is the compression ratio of 3:1 with long time constants, at presentation level of 65 dB SPL.

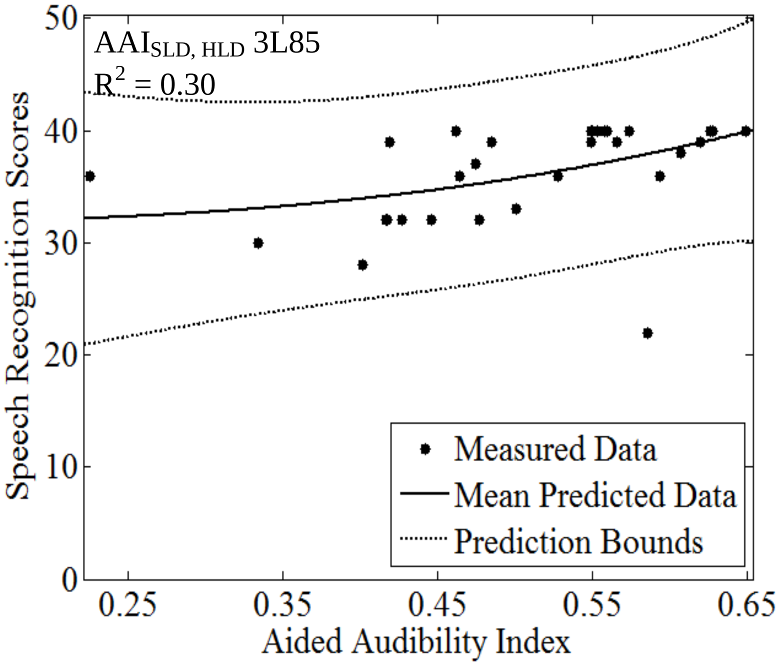

Figure 11. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 3L85 in Group II. The AAI$_{SLD, HLD}$ was computed using SFAT. Here, 3L85 is the compression ratio of 3:1 with long time constants, at presentation level of 85 dB SPL.

APPENDIX H

Measured and predicted speech recognition scores from $AAI_{SLD, HLD}$ computed using REAR in Group I

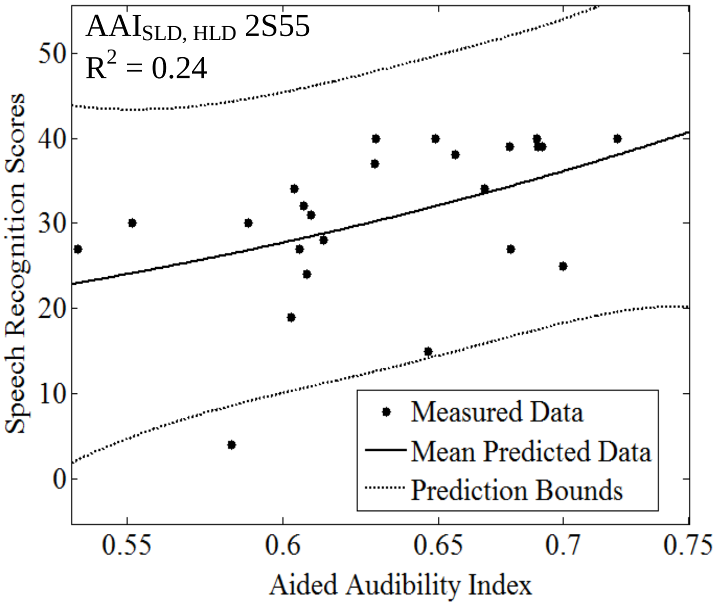

Figure 1. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 2S55 in Group I. The $AAI_{SLD, HLD}$ was computed using REAR. Here, 2S55 is the compression ratio of 2:1 with short time constants, at presentation level of 55 dB SPL.

