Doctoral Thesis

THE EFFECT OF INTENSITY AND TEMPORAL ENHANCEMENT ON SPEECH PERCEPTION IN INDIVIDUALS WITH AUDITORY NEUROPATHY SPECTRUM DISORDER (ANSD)

Jijo P.M

All India Institute of Speech and Hearing, Mysore

Guided by

Dr. Asha Yathiraj

All India Institute of Speech and Hearing, Mysore

Submitted to

The University of Mysore, India-570006

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1- INTRODUCTION

He, who has ears to hear, let him hear.

- Mark, 4:9

It is a known fact that hearing is one of the most important senses and perception of speech its major function. A normally functioning auditory system is essential for understanding speech for effective verbal communication. Deficits anywhere in the path of the auditory system are known to lead to hearing impairment and hence impaired speech perception.

Auditory Neuropathy Spectrum Disorder (ANSD) is a form of sensorineural hearing impairment reported to cause impaired neural conduction with preserved cochlear outer hair cells (Starr, Picton, Sininger, Hood, & Berlin, 1996). The initial term 'auditory neuropathy', coined by Starr et al. (1996) due to presence of peripheral neuropathy, was replaced with 'auditory dys-synchrony' by Berlin, Hood and Rose (2001). The term 'auditory neuropathy' was considered semantically incorrect, as the auditory nerve itself was not always affected, misleading clinicians to use cochlear implant as a management option. More recently, the term 'Auditory Neuropathy Spectrum Disorder' (ANSD) was recommended to represent the diversity in site-of-lesion and auditory perceptual abilities of this clinical condition at a 'Consensus conference on auditory neuropathy/dys-synchrony coordinated by Sininger and Hayes (2008).

Literature on the prevalence of ANSD has revealed that it varies from 1.8 to 11% in countries outside India (Berlin, Hood, Goforth-Barter, & Bordelon, 1999; Rance et al., 1999; Tang, McPherson, Yuen, Wong, & Lee, 2004) and varies from 0.53 to 2.27 within

India (Bhat, Kumar, & Sinha, 2007; Kumar, & Jayaram, 2006). The condition is reported to occur in two distinct age groups, infancy and adolescence as well as early adulthood (Berlin et al., 2010; Jijo & Yathiraj, 2012; Kumar & Jayaram, 2006; Narne, Prabhu, Chandan, & Deepthi, 2014a; Shivashankar, Satishchandra, Shashikala, & Gore, 2003; Sininger & Oba, 2001; Starr, Sininger, & Pratt, 2000). In India, higher prevalence has been noted in adults compared to children (Jijo & Yathiraj, 2012; Kumar & Jayaram, 2006; Prabhu, Avilala, & Manjula, 2012; Shivashankar et al., 2003). Further, the majority of the individuals with late onset ANSD have been observed to be from a poor socio-economic background (Kumar & Jayaram, 2006; Prabhu et al., 2012). The high prevalence and low socio-economic status of individuals with late onset ANSD, necessities the development of inexpensive and practical rehabilitative options for them.

Psycho-acoustical studies in individuals with late onset ANSD have revealed that temporal processing is more severely impaired than frequency or intensity processing (Barman, 2008; Starr et al., 1991; Zeng, Kong, Michalewski, & Starr, 2005; Zeng, Oba, Grade, Sininger, & Starr, 2001). Speech perception deficits observed in individuals with ANSD were found to correlate with their temporal processing abilities (Kumar & Jayaram, 2005; Narne, 2008; Rance, McKay, & Grayden, 2004; Zeng, Oba, grade, Sininger & Starr, 1999). It is reported that impaired temporal resolution leads to difficulty in perceiving short and dynamic signals (Krause et al., 2000) as well as increased masking effect (Zeng et al., 2005).

A measure used to determine the temporal processing deficits in individuals with ANSD is temporal modulation transfer function (TMTF). This measure has been used as a clinical tool to provide a direct measure of temporal envelope processing (Viemeister, 1979). Studies in individuals with ANSD have reported a high correlation between temporal modulation detection and speech perception (Kumar & Jayaram, 2005; Rance et al., 2004; Zeng et al., 1999). This was also observed using speech stimuli that were modified in terms of duration as well as the temporal envelope (Kumar, 2006; Narne & Vanaja, 2008).

In individuals with ANSD, difficulty in temporal processing has been found to affect the perception of specific acoustic cues like voice onset time (VOT), burst and formant transitions, resulting in poor perception of speech sounds, especially stops (Kumar & Jayaram, 2011; 2013). Time scale modification of these specific acoustic cues was noted to improve perception of stops (Kumar & Jayaram, 2011; 2013). However, difficulty in identifying these dynamic cues in long segments of speech necessitates the use of alternative techniques to alleviate temporal processing difficulties of individuals with ANSD. Jijo and Yathiraj (2013a) highlighted that expanding the entire speech signal, an easier task than expanding specific segments of speech, was useful in improving speech perception in individuals with late onset ANSD.

Besides temporal based problems, individuals with ANSD are known to exhibit more difficulty in perceiving low frequency information compared to high frequency (Zeng et al., 2005; Barman, 2008). This difficulty has been ascribed to their inability to use phase locking cues due to dys-synchronous discharge in the auditory nerve (Zeng et al., 2005). Founded on the difficulties individuals with ANSD have in processing signals in different frequencies, studies have been carried out to determine the utility of spectral modification to enhance speech perception. Narne and Vanaja (2012), using a spectral modification approach that eliminated low frequency information below 500 Hz, found no significant improvement in perception in most of their participants. However, a few individuals did show improvement in perception and a few showed deterioration. Krause et al. (2000) reported that individuals with ANSD showed deterioration in perception when the amplitude of formant transitions were enhanced. However, Narne, Barman, Deepthi, and Schachi (2014b) reported that companding, a specto-temporal modification approach, improved speech perception significantly in individuals with ANSD. Thus, the studies on the effect of different spectro-temporal enhancement strategies on speech perception in individuals with ANSD show mixed results.

Yet another method in rehabilitation of individuals with ANSD is the use of amplification. Studies on the usefulness of amplification in those with late onset ANSD revealed limited or unsuccessful outcome (Miyamoto, Kirk, Renshaw, & Hussain, 1999; Shallop, Peterson, Facer, Fabry, & Driscoll, 2001; Sininger, Hood, Starr, Berlin, & Picton, 1995; Widen, Ferraro, & Trouba, 1995). It was hypothesized by Hood (1998), Zeng and Liu (2006) that a compression circuit in hearing aids might distort the temporal envelope of speech, causing deterioration in speech perception. This leads to the speculation that hearing aids with linear amplification, reported to preserve the temporal envelope of speech by Van Tassel (1993), could be another method to improve speech perception in individuals with ANSD.

Although several studies have reported of limited usefulness of amplification in those with ANSD, a few researchers have demonstrated positive outcomes in some individuals with late onset ANSD using amplification (Jijo & Yathiraj, 2013b; Vanaja & Manjula, 2004; Narne et al., 2014a). Investigators have recommended evaluating temporal processing abilities in individuals with ANSD to get better insight regarding the usefulness of amplification (Narne et al., 2014a; Vanaja & Manjula, 2004). Further, it is also recommended that obtaining a performance-intensity function in these individuals might give better understanding of loudness perception that might help identify a subgroup of individuals who may benefit from hearing aids (Cone-Wesson, Rance & Sininger, 2001; Jijo & Yathiraj, 2013b).

In addition to the above techniques used to rehabilitate individuals with ANSD, other procedures used to enhance auditory perception include the use of cochlear implants (Berlin et al., 2010; Madden, Rutter, Hilbert, Greinwald, & Choo, 2002; Rance et al., 1999; Shallop et al., 2001; Trautwein et al., 2000; Zeng & Liu, 2006) and auditory training utilising fine-grained auditory stimuli (Yathiraj & Avilala, 2011). Positive outcomes have been reported in individuals who have utilised cochlear implants (Berlin et al., 2010; Madden et al., 2002; Rance et al., 1999; Shallop et al., 2001; Trautwein et al., 2000; Zeng & Liu, 2006) as well as undergone fine-grained auditory training (Yathiraj & Avilala, 2011).

From the literature on rehabilitation of those with ANSD, it can be surmised that several techniques have been utilised. While some techniques utilise modifications of speech stimuli (Hassan, 2011; Jijo & Yathiraj, 2013a; Kumar & Jayaram, 2011, 2013; Narne & Vanaja, 2009a), others recommend the use of hearing aids (Jijo & Yathiraj, 2013b; Narne et al., 2014a; Vanaja & Manjula, 2004) and cochlear implants (Berlin et al., 2010; Madden et al., 2002; Mason, De Michele, Stevens, Ruth, & Hashisaki, 2003; Rance et al., 1999; Shallop et al., 2001; Trautwein et al., 2000; Zeng & Liu, 2006). Additionally, benefits from fine-grained auditory training has also been reported (Yathiraj & Avilala, 2011). As a non-invasive and inexpensive rehabilitative option, the usefulness of hearing aids and signal enhancement strategies need to be further investigated.

Need for the study

Need to study different rehabilitation techniques in individuals with ANSD

It is evident from the literature that ANSD is not a rare disorder (Berlin et al., 1999; Bhat et al., 2007; Kumar & Jayaram, 2006; Rance et al., 1999; Tang et al., 2004). Research on individuals with ANSD has primarily focused on their perceptual deficits rather than rehabilitation. Among the different rehabilitative techniques that have been reported, cochlear implants have been noted to be the most beneficial (Berlin et al., 2010; Madden et al., 2002; Rance et al., 1999; Shallop et al., 2001; Trautwein et al., 2000; Zeng & Liu, 2006). However, there is a need for a non-invasive as well as an inexpensive form of rehabilitation.

Research on the usefulness of hearing aids as well as speech enhancement strategies has yielded mixed results, with some studies reporting of benefit (Jijo Yathiraj, 2013a; Kumar & Jayaram, 2011, 2013; Narne et al., 2014a; Narne & Vanaja, 2008; Vanaja & Manjula, 2004) and others of no benefit (Miyamoto et al., 1999; Narne & Vanaja, 2012; Shallop et al., 2001; Starr et al., 1996; Trautwein et al., 2000; Widen et al., 1995). Hence, there is a need to further study the effect of additional techniques that may enhance speech perception in individuals with ANSD.