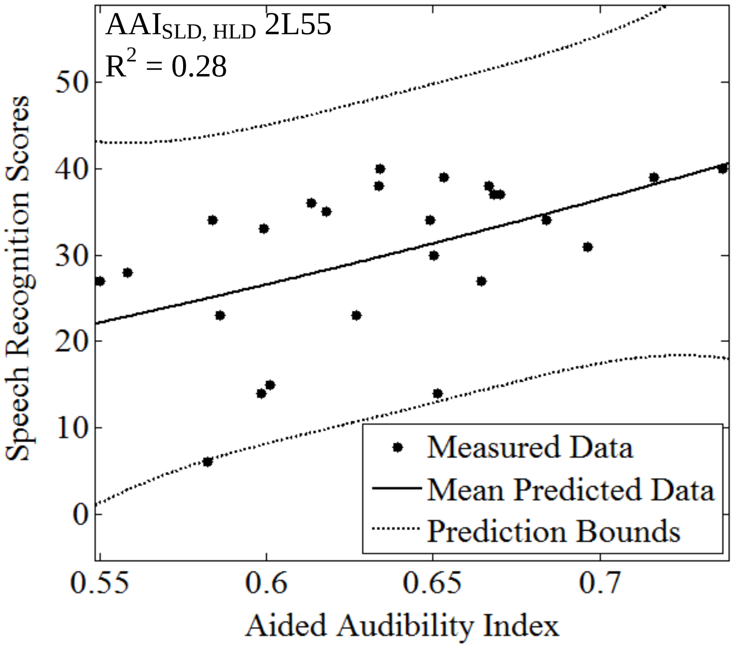

Figure 2. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 2L55 in Group I. The $AAI_{SLD, HLD}$ was computed using REAR. Here, 2L55 is the compression ratio of 2:1 with long time constants, at presentation level of 55 dB SPL.

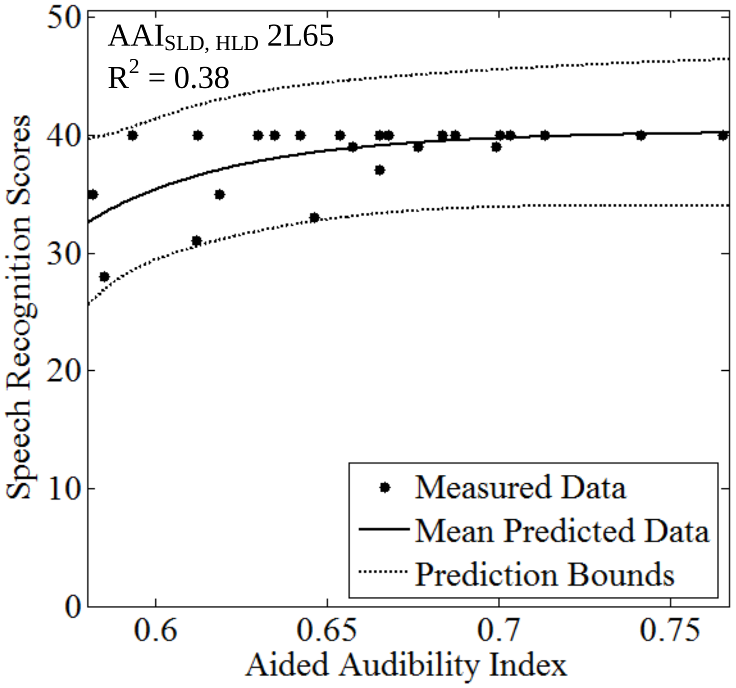

Figure 3. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 2L65 in Group I. The $AAI_{SLD, HLD}$ was computed using REAR. Here, 2L65 is the compression ratio of 2:1 with long time constants, at presentation level of 65 dB SPL.

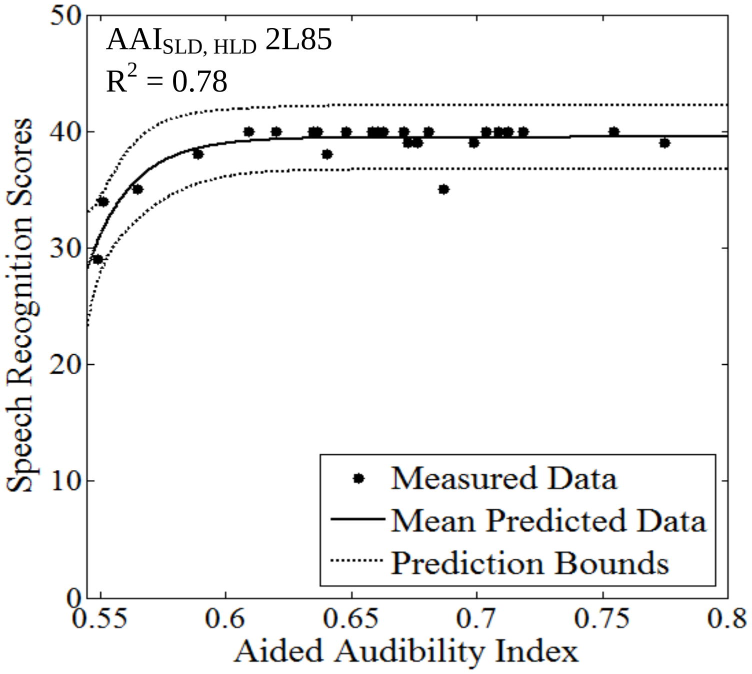

Figure 4. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 2L85 in Group I. The $AAI_{SLD, HLD}$ was computed using REAR. Here, 2L85 is the compression ratio of 2:1 with long time constants, at presentation level of 85 dB SPL.