Need to study speech perception at different sensation levels in individuals with ANSD

The effect of intensity on speech perception in individuals with ANSD is sparse. Cone-Wesson et al. (2001) speculated that such an investigation may help understand the perceptual deficits in individuals with ANSD and also throw light on the utility of management options such as hearing aids. They hypothesized that the presence of a flat performance-intensity function or rollover might contraindicate hearing aid benefit in individuals with ANSD. An investigation by Jijo and Yathiraj (2013b) demonstrated that individuals with ANSD, who had relatively higher speech perception at supra-threshold levels, benefited from amplification. In contrast, those who had poor speech perception at supra-threshold levels showed poor aided performance. Thus, they construed that speech perception scores at supra-threshold levels may be a good predictor of aided improvement. They recommended the use of a complete performance-intensity function to get a better understanding of the speech perception of individuals with ANSD unlike what is got from a single presentation level. Hence, there is a need to obtain a complete performance-intensity function that may help identify a subgroup of individuals who can benefit from hearing aids.

Need to investigate the effect of performance on TMTF on different signal enhancement strategies as well as amplification in individuals with ANSD

Studies have established the link between temporal modulation detection and speech perception in individuals with ANSD (Kumar & Jayaram, 2005; Rance et al., 2004; Zeng et al., 1999; Zeng et al., 2001). This link has also seen for stimuli modified in terms of duration and temporal envelope (Kumar & Jayaram, 2006; Narne & Vanaja, 2008). However, its impact on stretching the entire speech signal has not been studied. Further, the impact of temporal resolution on aided speech perception has not been investigated. Thus, the impact of temporal resolution, measured using TMTF, needs to be investigated to examine the relation between temporal resolution difficulties and temporally stretched speech and spectro-temporally modified speech.

Need to investigate the effect of aided performance in individuals with ANSD

There exists a controversy regarding the usefulness of amplification devices among those with late onset ANSD. While some studies report that amplification results in limited use or has a detrimental effect (Miyamoto et al., 1999; Shallop et al., 2001; Sininger et al., 1995; Starr et al., 1996; Widen et al., 1995), others have shown evidence of improvement in speech perception in at least a few individuals with late onset ANSD (Jijo & Yathiraj, 2013b; Vanaja & Manjula, 2004; Narne et al., 2014a). Further research is warranted to identify markers that will help identify a subgroup of individuals with ANSD who benefit from hearing aids.

Further, it is also reported that hearing aids with active compression may remove envelope features (Plomp, 1988). This has been speculated to diminish the performance in individuals with ANSD (Hood, 1998; Zeng & Liu, 2006). However, this has not been confirmed. Hence, it is necessary to investigate the effect of amplification using digital hearing aids without and with compression.

Need for temporal/spectro-temporal modification of speech signals

It was observed by Zeng and Liu (2006) that individuals with ANSD show significantly higher speech perception using clear speech when compared to conversational speech, with the former having twice the duration of the latter. It is hypothesised that the lowered rate of speech in the former condition might have led to improved speech perception in individuals with ANSD. Signal enhancement strategies that incorporate certain properties of clear speech have also been reported to improve speech perception. These strategies include stretching of formant transition duration (Kraus et al., 2000), time scale modification of short acoustical cues in speech (Kumar & Jayaram, 2011; 2013), and enhancement of temporal envelope of speech (Narne & Vanaja, 2009). Increased formant amplitude and duration are also observed by Picheny, Durlach, and Braida, (1986) to be seen in clear speech. However, incorporation of such modifications in speech signals have shown mixed results (Krause et al., 2000; Narne et al., 2014b).

Kumar and Jayaram (2011; 2013) reported that time scale modification of short acoustical cues in speech improved speech perception significantly. However, the acoustical cues of speech signal were manually identified and stretched. Implementation of this approach in running speech would be difficult. Additionally, due to co-articulatory effects of running speech, automatic identification of the necessary acoustical landmarks to stretch speech signals would be difficult. Hence, rather than stretching the acoustical landmarks alone, the effect of time scale modification of the entire speech signal should be evaluated.

Need to study specific speech sounds such as stops and liquids

Studies that have investigated consonantal perception errors made by individuals with ANSD have indicated that perception of stops and liquids are more affected compared to other speech sounds (Narne & Vanaja, 2008; Rance et al., 2008). It was inferred by Zeng et al. (1999) that the impaired perception of fast modulation of speech in these individuals led to poor perception of rapid events such as burst and transition, which is essential for the perception of stop consonants. Although the envelope enhancement used by Narne and Vanaja (2008) resulted in improvement in perception of stops, there was no improvement noted for the perception of liquids. They suggested that a spectro-temporal modification might be a better approach to improve the perception of liquids.

A large number of studies on consonant perception in individuals with ANSD use consonant-vowel syllables. However, in conversational speech, intervocalic consonants are found more frequently than initial and final consonants (Picket, Bunnel, & Revoile, 1995). Hence, it is essential to study speech perception using vowel-consonant-vowel (VCV) syllables, which are more akin to natural speech. Additionally, it is essential to investigate the perception of speech in different vowel contexts rather than a single one to determine co-articulatory influences.

Aim of the study

The aim of the study was to investigate the effect of two signal enhancement strategies as well as performance-intensity for phonemically balanced (PI-PB) function and aided performance in 30 individuals with late onset ANSD.

Objectives

The objectives of the study were to determine the following in individuals with ANSD:

1. Effect of temporal processing severity on word identification scores,
2. The effect of performance-intensity function on word identification scores,

3. Effect of two different speech modification strategies (stretch & spectro-temporal modification) on speech identification in individuals grouped based on their temporal processing difficulty,
4. Effect of two different forms of amplification (linear & non-linear) on speech identification in individuals grouped based on their temporal processing difficulty,
5. Effect of different sensation levels (0 dB SL, 10 dB SL, 20 dB SL, 30 dB SL 40 dB SL & 50 dB SL (ref: PTA) on speech identification scores,
6. Effect of two types of amplification (aided linear & aided non-linear) on speech identification in individuals grouped based on their PI-PB function,
7. Relationship between speech identification scores across different intensities and amplification conditions (unaided, aided linear, & aided non-linear) and
8. Comparison between peak modulation detection thresholds of normal hearing individuals and those with ANSD, grouped based on their temporal processing abilities.

Hypotheses

The null hypotheses formed to investigate the objectives of the study in individuals with ANSD are as follows:

1. There is no significant effect of temporal processing severity on word identification scores,
2. There is no significant effect of performance-intensity function on word identification scores,

3. There is no significant effect of speech modification (stretch & spectro-temporal modification) on speech identification in individuals grouped based on their temporal processing difficulty,
4. There is no significant effect of amplification (linear & non-linear) on speech identification in individuals grouped based on their temporal processing difficulty,
5. There is no significant effect of intensity levels on speech identification scores,
6. There is no significant effect of amplification (aided linear & aided non-linear) on speech identification in individuals grouped based on their PI-PB function,
7. There is no significant relation between speech identification score across different intensity levels and amplification conditions (unaided, aided-linear and aided non-linear),
8. There is no significant difference in the peak modulation detection thresholds of the normal hearing individuals and those with ANSD, grouped based on their temporal processing abilities.

In order to design the method of the study, a detailed review of literature was carried out. Literature available in India and from other countries were reviewed.

CHAPTER 2- REVIEW OF LITERATURE

Rehabilitation of individuals with Auditory Neuropathy Spectrum Disorder (ANSD) is a challenge for audiologist. Differing sites of lesion and diversity in auditory perceptual abilities makes their rehabilitation hard (Rance, 2005). Unlike, those with other sensorineural hearing losses, difficulty in speech perception seen in individuals with ANSD is attributed to deficits in temporal processing (Rance et al., 2004; Starr et al., 1996; Zeng et al., 2005) rather than audibility or spectral distortions. Varieties of rehabilitative options have been suggested in literature. The choice of options has been influenced by several variables. In order determine the lacunae in rehabilitation options, a review of literature was carried out. The review focussed on the following: Age of onset of ANSD; Etiological factors; Audiological characteristics in individuals with ANSD; Temporal processing and speech perception in individuals with ANSD; Effect of intensity on speech perception in individuals with ANSD; Amplification in individuals with ANSD, and; Signal enhancement strategies for individuals with ANSD.

Age of Onset of ANSD

The occurrence of ANSD has been reported in two distinct age groups, infancy and adolescence or early adulthood (Berlin et al., 2010; Jijo & Yathiraj, 2012; Kumar & Jayaram, 2006; Narne et al., 2014a; Shivashankar et al., 2003; Sininger & Oba, 2001; Starr et al., 2000). However, in literature it has been reported to occur predominantly in children below the age of 10 years (Berlin et al., 2010; Sininger & Oba, 2001; Starr et al., 2000). Sininger and Oba (2001) noted that in their 59 patients with ANSD, 75% had an onset below 10 years of age. They also noted that within this group, the onset in 80%

was before the age of 2 years. Starr et al. (2000) observed that out of 67 of their clients with ANSD, 75% were children under the age of 10 years, whereas only 25% were older than 10 years at the time of onset of the symptom. Similar findings were observed in a retrospective study by Berlin et al. (2010), which comprised of 260 clients with ANSD evaluated over a period of 12 years. They found that 85.76% of the clients were below the age of 12 years and only some of them had an onset between puberty and adulthood. The authors attributed the identification of the condition in the paediatric population to the mandatory use of Otoacoustic emission (OAE) and Auditory Brainstem Response (ABR) in hearing screening procedure in infants. They reported that lesser adults were identified as OAEs disappeared with increase in age or cochlear microphonics evaluation was not included in the diagnostic criteria, thus making the diagnosis of ANSD difficult.

Unlike the studies carried out in other parts of the world, studies done in India indicate that the problem is more pronounced in adults. Shivashankar et al. (2003) reported that the onset of the problem occurred during the first and second decade of life in all the 24 individuals they studied, except one who had an onset at the age of 44 years. This clinical data was gathered over a period of 10 years from a tertiary referral institution in South India. Likewise, in another retrospective study carried out in South India, Kumar and Jayaram (2006) reported that 59% of their 61 patients with ANSD had onset of the condition between 14 to 24 years of age. Similarly, Jijo and Yathiraj (2012) found that 54% of their 120 clients with ANSD had an onset of the disorder between 10.1 to 20 years. In only 23% was the onset below the age of 10 years. However, age-wise statistics of clients where their study was carried out showed that majority of individuals with history of hearing loss were below the age of 5 years. The authors observed that audiological services were sought primarily due to delayed speech and language in this group. They opined that despite universal hearing screening not being carried out, children with hearing loss were still identified due to delay in speech and language skills. However, this did not happen with the paediatric ANSD group. Hence, they justified that the absence of a widespread use of OAE and ABR in hearing screening in India was not the reason for fewer paediatric clients being identified with ANSD. Thus, it was concluded that late onset ANSD is the predominant group in Indian scenario. The presence of onset of ANSD being late was also reported in a Chinese based study by Wang, Gu, Han, and Yang (2003).

Thus, from the review on the age of onset of ANSD it can be seen that there is no consensus regarding the age at which it is noticed to occur. Studies carried out in non-Asian countries report that the onset occurs primarily in the paediatric population. On the other hand, studies carried out in Asian countries indicate that the onset primarily occurs in young adults.

Etiological Factors

Among children, the occurrence of ANSD is often reported to be linked with one or more risk factors. Neonatal hyperbilirubinemia (Berlin et al., 2010; Rance et al., 1999), anoxia and premature birth (Berlin et al., 2010; Rance et al., 1999; Sininger & Oba, 2001) have been identified to be the most common risk factors in the paediatric population. It is reported that 50% of individuals with ANSD are non-syndromic (Starr et al., 2000). Genetic analysis has led to the identification of a number of gene mutations that result in non-syndromic ANSD in children. Mutations in the otoferlin gene have been reported to be the cause of non-syndromic ANSD in children with congenital severe to profound hearing loss (Rodriguez et al., 2003, 2009; Varga et al., 2003, 2006). The Pejvakin gene has also been identified as a cause of non-syndromic ANSD in children from certain Iranian families (Delmaghani et al., 2006).

Among adults, Type I & II of hereditary motor and sensory neuropathies were commonly found etiologies for late onset ANSD (Butinar et al., 1999; Leonardis et al., 2000; Sininger & Oba, 2001). Friedreich's ataxia, another inherited condition, is also reported to result in ANSD (Merlini, Villanoa, & Sabtalli, 1998; Sininger & Oba, 2001). Genetic factors leading to ANSD in the above neurological disorders have been confirmed in studies carried out by Kalaydjieva et al. (2000) and Kovach, Lin, and Boyajiev (1999).

Information regarding the cause of non-syndromic ANSD among adults is sparse. Kumar and Jayaram (2006) reported that no specific aetiology could be tracked among their 61 individuals with late onset ANSD. However, two of them had onset of the condition after giving birth to their first child. Prabhu et al. (2012) reported that idiopathic onset of ANSD was found in 80% of the individuals with late onset ANSD. They analyzed the possible predisposing factors that might have caused late onset ANSD. It was found that 80% of the patients belonged to low socio-economic status, 47.6% had onset of the condition soon after puberty, 10% had exposure to toxic chemicals and family history of ANSD. Similarly, Jijo and Yathiraj (2012) reported of family history of hearing loss (30%) and parental consanguinity (25%) in the 120 clients, highlighting the possibility of genetic cause of late onset ANSD. Additionally, the occurrence of ANSD during puberty or pregnancy insinuated the influence of hormonal factors. Wang et al. (2003) analyzed the pattern of inheritance in 12 Chinese patients with non-syndromic

ANSD whose onset of the problem was during the first and second decade of life. The pedigree analysis revealed X-linked recessive inheritance in one family and autosomal recessive inheritance in the other three families. Similarly, Wang et al. (2010) noted mutational changes in otoferlin gene in only 4 out of 73 Chinese Han patients with ANSD. All the clients had a non-syndromic form of ANSD with the age of onset prior to or during adolescence. In contrast, Shivashankar et al. (2003) reported that none of their clients (24 individuals with late onset ANSD) had any relevant etiological history.

It is clear from the above literature that congenital ANSD is often associated with certain risk factors. Although late onset ANSD is often due to neurological conditions, the cause for non-syndromic late onset ANSD is not clear. Genetic, hormonal and idiopathic conditions are often reported to be associated with non-syndromic late onset ANSD.

Audiological Characteristics in Individuals with ANSD

Audiological findings of individuals having ANSD are well documented. Individuals with ANSD are noted often to exhibit bilateral, symmetrical sensorineural hearing loss. Sininger and Oba (2001) reported that while 82% of their patients had bilateral symmetrical hearing loss, only 14% had asymmetrical hearing loss. Unilateral hearing loss was noted in only 4% of the patients. Kumar and Jayaram (2006) found that all their 61 clients had bilateral hearing loss, though a few of them exhibited asymmetry. The degree of hearing has been noted to range from normal to profound (Berlin et al., 2010; Starr et al., 2000). Various audiometric configurations are reported to be found in individuals with ANSD. Kumar and Jayaram (2006) noted that among the 61 patients studied by them, 26 showed peaked, 11 had flat and rising, 8 had saucer shaped and 3 had sloping audiometric configurations. Starr et al. (2000) found that 41% of their clients had flat audiometric configuration, 29% had a rising couture, and only 11% of the participants had sloping configuration.

Speech identification abilities have been noted to range from no measurable scores to 90% (Berlin et al., 2010; Kumar & Jayaram, 2006). Starr et al. (2000) reported that patients who had hearing loss greater than 30 dB HL exhibited more impairment in speech identification than expected. Berlin et al. (2010) found that among their 95 patients, 25 had word recognition abilities in quiet and only 5 had in noise. Kumar and Jayaram (2006) and Jijo and Yathiraj (2012) observed that those with peaked audiometric configuration had better speech identification scores compared to other audiometric contours. Speech identification scores of individuals with ANSD were found to not correlate with pure-tone thresholds by Kumar and Jayaram (2006), Starr et al. (2000), and Zeng et al. (2001). However, a small percentage of subjects were reported by Sininger and Oba (2001) and Starr et al. (1996) to have speech identification proportionate with their degree of hearing loss.

Otoacoustic emissions have been reported to be present in three-fourth of the individuals with ANSD evaluated by Berlin et al. (2010), whereas middle ear muscle reflexes were absent in 90% of the clients. Kumar and Jayaram (2006) found that TEOAEs were present in all their 61 individuals with ANSD while acoustic reflexes were absent in all. Absence of acoustic reflexes were reported by Berlin et al. (2005) in 113 of the 128 patients evaluated whereas reflexes were present in only six ears of the five participants. Starr et al. (2000) noted that middle ear muscle reflexes were absent in 91%

of the participants. Normal acoustic reflexes were found in 7% of the patients whereas, 2% of the clients had elevated reflex.

Auditory brainstem responses were often found to be absent or abnormal in individuals with ANSD (Rance et al., 1999; Sininger & Oba, 2001; Starr et al., 1996). Starr et al. (2000) noted that 73% of their patients had absent ABR whereas, 21% had wave V present but with reduced amplitude and prolonged latency. Only 6% of the patients had wave III and V, but with an abnormal morphology.

It can be summarised from the above literature on audiological findings of those with ANSD that pure-tone hearing thresholds ranges from normal to profound degree. Similarly, speech identification scores also varies widely. Unlike other sensorineural hearing loss, individuals with ANSD often had speech identification abilities disproportionate with their degree of hearing loss. Though otoacoustic emissions were present in three-fourth of the ANSD population, middle ear muscle reflexes and auditory brainstem responses were absent in the majority.

Temporal Processing and Speech Perception in Individuals with ANSD

Research on the auditory perceptual difficulties of individuals with ANSD has demonstrated that they have considerable difficulty in the perception of temporal cues (Zeng et al., 1999; Zeng et al., 2005). On the other hand, their perception of frequency cues and intensity cues have been observed to be less affected (Barman, 2008; Zeng et al., 2005). Hence, the below review has focused on the temporal processing difficulties of individuals with ANSD.

Zeng et al. (1999) investigated temporal integration, gap detection and TMTF in eight individuals with ANSD. Additionally, six normal hearing individuals were tested with temporally smeared stimuli that simulated four degrees of temporal processing impairments found in individuals with ANSD. The results revealed that individuals with ANSD had normal or nearly normal temporal integration function. In contrast, gap detection thresholds were 2 to 25 times greater than the normal thresholds. Similarly, TMTF threshold showed impaired peak modulation detection for both slow and fast temporal modulations. Zeng et al. ascribed this poor performance on temporal resolution (gap detection and TMTF) to be the reason for impaired speech perception in individuals with ANSD. Additionally, the normal hearing individuals tested with material simulating temporal processing impairment showed speech perception deficits similar to that of ANSD. The poor word recognition scores in the normal hearing listeners were consistent with the degree of impaired temporal processing in individuals with ANSD.

Kumar and Jayaram (2005) investigated temporal resolution and speech perception in individuals with ANSD. They analyzed TMTF peak modulation thresholds and open set speech identification scores in 14 participants. Additionally, the relation between TMTF peak modulation thresholds and speech identification scores were obtained using stimuli (unprocessed & transition duration modified). It was noted that seven of the eight patients who had peak sensitivity more than -10.4 dB also had open-set speech perception greater than 50%. However, among the six patients who had peak sensitivity less than -5.6 dB, five had speech identification scores less than 20%. In each TMTF group there was one individual who had extreme speech identification and TMTF scores. When the data from these outliers were excluded, there was a significant correlation found between peak sensitivity and speech identification scores. It was found that there was a significant correlation between temporal processing abilities evaluated using TMTF and speech identification scores obtained in the unprocessed, transition duration modified stimuli. Those who had better modulation threshold had better speech identification scores in the unprocessed and transition duration modified conditions.

Rance et al. (2004) investigated speech perception and psychophysical abilities in children with normal hearing (N = 10), sensorineural hearing loss (N = 10) and ANSD (N = 14). Based on a consonant-nucleus-consonant perception test, individuals with ANSD were classified into two groups, those who had phoneme scores greater than 30% and less than 30%. Modulation detection thresholds, obtained at modulation frequencies 10, 50 and 150 Hz showed no significant difference between the normal hearing group and those with sensorineural hearing loss. Children with ANSD having a phoneme score of less than 30% had significantly poor modulation detection compared to those with normal hearing, sensorineural hearing loss and those with ANSD having a phoneme score greater than 30%. This was noted in all three modulation frequencies. Those children with ANSD, having greater than 30% phoneme score, had significantly poor modulation detection threshold compared to the normal hearing children. However, this was found only at higher modulation frequencies (50 & 150 Hz) indicating mild impairment in temporal envelope perception. Additionally, there was a strong correlation between consonant-nucleus-consonant scores and modulation detection thresholds at each of the modulation rates.