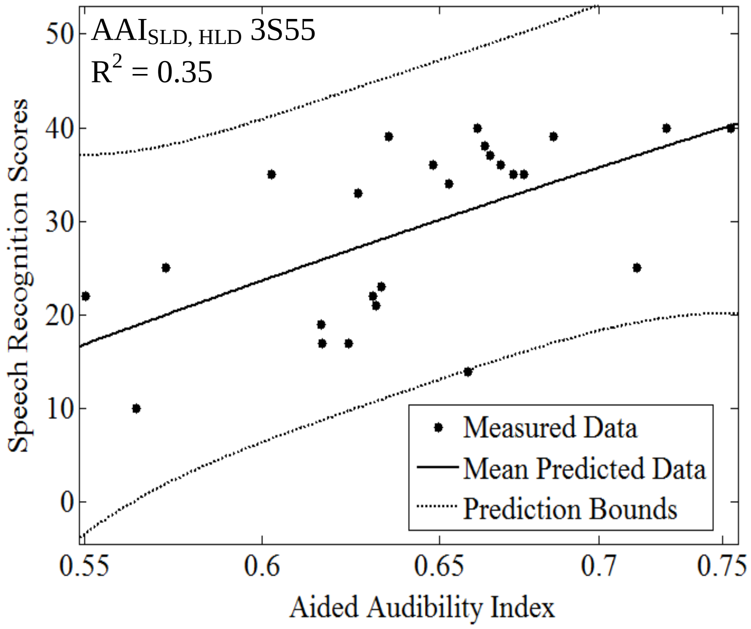

Figure 5. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 3S55 in Group I. The AAI$_{SLD, HLD}$ was computed using REAR. Here, 3S55 is the compression ratio of 3:1 with short time constants, at presentation level of 55 dB SPL.

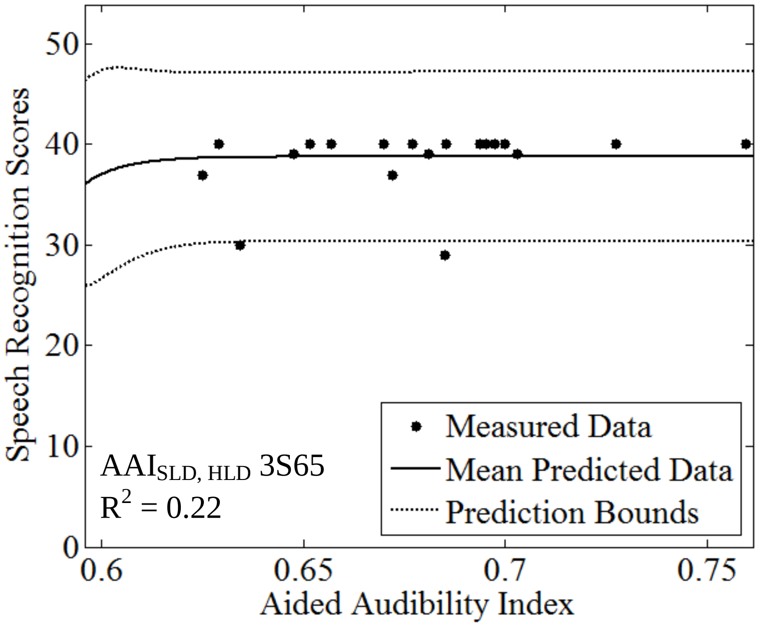

Figure 6. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 3S65 in Group I. The AAI$_{SLD, HLD}$ was computed using REAR. Here, 3S65 is the compression ratio of 3:1 with short time constants, at presentation level of 65 dB SPL.