Evaluation of temporal and frequency resolution and their effect on perception of place, manner and voicing features in individuals with ANSD was studied by Nike and

Barman (2011). The responses were compared with individuals with cochlear hearing loss and those with normal hearing sensitivity. It was reported that those with ANSD had significantly lower peak sensitivity and bandwidth of TMTF compared to those having cochlear hearing loss and those with normal hearing sensitivity. However, there was no significant difference in peak sensitivity and bandwidth of TMTF across the sub-groups of ANSD having different audiometric patterns. Perception of manner, place and voicing of consonant was more difficult in individuals with ANSD compared to those with cochlear hearing loss. Among the individuals with ANSD, voicing feature was perceived the lowest followed by place and manner. Additionally, there was a significant correlation between peak sensitivity of TMTF and palace and manner features. However, voicing feature did not correlate with peak sensitivity of TMTF. Further, there was a significant correlation between voicing features with bandwidth of auditory filter at 500 Hz and the slope of the tail of 1000 Hz. The authors construed that voicing murmur, a major cue in Vowel-Consonant-Vowel stimuli, was significantly affected by poor frequency resolution at low frequencies.

Rance et al. (2008) studied speech perception ability in 10 individuals with Friedreich's ataxia (3 with & 7 without elctrophysilogical evidence of ANSD) and compared them with individuals having normal auditory function (N = 30) and sensorineural hearing loss (N = 3). Perception of vowels and phonemically balanced Consonant-Nucleus-Consonant words comprising of fricative, sibilant, plosive, burst semivowel and nasal phonemes were investigated. Information transfer analysis in the three participants with ANSD and the three with sensorineural hearing loss showed that vowel perception was similar in the two groups. Perception of sibilants was significantly better in the ANSD group. However, perception of stops, semivowels, nasals and diphthongs were poor in those with ANSD. Voiced-unvoiced discrimination of /p, t, k/ and /b, d, g/ showed that those with sensorineural hearing loss could discriminate better than those with ANSD. The good perception of vowels in those with ANSD was attributed to normal frequency resolution and the steady state nature of vowels. The good perception of sibilants was ascribed to their high frequency energy and good high frequency discrimination in those with ANSD. The poor perception of nasals and stops was considered to occur due to poor low frequency discrimination and impaired perception of rapid spectral changes respectively. Further, the poor discrimination of voiced-unvoiced sounds were attributed to difficulty in perceiving short acoustic events such as VOT by individuals with ANSD.

In a similar investigation, Rance et al. (2010) studied temporal and spectral processing in 14 individuals with Friedreich's ataxia (7 with & 7 without electrophysiological evidence of ANSD) and compared their findings with seven individuals having sensorineural hearing loss. Temporal processing was assessed using a gap detection test (broadband noise having silent period of 1 to 60 ms) and TMTF (modulation rate of 10, 50 and 150 Hz). Spectral processing was evaluated using low (500 Hz) and high (4000 Hz) frequency signals. Speech perception was evaluated using Consonant Nucleus Consonant word test. Phoneme pair discrimination was carried out for /p/ and /b/, /t/ and /d/, /k/ and /g/. Discrimination of vowel length was also carried out. Finally, spectral discrimination was assessed using /f/ and /s/, /z/ and /v/.

The results of the study by Rance et al. (2010) revealed that the gap detection threshold for those without auditory brainstem response (9.8 ms) was poorer than those with auditory brainstem response (5.5 ms) and sensorineural hearing loss (6.1 ms). Modulation detection at 10 and 50 Hz was significantly poorer in those without auditory brainstem response compared to those with sensorineural hearing loss and those with auditory brainstem response. At a higher rate (150 Hz), performance of those with auditory brainstem response and sensorineural hearing loss was mildly elevated and those without auditory brainstem response were significantly poor. Low frequency discrimination was poor in those without auditory brainstem response compared to normal, sensorineural hearing loss and those with auditory brainstem response. High frequency discrimination was poor in the sensorineural hearing loss group compared to the normal hearing group, as well as those with and without auditory brainstem response. Poor low frequency discrimination in those without auditory brainstem response was attributed to poor temporal processing, resulted from impaired phase locking.

Further, discrimination of /p/ and /b/, /t/ and /d/, was significantly poor in those without auditory brainstem response compared to those with sensorineural hearing loss and those with auditory brainstem response. However, no difference was found for /k/ and /g/ between the three groups. Spectral discrimination of /f/ and /s/ as well as /z/ and /v/ were significantly poor in those with sensorineural hearing loss compared to those with and without auditory brainstem responses. Poor discrimination of voiced-unvoiced sounds was reported to be due to difficulty in perceiving short acoustic events, since voice onset time was shorter in /p/ and /b/, /t/ and /d/, compared to /k/ and /g/. Poor perception of /f/ and /s/, /z/ and /v/ in the sensorineural hearing loss group was ascribed to poor high frequency discrimination.

The relation of speech perception in quiet as well as in noise (signal to noise ratio of 0, 5 & 10 dB) with temporal resolution ability was evaluated by Narne (2013). Two temporal resolution experiments were carried out that included TMTF and frequency modulation detection. The results revealed that the 25 individuals with ANSD who were studied had significantly poorer peak detection thresholds compared to the 25 normal hearing individuals. Frequency modulation detection thresholds in individuals with ANSD were 10 times higher than that observed in the normal hearing group at low carrier frequencies (0.5 & 1 kHz), and 2 to 4 times in the higher carrier frequencies (2 & 4 kHz). Speech identification in noise in those with ANSD was significantly poorer than the normal hearing group. Further, in the ANSD group, speech identification scores at lower SNRs were significantly poorer than that of higher SNRs except between 0 dB SNR and 5 dB SNR, where no significant difference was found. Additionally, there was a significant correlation between speech identification in quiet as well as noise with TMTF peak threshold and frequency modulation detection of 2 Hz modulation rate at 500 Hz. Four individuals with ANSD had good speech perception in quiet (90%) with amplitude modulation detection similar to the normal hearing individuals. However, frequency modulation detection thresholds of these individuals were 3 to 4 times higher than the normal hearing group at low carrier frequencies. Their scores reduced by 35 to 40% in the presence of noise. This reduction in score was similar to that of the speech perception score in the normal hearing group without fine structure cues. The authors opined that individuals who exhibited good speech perception in quiet were able to extract envelope cues but failed to use fine structure cues.

It is clear from the above literature that impaired temporal resolution results in speech perception deficits in individuals with ANSD. Studies indicate that temporal resolution measures using TMTF, gap detection and frequency modulation detection correlate with speech identification scores. Unlike those with sensorineural hearing loss whose speech perception deficits are attributed to impaired spectral resolution, in individuals with ANSD speech perception defects are ascribe to temporal processing deficits.

Effect of Intensity on Speech Perception in individuals with ANSD

The effect of intensity on speech perception is extensively studied in individuals with cochlear hearing loss and acoustic neuroma (Dirks, Kamm, Bower, & Betsworth, 1977; Jerger & Jerger, 1971). Unlike cochlear hearing loss, performance-intensity rollover was found in all the ears with confirmed 8^{th} nerve tumour. Similarly, performance-intensity rollover was noted in a few elderly individuals, although none of them had 8^{th} nerve tumours (Gang, 1976). Performance intensity rollover in elderly individuals without 8^{th} nerve tumour was ascribed to aging process that led to retro-cochlear changes in the auditory system (Jerger & Jerger, 1976). Rising performance-intensity function was also reported in elderly individuals (Shrinian, 1980). It was opined that amplification might be useful in those with a rising performance-intensity function. Miranda and Pichora-Fuller (2002) suggested that performance-intensity rollover occurred due to the presence of a neurological involvement. They demonstrated that perception of temporally jittered stimuli in normal hearing listeners led to speech perception deficits similar to retro-cochlear disorder. The authors concluded that performance-intensity rollover in normal hearing listeners was due to disrupted temporal synchrony created by jittering the signal. From the studies, it is clear that performance-intensity rollover is linked with temporal dys-synchrony.

Based on the observations from individuals with 8th nerve tumour Cone-Wesson et al. (2001) suggested that performance-intensity function in individuals with ANSD might provide valuable input regarding them using hearing aids. They opined that flat or rollover performance-intensity functions might contraindicate the use of hearing aids whereas a rising performance-intensity function might be an indication of hearing aid benefit.

Deltenre et al. (1999) assessed speech identification at a low (55 dB) and a high (70 dB) presentation level in a child with ANSD. Although a complete performance-intensity function was not obtained, the child had 0% score at low presentation levels whereas at higher presentation level the performance improved to 80%. It was also noted that the child achieved a score similar to that obtained at higher presentation level with the use of a hearing aid. The study highlighted that improvement in speech perception could occur by enhancing the presentation level of the signal or with the use of amplification.

Amplification in Individuals with ANSD

Management of individuals with ANSD is an open question for audiologists. In literature, many rehabilitative techniques such as use of hearing aids (Deltenre et al., 1999; Rance et al., 1999), cochlear implants (Berlin et al., 2010; Breneman, Gifford, & Dejong, 2012), signal enhancement strategies have been suggested (Hassan, 2011; Jijo & Yathiraj, 2013a; Kumar & Jayaram, 2011; Narne & Vanaja, 2008). Though cochlear implants have been found to be the most successful option, the expense and invasive nature of the device advocates the need for alternate rehabilitative options.

Two major arguments have been put forth in literature that questions the use of amplification in individuals with ANSD. The first argument highlights the possible risk of harming the preserved outer hair cells (Hood, 1998; Berlin et al., 1999). The second dispute highlights that hearing aids are designed to compensate for the loss of outer hair cells (OHC) rather than temporal dys-synchrony resulting from neural dysfunction (Berlin et al, 1999). Hence, it is suggested that hearing aids should be recommended cautiously for those with ANSD. Hood (1998) recommended that OHC functioning should be monitored using OAE in those who were prescribed amplification. Further, it was also suggested that if amplification is used, it should be monaural, low gain having wide dynamic range compression even in individuals with severe-to-profound hearing loss. It was suggested by Berlin (1999) that amplification should be considered in those with ANSD only after OHCs degenerates leading to the disappearance of oto-acoustic emissions.

Studies concerning the impact of hearing aids on OHC functioning have shown variable results. A few studies have reported reduced OAE amplitude in children using high gain hearing aids (Sininger & Oba, 2001; Trautwein et al., 2001) whereas a number of studies found normal OAE amplitude even after long term hearing aid use (Katona et al., 1993; Rance et al., 1999; Sininger & Oba, 2001; Starr et al., 2000). Furthermore, a large number of subjects were noted to exhibit loss or reduction in OAE amplitude without any amplification (Deltenre et al., 1999; Starr et al., 2000). The importance of preserving OAEs has been considered to not have any practical implication, as there is no relation between the presence/absence OAEs and hearing thresholds or speech perception abilities (Deltenre et al., 1999; Rance et al., 1999; Starr et al., 2000). Overall, the above studies revealed that OHC functioning in individuals with ANSD did not relate with hearing aid usage.