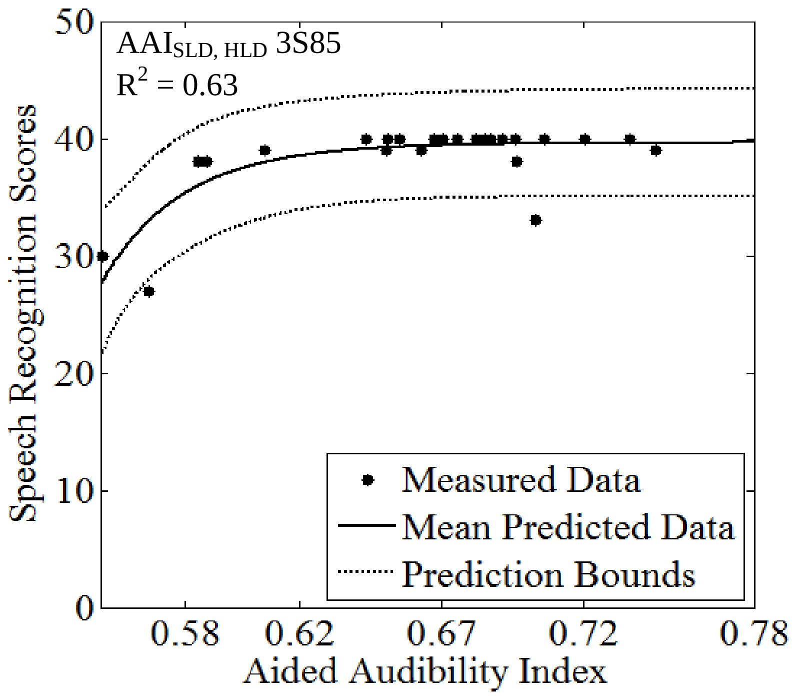

Figure 7. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 3S85 in Group I. The $AAI_{SLD, HLD}$ was computed using REAR. Here, 3S85 is the compression ratio of 3:1 with short time constants, at presentation level of 85 dB SPL.

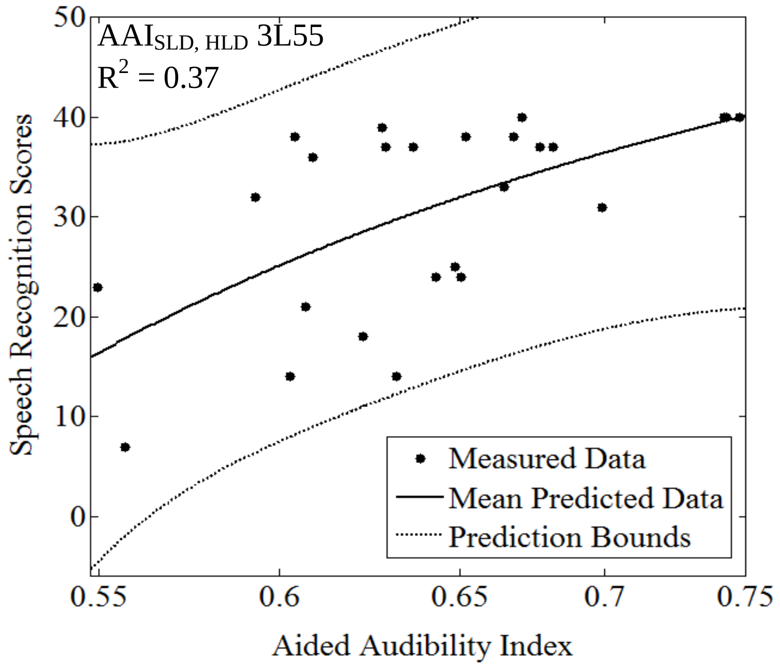

Figure 8. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 3L55 in Group I. The $AAI_{SLD, HLD}$ was computed using REAR. Here, 3L55 is the compression ratio of 3:1 with long time constants, at presentation level of 55 dB SPL.

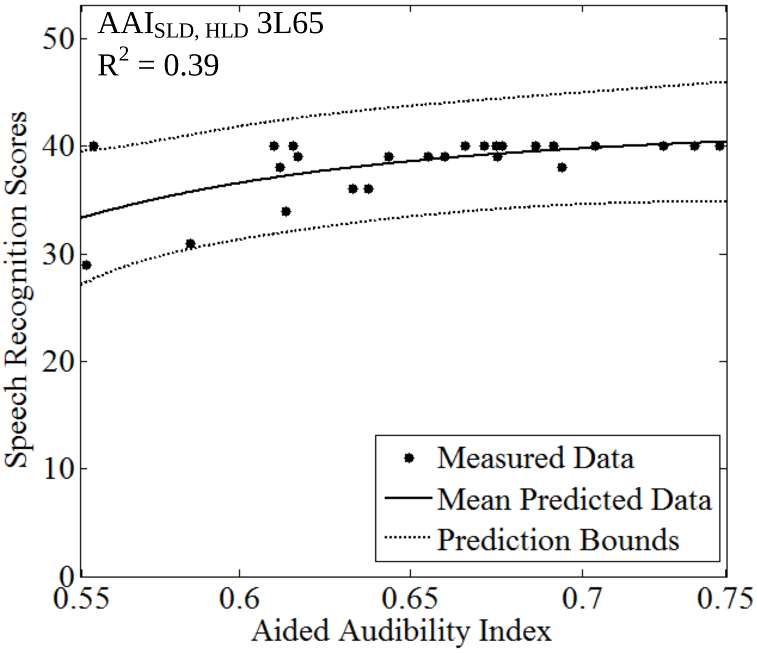

Figure 9. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 3L65 in Group I. The AAI$_{SLD, HLD}$ was computed using REAR. Here, 3L65 is the compression ratio of 3:1 with long time constants, at presentation level of 65 dB SPL.

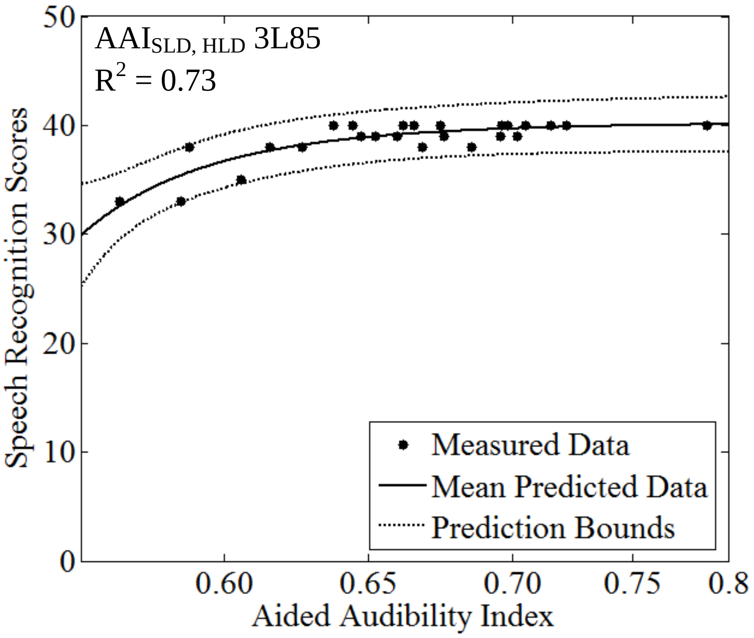

Figure 10. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 3L85 in Group I. The AAI$_{SLD, HLD}$ was computed using REAR. Here, 3L85 is the compression ratio of 3:1 with long time constants, at presentation level of 85 dB SPL.

APPENDIX I

Measured and predicted speech recognition scores from AAI_{SLD} and $AAI_{SLD, HLD}$ computed using REAR in Group II

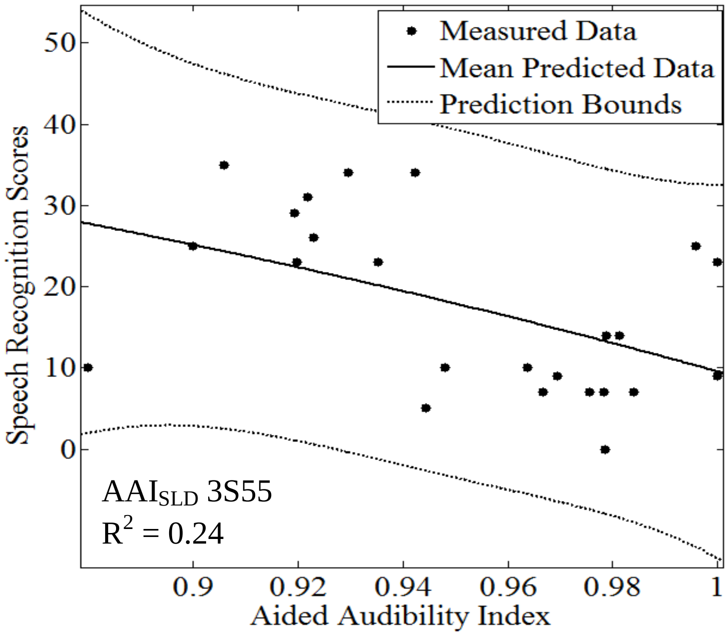

Figure 1. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI_{SLD} in 3S55 in Group II. The AAI_{SLD} was computed using REAR. Here, 3S55 is the compression ratio of 3:1 with short time constants, at presentation level of 55 dB SPL.