The second argument against the use of amplification in individuals with ANSD was based on the assumption that amplifying the signal would not overcome the perceptual deficits resulting from neural dysfunction (Berlin et al., 1999). Instead of being of help, amplification was considered to produce loud distorted signals. This has been substantiated by a number of studies that have reported of poor aided performance in individuals with ANSD (Berlin, Hood, Cecola, Jackson, & Szabo, 1993; Berlin et al., 1999; Berlin, Hood, Morlet, Rose, & Brashears, 2002; Lee, McPherson, Yuen, & Wong, 2001; Miyamoto et al., 1999; Shallop et al., 2001; Sininger et al., 1995; Starr et al., 1996; Trautwein et al., 2000; Widen, et al., 1995).

Among the studies that reported of poor aided benefit, a few of them were anecdotal reports or clinical experiences without giving any statistical data on aided performance (Berlin et al., 1993; Berlin et al., 1999; Berlin et al., 2002; Krause et al., 1984; Raveh, Buller, Ola Badrana, Attias, 2007). A few studies have been carried out on clients having rapidly progressing, late onset ANSD (Miyamoto et al., 1999; Shallop, 2002; Starr et al., 1996; Widen et al., 1995). Moreover, these studies were done on small sample sizes. Widen et al. (1995) reported of a 35-year-old female with onset of hearing problem at the age of 15 years. The hearing sensitivity and speech understanding was found to deteriorate dramatically over a period of 20 years. Aided speech perception performance on three closed set tests (four choice spondee, Iowa vowels, & Iowa medial consonants) was found to be at chance level or better. On the other hand, performance on an open-set test was poor with only a few correct responses. Similarly, Shallop (2002) described two clients with ANSD who were diagnosed in their late 20s. Both clients were fitted cochlear implants as hearing aids were found not to be beneficial. One client was recommended a cochlear implant since the loss progressed to a profound degree, precluding the use of amplification. The other client, with a hearing problem from childhood, was implanted in the ear with poor speech-in-noise scores. Another study by Starr et al. (1996) also reported of limited benefit from hearing aids in individuals with ANSD. Ten individuals with ANSD having mild to severe progressive hearing loss, 8 of whom had clinical signs of peripheral neuropathy as per a neurological evaluation, were found to have no benefit from amplification.

From the studies on individuals with AND having progressive hearing loss, despite small sample sizes, it can be construed that the progressive nature of the disorder resulting from neurological conditions might have resulted in poor aided performance. Contrary to the above studies, there are reports of improvement in speech perception with the use of amplification in individuals with ANSD, especially children (Berlin et al., 2010; Cone Wesson et al., 2001; Deltenre et al., 1999; Katona et al., 1993; Madden et al., 2002; Rance & Barker, 2009; Rance et al., 1999; Rance, Cone-Wesson, Wunderlich, & Dowell, 2002; Raveh et al., 2007). A few studies however, do report of improvement with hearing aids even in those with late onset ANSD (Jijo & Yathiraj, 2013b; Vanaja & Manjula, 2004).

Despite controversy existing regarding the utility of hearing aids in individuals with ANSD, the few studies that report of improvement with the device indicate that their use does hold promise. The following sub-section provides details of the studies that report of improvement in children having ANSD (Berlin et al., 2010; Deltenre et al., 1999; Rance et al., 1999; Rance et al., 2002; Rance, 2005; Rance & Barker, 2009; Raveh et al., 2007) and those with late onset ANSD (Jijo & Yathiraj, 2013b; Vanaja & Manjula, 2004). Overall, the improvement in speech perception using hearing aids in these studies advocate the need for hearing aid trial in clients with ANSD who exhibit some amount of hearing loss.

Benefits of amplification in children with ANSD. Studies that report of benefit with amplification in those with ANSD are predominantly done on the paediatric population. A retrospective study by Madden et al. (2002) on 22 children identified to have ANSD, reported of hearing aids being recommended for 16 of them. Although details on aided performance was not discussed, it was reported that those who had persistent and significant hearing loss responded well to amplification and cochlear implantation.

In a study that compiled demographic and audiological findings of 260 clients with ANSD, Berlin et al. (2010) reported that hearing aids helped in language acquisition in 11 out of 94 individuals. The authors noted that hearing aids were beneficial for a sub-group of individuals, though it did not help in the development of age appropriate speech and language in the majority of their clients. They recommended that the period of hearing aid trial prior to implantation should be monitored carefully, as it might delay the ability to use hearing for language acquisition. The authors reported that cued speech or signs might be helpful to avoid the delay.

Similarly, Cone-Wesson et al. (2001) reported that among the 29 children with ANSD studied by them, 14 (52%) did not benefit from hearing aids. However, 10% showed improvement in pure-tone threshold and speech perception with hearing aids, while 17% had improvement in aided threshold, but with no speech perception benefit. The remaining subjects were either too young or difficult to test.

Similar to the earlier studies, Raveh et al. (2007) reported that amplification was useful and helped in speech and language development, but only in 1 out of their 19 participants with ANSD. In the remaining 18 children, 14 did not show significant aided improvement and 4 were still in the process of being rehabilitated.

Although the above studies reported that children with ANSD benefited from amplification, they did not provide the actual aided speech perception scores. Hence, the quantum of improvement that resulted from hearing aids is unknown in these studies. However, other studies have provided information about aided speech perception performance in children with ANSD.

Deltenre et al. (1999) reported of benefit from amplification in a child in whom amplification was withheld until 4 years. Binaural linear hearing aids were given at the age of 4 years soon after the loss of OAEs. At the age of 6 years, word and phoneme identification scores improved from 0% in the unaided condition to 80% and 96% respectively in the aided condition. At the age of 7 years, binaural word identification scores further improved to 95%. The child, who had failed a spoken language comprehension test at the age of 5 years, acquired spoken language comprehension correspond to five year old children, by the age of 7 years.

Similarly, Rance et al. (1999) evaluated speech perception in 8 children who consistently used non-linear hearing aids for more than 1 year. All were fitted with binaural hearing aids, using the NAL prescriptive method. It was found that four of the eight children had significantly better aided open or closed-set scores compared to their unaided scores. Additionally, those who benefited from amplification had significantly better aided thresholds than the unaided condition, whereas no such difference in threshold was found in those who did not benefit from hearing aids.

Amplification benefit in the above studies has been attributed to early diagnosis and management during the sensitive period of speech and language development. Furthermore, studies have demonstrated that improvement in detection threshold might result in better language development by a more versatile brain in the pre-lingual group. In contrast, in acquired post-lingual ANSD, the improvement in detection thresholds was not thought to compensate the distortion of the neural code that resulted from neural dys-synchrony (Deltenre et al., 1999). The studies that showed improvement in speech perception using hearing aids (Deltenre et al., 1999; Rance et al., 1999) used two different amplification strategies (linear and non-linear).While Deltenre et al. (1999) reported of benefit from linear amplification, non-linear amplification was found to be beneficial by Rance et al. (1999). Thus, it appears that either linear or non-linear hearing aids could bring about improvement in those with ANSD. Nevertheless, definite conclusion cannot be drawn in this regard, as heterogeneity of the participants may influence the findings.

Rance et al. (2002) compared unaided and aided speech perception in children with sensorineural hearing loss (N = 18) and ANSD (N = 18). All the participants used hearing aids consistently for more than 12 months. The hearing aids were programmed using NAL non-linear prescriptive method. The sensorineural hearing loss group had unaided score ranging from 2 to 92% with the mean score being 16.9%. All these clients showed significant aided improvement with the mean difference in improvement (aided minus unaided) being 49.4%. The ANSD group had unaided score ranging from 2 to 20% with the mean score being 8.1%. Based on the aided scores, the ANSD group was divided into two subgroups, those performing at chance level (< 10%) and those at a significant level (> 35%). The speech perception scores of the latter group negatively correlated with degree of hearing loss. A similar trend was noticed in children with sensorineural hearing loss. Hence, the authors inferred that children with ANSD who exhibit good perceptual abilities might have a pathology similar to those having sensorineural hearing loss, leading to similar functional deficits. In contrast, the other group might have neuronal deficits similar to that of adults presented by Starr et al. (1996). The authors opined that increased access to speech spectrum along with improved phase locking at higher sensational levels might have helped in aided improvement in these clients.

Additionally, Rance et al. (2002) found that those with auditory event related potentials had significant open-set speech identification and amplification benefit unlike those with absent event related potentials who had poor speech perception and aided performance. The authors opined that preserved neural synchrony, at least at the cortical level, indicated by the presence of auditory event related potentials might have helped in better speech perception and aided performance. Further, the presence of cortical potentials was considered to indicate the existence of sufficient neural synchrony to encode the temporal information necessary for speech perception.

In line with the earlier study carried out by Rance et al. (2002), Rance, Barker, Sarant and Ching (2007a) compared receptive and spoken language abilities in children with ANSD with that of children having sensorineural hearing loss. The ANSD group consist of 12 children, fitted bilaterally with hearing aids that they used consistently for over 4 years. Similarly, the sensorineural hearing loss group had 12 children who were also consistent hearing aid users. Receptive and speech production abilities in the ANSD group were similar to the sensorineural hearing loss counterparts. The authors attributed the similar good receptive and speech production abilities in the two groups to early intervention and the school program that adopted oral language for communication. However, the results should be interpreted with caution because the authors selected only those subjects who responded well to hearing aids, and those with poor performance were implanted.

Similarly, Rance, Barker, Mok, Dowell, Rincon and Garratt (2007b) compared speech perception in quiet and noise in those with normal hearing, cochlear hearing loss and ANSD using open and closed-set speech identification tests. It was found that the closed-set speech perception scores in quiet in the ANSD group was similar to that of cochlear hearing loss. This was attributed to early intervention program and auditory experience in the ANSD group (> 4 years). In the presence of noise both the ANSD and the cochlear hearing loss groups needed a higher signal-to-noise ratio (9 dB) than the normal hearing group to identify closed-set spondees. The poor score in the cochlear hearing loss group was ascribed to poor frequency resolution that caused excessive masking. Although frequency resolution was normal in the group with ANSD, impairment in both simultaneous and non-simultaneous masking was ascribed to poor speech perception in noise.

To compare the receptive language and speech production in children with ANSD using hearing aids with those using cochlear implants, Rance and Barker (2009) studied three groups, each having 10 children. The groups consisted of long-term hearing aid users with ANSD, children with ANSD who received cochlear implant in either one or both ears, and cochlear implant users with sensorineural hearing loss. Although receptive vocabulary was delayed in all the subjects, it was not significantly different across the three groups. Similar findings were noted in speech production with 70% score in all three groups except one implanted child with ANSD who had very poor scores. The results revealed that some children with ANSD using hearing aids perform similar to their implanted peers. Hence, it was recommended that the diagnosis of ANSD should not be immediately followed with cochlear implantation. However, once severe to profound hearing loss is established in children with ANSD, cochlear implants should be considered for those who have limited access to speech spectrum even after amplification.

Rance and Barker (2007) compared speech perception in children with ANSD who used either hearing aids (N = 10) or cochlear implants (N = 10). The 10 hearing aid users wore binaurally BTE devices that were programmed using NAL prescriptive method. The 10 children with cochlear implants used their device consistently for 2 years. Eight of the 10 hearing aid users had Consonant-Nucleus-Consonant word scores within the expected range for children with sensorineural hearing loss. There existed no significant difference in perception between the two groups of children having ANSD.

Pinsky (2011) reported of a paediatric ANSD client with bilateral moderate to severe sensory neural hearing loss. The child was initially fitted with low gain hearing aids so as to prevent any outer hair cell damage but was later refitted according to the audiogram. Despite of consistent use of hearing aids that were refitted to the audiogram and aural rehabilitation, the child's aided speech perception was poor, with no open set speech identification scores and closed set scores of than 50% on the Word Intelligibility by Picture Identification test. However, a later evaluation indicated that the client's hearing thresholds in one ear had dropped to a moderately-severe to profound degree. Hence, the aided performance was again evaluated using high gain hearing aids. The child showed marked improvement with the word score increasing to 84%. The aided improvement was ascribed to adequate amplification and team approach in aural rehabilitation. The authors concluded that as a few children might show adequate improvement with hearing aids, not all individuals with ANSD should be recommended cochlear implants.

In a review on audiological management of ANSD, Roush, Frymark, Venediktov and Wang (2011), analyzed four studies that had evaluated aided pure-tone and speech perception thresholds. The findings of a total of 28 participants with ANSD were analysed. Their results revealed that though the acoustic amplification has limited benefits, a subset of children showed improvement in speech perception and pure-tone detection thresholds.

The utility of specific hearing aid setting in children with ANSD has been studied by several authors (Deltenre et al., 1999; Rance at al., 1999; 2002; 2007a; 2007b; Rance & Barker, 2007; 2009). However, none of these studies investigated the effect of different compression settings of a hearing aid on speech perception. In a recent study, Spirakis (2011) compared speech identification scores in a 6 year old child with ANSD using hearing aids having compression parameters that could be varied to be slow (attack/release time of 5000 ms/5000 ms) or fast (attack/release time of 20 ms/2000 ms). The child was fitted binaurally and word recognition scores were obtained in the unaided and two aided conditions. It was found that word recognition scores improved by 20% in the aided condition using slow attack/release time compared to the unaided condition. It was also found that the slow compression times resulted in 32% higher word recognition scores compared to the fast compression times. The authors opined that slowing compression parameters could improve speech perception in those with ANSD due to enhanced temporal envelope. It was recommended that comparison of amplitude envelopes of speech processed through different circuits (linear, slow compression times) might help in the selection of amplification strategies for those with ANSD.

In the above studies, the benefit derived using amplification was attributed to various reasons. Early intervention and auditory experience was reported to be the prime reason for aided speech perception improvement in children with ANSD (Deltenre et al., 1999; Rance et al., 1999). Further, auditory stimulation resulting from oral rehabilitation methods used in schools was also ascribed to be a reason for improvement (Rance et al., 2007a; 2007b). It was also reported that children who showed benefit using amplification were good hearing aid users as many poor performers in the ANSD group were already implanted (Rance et al., 2007a; 2007b). Hence, it can be inferred from the above studies that cochlear implantation should not be considered in all the clients with ANSD as a few of them might benefit using hearing aids.

Benefits of amplification in late onset ANSD. To date only a few studies have reported of benefit from amplification in adults with ANSD. Vanaja and Manjula (2004) analyzed the relation between late latency response (LLR) and aided performance in 5 clients with ANSD between the age of 16 to 35 years. Monaural analogue hearing aids having gain matched using the NAL-R prescriptive formula were used. Only one participant obtained some benefit from the hearing aid (40%), with two having minimal benefit (20%) and the remaining two clients having no improvement. It was observed that the client with normal LLR amplitude had maximum aided benefit, whereas those who had lower amplitude had lesser benefit from hearing aids. The clients who did not benefit from hearing aids had no replicable LLR. The authors concluded that in participants with abnormal ABR and normal LLR, the functional deficiency at the level of the brainstem is compensated by the cortical mechanisms. In contrast, in those with abnormal ABR and abnormal LLR, speech understanding would be more affected because of deficits in the cortical as well as brainstem structures.

In a retrospective study, Narne et al. (2014a) reported audiological findings and hearing aid benefit in 198 individuals with ANSD. It was noted that 82% of the ANSD clients they reviewed had late onset. Among the 128 participants who had undergone hearing aid trial, 39 were recommended to use hearing aids. Among those recommended hearing aids, 26 had 20% improvement in speech perception in the aided condition over the unaided. The remaining 13 clients had improvement in auditory awareness. Cortical auditory evoked potentials were present in those 26 clients who showed some functional benefit using hearing aids. Presence of cortical auditory evoked potentials in these individuals was considered to suggest preserved neural synchrony in them that was substantiated by good speech identification scores. Hence, it was conclude that aided speech perception improvement in individuals with ANSD depends on neural synchrony.

Zeng and Liu (2006) investigated perception of clear and conversational speech in 13 individuals with ANSD in the age range of 9 to 41 years. Speech perception was evaluated in quiet and noise in four different conditions (monaural acoustic, diotic acoustic, monaural electric, & combined acoustic electric). Results in quiet showed that clear speech was significantly better than conversational speech in all the four conditions. Diotic acoustic stimulation was significantly better than monaural acoustic stimulation. Similarly, binaural combined acoustic and electric stimulation was significantly better than monaural acoustic or electric stimulation. However, contrastive results were noted in noise where diotic acoustic stimulation was not significantly better than monaural acoustic stimulation. Further, binaural combined acoustic and electric stimulation was not significantly better than monaural acoustic or electric stimulation. Improvement noted using clear speech was ascribed to enhanced temporal properties in it. Poor performance in noise was attributed to interference of low frequency inter-aural timing cues in a binaural situation. Although the details of the amplification and quantum of improvement was not provided, the study highlights the benefit of binaural amplification over monaural. The authors recommended that linear amplification should be considered for individuals with ANSD, as non-linear amplification reduces the temporal modulation in speech signal.

Jijo and Yathiraj (2013b), in a retrospective study, analyzed aided speech identification scores in 64 clients with late onset ANSD. They also evaluated the relation between audiological test results and aided improvement. It was found that hearing aids resulted in improvement in speech perception in 39 of the 104 ears of individuals with ANSD. Aided improvement correlated positively with speech identification scores that were measured at 40 dB SL (ref to SRT). However, there was no relation between aided improvements and unaided speech identification scores or pure-tone average. The authors opined that those who had relatively better speech identification scores might have had preserved neural synchrony that compensated for distortion in spectral cues that occurred at higher presentation level. In contrast, those who had poor speech identification scores at higher level (40 dB SL ref to SRT) might have had poor neural synchrony causing poor speech perception at higher level of presentation. Hence, it was recommended to carry out a performance-intensity function in individuals with ANSD that might throw light on their aided performance.

It can be observed from the above studies that a few individuals with late onset ANSD showed improvement in speech perception using hearing aids. Preserved neural synchrony, that was evident through cortical potentials or higher speech identification scores, was considered to be the reason for the aided improvement (Vanaja & Manjula, 2004; Jijo & Yathiraj, 2013b; Narne et al., 2014a). Enhanced temporal properties, that occurs in clear speech, was also felt to result in improved speech perception (Zeng & Liu, 2006). Additionally, it was opined that linear amplification that preserve temporal envelope of speech would be beneficial for individuals with ANSD.

Signal Enhancement Strategies for ANSD

With the aim to determine the acoustical parameters that can enhance speech perception in individuals with ANSD, studies have been carried out using signal enhancement strategies. Increased modulation depth, increased spectral energy at mid and high frequencies and reduced speaking rate are a few major acoustical properties of clear speech (Krause & Braida, 2004; Picheny et al., 1986) that have been studied in ANSD. Use of clear speech or implementing some of its features have been shown to improve speech perception in individuals with ANSD (Hassan, 2011; Jijo & Yathiraj 2013a; Kumar & Jayaram, 2011, 2013; Narne, 2008; Narne & Vanaja, 2008, 2009a; Narne et al., 2014b; Zeng & Liu, 2006). Given below are details of the studies that have evaluated speech perception of individuals with ANSD / or other clinical conditions after incorporating various acoustic modifications.

Time scale modification strategies in individuals with ANSD.

Psychoacoustical studies in individuals with ANSD have proven that they have deficits in perceiving short duration acoustical signals (Zeng et al., 1999, 2005). This was demonstrated using gap detection studies. Among normal listeners, gap detection thresholds improved from 50 ms to 3 ms when the presentation level was increased from 5 dB SL to 30 to 40 dB SL. Although individuals with ANSD performed similar to normal listeners at the low sensation level, they were found to require longer gaps at the high sensation level. The difficulty in detecting short duration signals was considered to cause problems in processing brief, yet important elements of speech signals. Further, a temporal masking study by Krause et al. (2000) showed that individuals with ANSD had 60% masking even after a separation of 100 ms between the signal and masker. However, normal listeners had only 15% masking when the time interval between signal and masker was 20 ms. The authors opined that the reason why those with ANSD performed differently from the normal hearing listeners was due the difficulty the former had in separating sounds that occur successively. This was considered to lead to difficulty in perceiving short acoustic events such as transition, burst and voice onset time that occurs in succession and vital for speech perception.