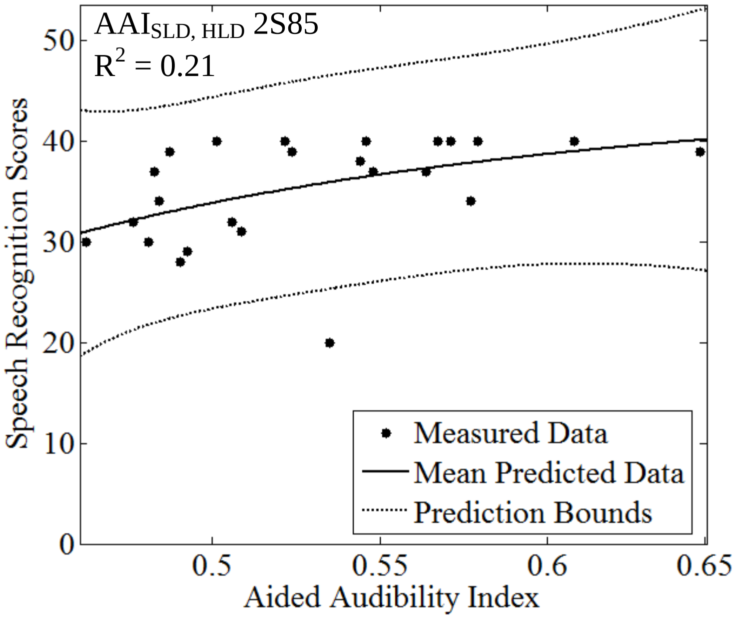

Figure 2. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 2S85 in Group II. The $AAI_{SLD, HLD}$ was computed using REAR. Here, 2S85 is the compression ratio of 2:1 with short time constants, at presentation level of 85 dB SPL.

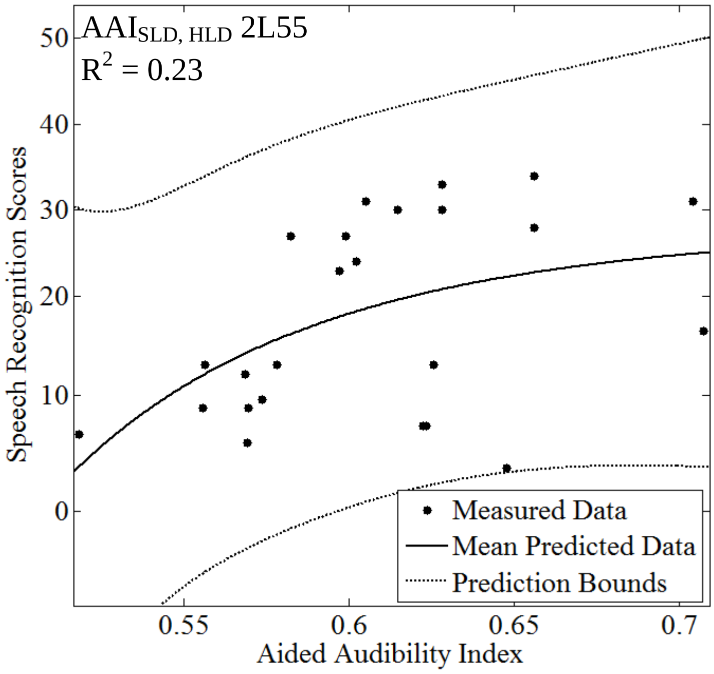

Figure 3. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 2L55 in Group II. The AAI$_{SLD, HLD}$ was computed using REAR. Here, 2L55 is the compression ratio of 2:1 with long time constants, at presentation level of 55 dB SPL.

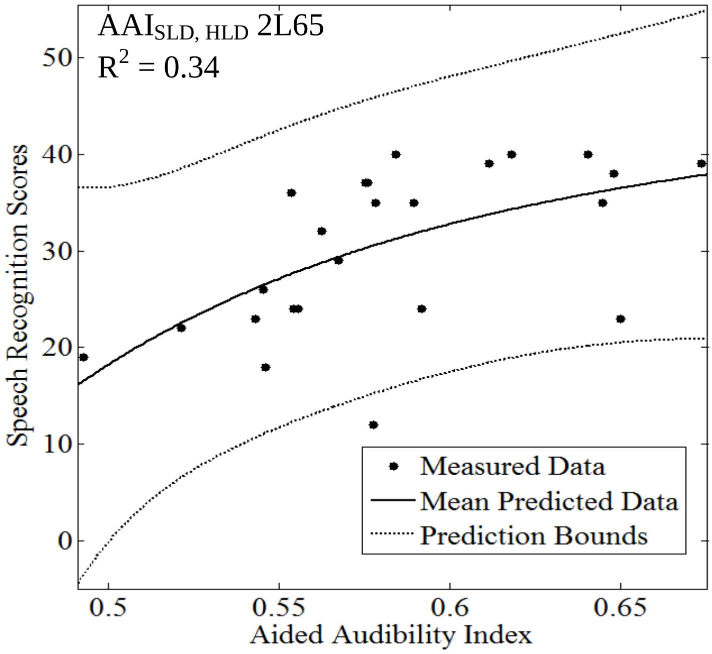

Figure 4. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 2L65 in Group I. The AAI$_{SLD, HLD}$ was computed using REAR. Here, 2L65 is the compression ratio of 2:1 with long time constants, at presentation level of 65 dB SPL.

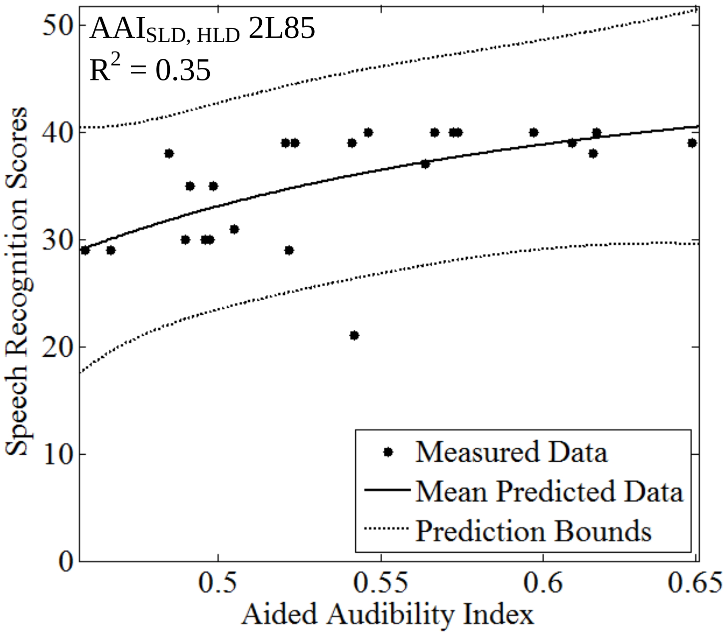

Figure 5. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $\text{AAI}_{\text{SLD, HLD}}$ in 2L85 in Group II. The $\text{AAI}_{\text{SLD, HLD}}$ was computed using REAR. Here, 2L85 is the compression ratio of 2:1 with long time constants, at presentation level of 85 dB SPL.

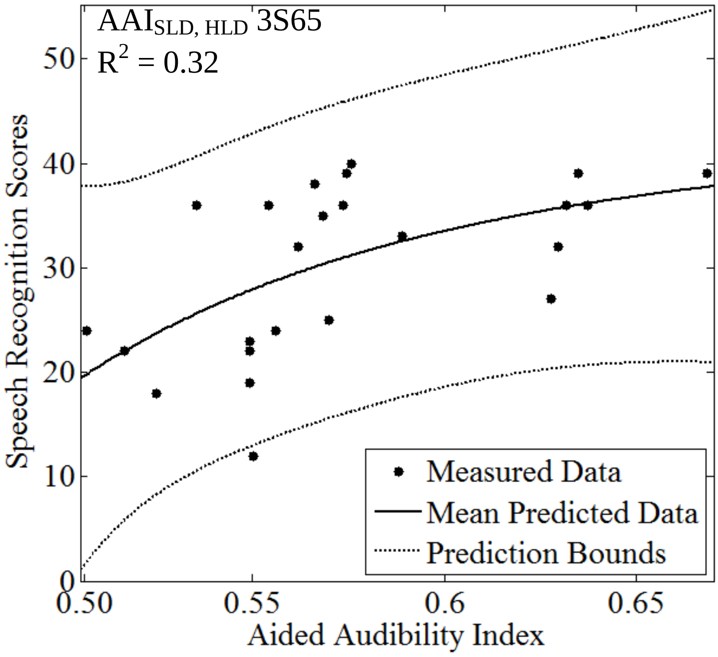

Figure 6. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $\text{AAI}_{\text{SLD, HLD}}$ in 3S65 in Group II. The $\text{AAI}_{\text{SLD, HLD}}$ was computed using REAR. Here, 3S65 is the compression ratio of 3:1 with short time constants, at presentation level of 65 dB SPL.