In addition to studying gap detection, the effect of temporally modifying the transitions of speech sounds has been investigated in individuals with ANSD. Kumar and Jayaram (2011) investigated the effect of lengthening the transition duration on speech syllable perception. Thirty clients with ANSD and 30 age and gender matched normal hearing individuals were studied. Eight consonant-vowel syllables consisting of voiced and unvoiced stops (/pa/, /ba/, /ta/, /da/, /ka/, /ga/, / t̪ / /d̪/) were modified by stretching the transition duration using PRAAT software. Initially the just noticeable difference for transition duration was obtained from both normal hearing individuals and those with ANSD. This was determined by calculating the difference in transition duration between natural stimuli and modified stimuli to achieve 69% correct score. The just noticeable difference obtained from individuals with ANSD was used to modify the natural stimuli used in the study. The natural stimuli were modified by stretching the duration of the transitions in multiples of the just noticeable difference (1, 2, 3 & 4). The identification scores of the individuals with ANSD were obtained for the unmodified and modified speech stimuli. The results revealed that there was a significant difference in the just noticeable difference between the two groups with it being 3 to 4 times longer in those with ANSD, indicating the presence of severe deficit in temporal processing. It was found that in the ANSD group, speech identification scores for the unmodified signal ranged from 0 to 87%, where only 4 clients had scores above 50%. The speech identification scores for the modified speech ranged from 0 to 100% where 6 clients scored above 100%. Sequential information analysis showed that lengthening of the transition duration resulted in better perception of place than voicing. The authors hypothesized that lengthening the transition duration reduced the modulation frequency without altering the modulation depth. Thus, they concluded that stretching the transitions of speech sounds might help those with ANSD having difficulty in processing high modulation frequency.

In a continuation of their earlier study, Kumar and Jayaram (2013) investigated the effect of lengthening the voice onset time and burst duration on just noticeable difference and speech syllable perception. Additionally, the combined effect of lengthening the voice onset time, burst and transition duration were also evaluated. The participants, stimuli and procedure were the same as their earlier investigation carried out in 2011. A significant difference in the just noticeable difference was found for both voice onset time and burst duration between the clinical and control group. Lengthening the voice onset time resulted in higher improvement in perception than lengthening the burst duration alone. The combined effect of lengthening of voice onset time, burst and transition duration resulted in higher, though not significant speech identification scores than lengthening the transition duration alone.

Hassan (2011) investigated the perception of temporally modified speech in 14 adults with ANSD in the age range of 15 to 28 years and 14 adults with bilateral moderate cochlear hearing loss. Four Arabic consonant-vowel pairs were chosen from Arabic phoneme contrasts (/ki/-/gi/, /to/-/do/, /si/-/sti/, /so/-/zo/). The consonants selected [stop (k, g, t, d) & fricatives (s, st, s, z)] were frequently used in Arabic and were presented in two forms. In the natural form, the inter-stimulus interval between consonant-vowel pairs was changed from 1000 to 300 in step size of 100 ms. In the modified form, both the inter-stimulus interval and formant transition were expanded and presented in a descending order. Along with similar inter-stimulus intervals used in the natural form, the formant transition was reduced gradually from 250, 200, 150, 100, 80, 60, 40, to 20 ms. In both the conditions, the lowest inter-stimulus interval at which consonant-vowel pairs could be discriminated was established. It was found that in the ANSD group, modified consonant-vowel pairs were discriminated at lower inter-stimulus interval than that of natural consonant-vowel pairs. Prolongation of transition duration was found to be more beneficial than prolonging the pause between pairs. At the slow inter-stimulus interval (1000 ms) those with ANSD performed similar to those with sensorineural hearing loss, but their performance dropped at the rapid inter-stimulus interval. High inter-stimulus interval was obtained for stops than fricatives. Among the different speech sounds studied by Hassan, stops required the highest inters-stimulus interval to be perceived correctly, highlighting the great difficulty in perceiving this class of speech sounds. Among the stops sounds, /k/ and /g/ were perceived poorer than /t/ and /d/. This was ascribed to the frequency composition of these speech sounds, with the former pair having lower frequencies (1500-4000 Hz) and the latter pair having higher frequencies (above 4000 Hz). It was reported that poor phase locking in those with ANSD could be the reason for lower frequency speech sounds being perceived poorer. The authors concluded that modification of transition duration, reducing speaking rate and binaural hearing brought about improve speech perception in those with ANSD.

Jijo and Yathiraj (2013a) investigated the effect of temporal modification and vowel context on speech perception in individuals with late onset ANSD. Eight stops and two liquids in the context of the vowels /a/, /i/ and /u/ were used. The stimuli were temporally enhanced using ‘pitch synchronous and overlap and add’ algorithm by three different time scaling factors (25%, 35%, & 50%). It was establish that 25% stretching resulted in significant improvement in perception in all three vowel context while 35% stretching improved perception only in the context of /a/. The stimuli stretched to 50% resulted in deterioration in perception in all three vowel contexts. The authors concluded that improvement in consonant perception with 25% stretching resulted from lengthened consonantal portion of the stimuli. In contrast, reduced consonant perception with further stretching was ascribed to excessive backward masking caused by the second vowel in the VCV. It was also noted that consonant perception was lower in the context of /i/ compared to that of /a/ and /u/. Sequential information analysis revealed that place and voicing perception was lower in the context of /i/. Poor place perception in the context of /i/ was attributed to steeper F2 transition compared that of /a/ and /u/. Poor voicing perception was reported to due to a lowered F1, a major cue for voicing perception of the intervocalic stop consonants. The improvement noted in terms of transfer of place and voicing information after stretching the entire signal by 25%, was similar to the reports of Kumar and Jayaram (2011; 2013). Hence, the authors concluded that without the tedious process of identifying and stretching the acoustical landmarks alone, similar improvement in speech perception can be achieved by stretching the whole signal. They opined that stretching the signal beyond 25% might require additional signal enhancement strategies to reduce the masking effect of preceding and/or following vowels. The effect of vowel context on consonant perception highlighted the need for studying speech perception in different vowel contexts.

Zeng and Liu (2006) compared the perception of clear and conversational speech in 13 individuals with ANSD in the age range of 9 to 41 years using BKB sentences (Bench and Bamford, 1979) in quiet and in noise. The testing was done in four different conditions: monaural acoustic, diotic acoustic, monaural electric and combined acoustic electric. The results revealed that, clear speech was significantly better than conversational speech, in both quiet and noise in all the four conditions. The improvement using clear speech was ascribed to enhanced amplitude modulation depth of clear speech. Hence, the authors opined that signal processing schemes that enhance the amplitude modulations of speech might help these individuals. It was noted that the average duration of sentences were 3.3 s for clear speech whereas, the conversational speech was only 1.5 s. Hence, it was concluded that increasing the overall duration of the signal could help improve speech perception in individuals with ANSD.

From the above literature, it is clear that time scale modification of either brief acoustic elements or the entire signal improves speech perception in those with ANSD. Further, it was found that stretching of entire signal resulted in speech perception improvement similar to that of stretching the brief acoustic elements alone. Although time scale modification of the entire signal is a good way to improve speech perception, the effect of it in those having different temporal processing abilities has not been studied.

Envelope enhancement strategies in individuals with ANSD. Psychoacoustical studies have proven that reduced speech perception in individuals with ANSD is linked to their inability to follow amplitude variations in speech. This has been demonstrated by the existence of a relation between TMTF and speech perception (Kumar & Jayaram, 2005; Narne, 2008, Rance et al., 2004, Zeng et al., 1999). Furthermore, normal hearing listeners have been found to perceive temporally distorted speech in a manner similar to those with ANSD (Zeng et al., 1999; Narne & Vanaja, 2009a). These studies highlight the fact that perceptual problems in individuals with ANSD are associated with temporal processing deficits. It can be inferred from these studies that enhancing the temporal envelope of speech signals would resolve the perceptual problems of individuals with ANSD.

Narne and Vanaja (2008) studied the effect of envelope enhancement on speech perception in eight individuals with ANSD. The envelope of 15 CV syllables was enhanced by 15 dB in four different bandwidth (3 to 10 Hz, 3 to 20 Hz, 3 to 30 Hz, & 3 to 60 Hz) using PRAAT software. They reported of a significant improvement in perception in the envelope enhanced condition compared to the unprocessed condition in six clients. The broader bandwidth was significantly better than narrow bandwidth of 3 to 10 Hz. Sequential information analysis in the unprocessed condition, showed higher information transfer for manner compared to place and voicing. In the enhanced condition, place and manner was found to convey greater information than voicing. Further, from the information transfer for manner of articulation, it was noted that in the unprocessed condition nasals and fricatives conveyed greater information than affricates, plosives, and liquids. In the enhanced condition, except for liquids and nasals, the other speech sounds have other manners of articulation transmitted greater information than the unprocessed condition.

Narne and Vanaja (2008) also reported that in the unprocessed condition, the poor processing of plosives compared to nasals and fricatives was due to their faster temporal envelope. This was credited to be the reason individuals with ANSD required higher depth of modulation to process the faster envelope of stops. They observed that enhancing the envelope resulted in increased modulation depth and improved perception of plosives. Poor perception of liquids in the unprocessed condition was attributed to their low frequency formants and transitions. The clients with ANSD, who had poor differential sensitivity in the low frequencies, faced difficulty in perceiving these low frequency components. The authors recommended spectro-temporal modification of liquids as no improvement in the perception of liquids occurred even after envelope enhancement. It was found that in the unprocessed condition place errors were commonly noted for stop consonants. The authors opined that faster envelope of the burst and formant transition of stop sounds might have hindered place perception. They noted that enhancing the temporal envelope of stops helped in better processing of the fast elements and improvement in speech perception. Poor perception of voicing was attributed to low frequency hearing loss or difficulty to detect short duration signal. Despite enhancement, voicing did not improve as it did not increase the amplitude of the voicing bar. It was noted that envelope enhancement did not improve speech perception in two clients who had poor speech identification. Further, none of the individuals obtained 100% identification even after envelope enhancement. The authors highlighted the need for research on other signal enhancement strategies for individuals with ANSD.

Narne (2008) compared the perception of unprocessed and envelope enhanced speech in individuals with ANSD. Based on the peak sensitivity of TMTF, the participants were sub-grouped as mild (-13.5 dB), moderate (-8.5 dB) and severe (-4.0 dB). They found that envelope enhancement significantly improve speech perception in all the TMTF sub-groups. Additionally, they observed a significant difference between the TMTF sub-groups in the unprocessed condition. However, with envelope enhanced stimuli there was a significant difference between all the sub-groups except mild the TMTF sub-group and the normal hearing participants. Further, they reported of a strong negative correlation between peak sensitivity and speech identification in the unprocessed as well as envelope enhanced condition. The results of the study indicated that speech perception in individuals varies depending on their temporal resolution abilities.