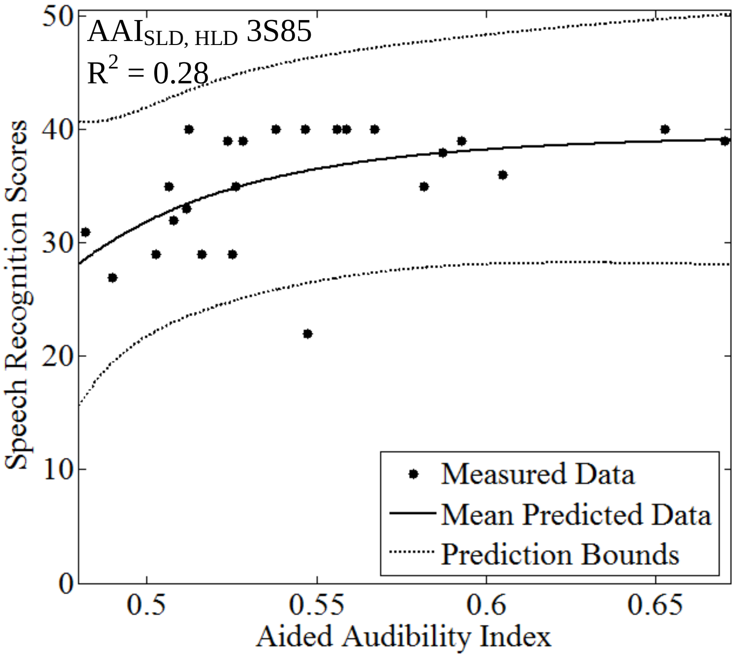

Figure 7. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 3S85 in Group II. The AAI$_{SLD, HLD}$ was computed using REAR. Here, 3S85 is the compression ratio of 3:1 with short time constants, at presentation level of 85 dB SPL.

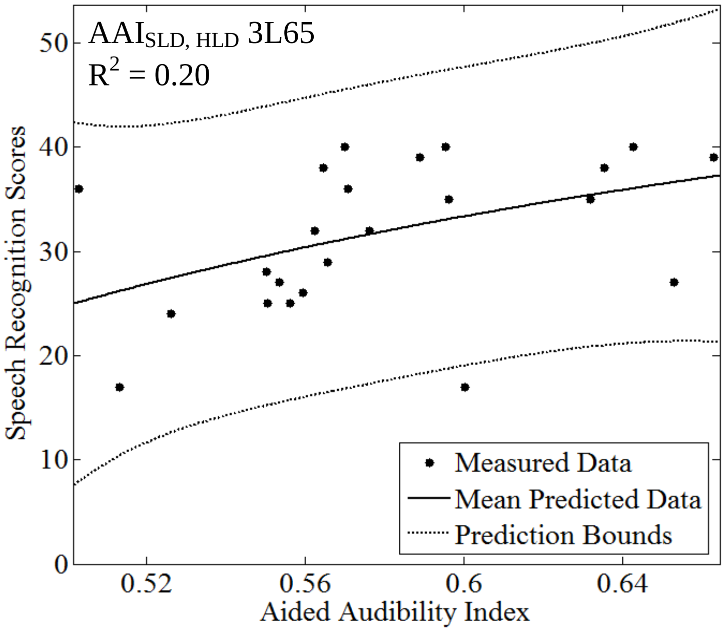

Figure 8. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from AAI$_{SLD, HLD}$ in 3L65 in Group II. The AAI$_{SLD, HLD}$ was computed using REAR. Here, 3L65 is the compression ratio of 3:1 with long time constants, at presentation level of 65 dB SPL.

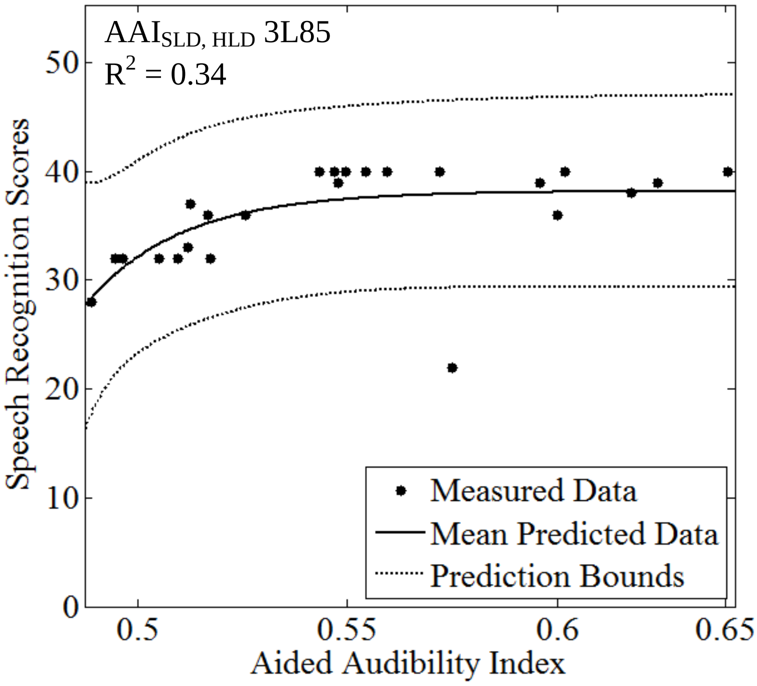

Figure 9. Measured SRS (filled circles), mean (solid line) and 95% bounds (dotted lines) of SRS predicted from $AAI_{SLD, HLD}$ in 3L85 in Group II. The $AAI_{SLD, HLD}$ was computed using REAR. Here, 3L85 is the compression ratio of 3:1 with long time constants, at presentation level of 85 dB SPL.