Using a different envelope enhancement scheme, Narne and Vanaja (2009b) investigated the effect of noise on the perception of unprocessed and enhanced speech in 15 individuals with ANSD (8 males & 7 females). The participants were assessed using words processed by an envelope enhancement algorithm used by Apoux, Tribut, Debruille, and Lorenzi (2004), in which the consonantal portion was enhanced while the vowel was compressed. Perception of words was evaluated in quiet and in three different signal-to-noise ratio conditions (0, 5, & 10). Over the unprocessed stimuli, envelope enhancement significantly improves speech perception in all three SNRs condition. Participants having speech identification score greater than 50% (good performers) had significantly higher scores than those having speech identification score less than 50% (poor performers) when tested with envelope enhanced stimuli in all the signal-to-noise ratio conditions. The poor performers also showed improved speech perception with envelope enhancement in quiet and 10 dB SNR. Enhancement of envelope, which improves the consonant vowel ratio, was found to improve speech perception in the participants with ANSD. Reduced speech identification score in noise in individuals with

ANSD was attributed to excessive masking phenomenon found in ANSD and also due to their difficulty in extracting envelope information in speech.

Narne and Vanaja (2009a) studied the effect of temporal smearing of unprocessed and envelope enhanced stimuli on speech perception in listeners with normal hearing. Further, the effect of envelope enhancement on speech perception in individuals with ANSD was also evaluated. Envelope enhancement was done using a procedure similar to that of Apoux et al. (2004). Temporal smearing was carried out on the unaltered signal as well as the envelope enhanced signal using a procedure similar to that given by Zeng et al. (2001). They noted that perceptual impairment of ANSD could be simulated in individuals with normal hearing. Speech identification scores obtained from the normal hearing listeners was similar to that of individuals with ANSD for temporally smeared speech. However, envelope enhancement did not improve speech identification in the normal hearing listeners when tested with stimuli simulating severe to profound degree of ANSD. Similarly, those with ANSD who had very poor unprocessed speech identification scores did not improve using envelope enhancement. Lack of improvement in the normal hearing listeners, even after envelope enhancement, was attributed to poor consonant-vowel distinction in the stimuli that was simulated for severe degree of impairment.

Using envelope enhancement and high pass filtering (500 Hz), Narne and Vanaja (2012) investigated speech perception in 12 individuals with late onset ANSD. Their findings revealed that envelope enhancement led to 8% to 36% improvement in word identification scores with a mean improvement of 18.3%. It was reported that the envelope enhancement strategy might have compensated for impaired processing of amplitude variation in the speech signals. Although there was a significant improvement, envelope enhancement did not help four participants who had poor unprocessed speech perception. The authors speculated that poor temporal processing in these individuals might have led to the poor performance. In contrast, to envelope enhancement, high pass filtering of the signal did not significantly improve speech perception. The authors opined that simply eliminating the low frequency part of speech signal may not compensate for poor speech perception in those with ANSD as their speech perception problem is due to poor temporal processing.

It can be noted from the research by Narne and Vanaja that enhancement of temporal envelope results in improved speech perception in individuals with ANSD. However, the extent of improvement resulting from envelope enhancement was lesser compared to stretching brief acoustic elements of speech observed by Kumar and Jayaram (2011). It can also be noted that voicing perception did not improve after envelope enhancement whereas stretching the brief acoustic elements have shown to improve voicing perception (Kumar & Jayaram, 2013). Thus, there is a need for alternate signal enhancement strategies that might improve voicing perception in individuals with ANSD.

Spectral modification strategies in individuals with ANSD. In addition to temporal processing deficits, individuals with ANSD exhibit deficits in processing of frequency related information. Experiments on frequency discrimination in individuals with ANSD showed significantly poor performance compared to normal hearing subjects (Barman, 2008; Starr et al., 1991; Zeng et al., 2001). They exhibit severely impaired frequency discrimination especially in the lower frequencies (Barman, 2008; Zeng et al., 2001). This has been ascribed to their inability to use phase locking cues to the same extend as normal hearing subjects. In this context, speech perception experiments were carried out in individuals with ANSD after eliminating the low frequency information of speech.

In a single case study, Krause et al. (2000) reported of a 24 year old woman who had difficulty in hearing in noise, despite normal pure-tone thresholds, normal tympanometry with absent reflexes, and distortion product otoacoustic emission present in both ears but with auditory brainstem response absent. Fine grained discrimination task was carried out where just noticeable difference of consonant vowel pairs was established using parameter estimation by sequential tracking. Three consonant vowel syllables were presented: /ba - wa/ that differ in transition duration, / da - ga/ that differed in onset of the third formant frequency, and /da - ga/ that was similar to /da - ga/ but had formant frequencies enhanced. It was found that compared to the normal hearing listeners who had a just noticeable difference of 6 ms for the /ba - wa/ continuum, the participant's just noticeable difference was only 3 ms. In contrast, the just noticeable difference for the /da - ga/ continuum, in terms of third formant onset frequency, was higher than normal. The just noticeable difference for the third formant onset frequency was 80 Hz in normal subjects whereas the client required 120 Hz to perceive a difference. The just noticeable difference for the third formant onset frequency for the enhanced stimuli was 55 Hz in normal subjects whereas it was above 140 Hz in the client. The poorer perception of /da - ga/ compared to /ba - wa/ was attributed to difficulty in perceiving rapid spectro-temporal changes that occurs at the stimulus onset. The difference between the /da - ga/ continuum was considered to occur during the stimulus onset (onset of third formant), whereas for the /ba - wa/ continuum, the difference was within the syllable (transition duration). The poor perception of the rapid spectro-temporal changes was credited to be the reason for impaired temporal resolution.

Narne (2008) investigated the effect of upward spectral shift on speech perception in individuals with ANSD. Stimuli, that linearly shifted low frequency information (< 500 Hz) upward above 500 Hz were used. The participants were found to have a significant reduction in speech perception after the spectral shift. They concluded that shifting the low frequency information to higher frequencies might completely change the frequency coding in the auditory system. They also opined that long term training might help the participants to adapt with the new processing strategy.

Prabhu, Avilala and Barman (2011) investigated the effect of spectral modification on speech perception in 12 individuals with ANSD and 30 normal hearing individuals. Phonemically balanced words in Kannada (Yathiraj & Vijayalakshmi, 2005) were filtered using Adobe audition software at a low pass cut-off frequency of 1700 Hz and high pass cut-off frequency of 1700 Hz at an attenuation rate of 115 dB/octave. A significant difference between those with normal hearing and those with ANSD was noted for both high pass and low pass filtered speech. In the normal hearing participants, the 1700 Hz high pass condition resulted in slight reduction in speech identification compared to the unfiltered condition. This was thought to occur due to the lack of low frequency information. There was no significant difference between unfiltered and 1700 Hz high pass signals in the ANSD group. In contrast, 1700 Hz low pass condition was significantly poorer than the unfiltered speech. This indicated that individuals with ANSD were unable to make use of low frequency cues but the high frequency information helped them in perceiving speech. Deficit in phase locking in individuals with ANSD was considered to have resulted in poor perception of the low pass filtered speech. The authors speculated that spectral modification, which eliminates the low frequency energy into high frequency, might improve speech perception in individuals with ANSD.

Narne et al. (2014b) investigated the effect of combined temporal and spectral enhancement on speech perception in 10 individuals with ANSD. A companding algorithm given by Bhattacharya and Zeng (2007) was used to enhance the speech signals. The signal to noise ratio at which 50% of the sentences could be perceived were estimated (SRTn) along with Vowel-Consonant-Vowel syllable identification at different SNRs. The results revealed that there was a significant difference in SRTn between the unprocessed and enhanced stimuli in both the groups. Among normal listeners, companding improved Vowel-Consonant-Vowel syllable perception only at 0 dB SNR. In those with ANSD, companding improved syllable identification across all SNRs except 0 dB SNR. The maximum improvement was found in the quiet situation. Acoustic analysis of stimuli revealed that companding the speech signal resulted in increased spectral and temporal contrast. Compared to the unaltered original signal, spectral peaks were preserved even at -5 dB SNR. Similarly, the temporal analysis also showed higher envelope energy compared to the original signal. The authors concluded that enhancing the spectral temporal contrast through companding is beneficial for individuals with late onset ANSD.

Thus, the literature search indicates that several studies have been carried out to investigate the effect of spectral modification strategies on speech perception in individuals with ANSD. Enhancement of formant frequencies and shifting the lower frequency information to the higher frequency region were found to deteriorate speech perception in ANSD. Further, eliminating the low frequency information from the speech signal did not lead to change in speech perception. However, enhancement of spectro-temporal contrast through companding was found to be beneficial to individuals with late onset ANSD.

Spectro-temporal modification strategies in other clinical population. Researches in language learning impaired children has shown deficits in temporal processing leading to poor perception of short and rapidly occurring acoustic elements of speech (Merzenich et al., 1996). Merzenich et al. (1996) reported that training children with language learning impairment led to marked improvement in recognising brief and fast elements of speech as well as non-speech stimuli. Likewise, Tallal et al. (1996) reported that a multi-week training program using modified speech resulted in a significant improvement in language age in individuals with learning impairment. The speech modifications they used were time scale modification by as much as 50% along with amplification in the spectral envelopes, as given by Nagarajan et al. (1998). The authors reported of a significant improvement in speech perception that was generalised to unmodified natural speech. They recommended that the training strategy may be beneficial to other clinical population who exhibit temporal processing based speech perception problems.

Uchanski, Geers and Protopapas (2002) investigated the effect signal modification strategies, used by Tallal et al. (1996) in individuals with severe to profound hearing loss without any training. Additionally, they evaluated normal hearing individuals in the presence of noise. They studied the effect of time scale modification and envelope amplification strategies separately and in combination. In the hearing impaired group it was found that envelope amplification resulted in significant deterioration in speech intelligibility with and without time scale modification. Time scale modification alone did not vary significantly from unprocessed speech. The results from the normal group showed that envelope amplification alone led to deterioration in performance. There was no significant difference between time scale modified speech and unprocessed speech. The results that were contrastive to that found by Tallal et al. (1996) were attributed to difference in the population studied and lack of training. Tallal et al. had studied children with learning disability whereas Uchanski et al. (2002) evaluated individuals with hearing impairment and normal listeners. Further, Tallal et al. carried out intensive training using the enhanced stimuli whereas no such training was offered in the other study. Though Tallal et al. reported change in speech quality after the amplification of temporal envelope, the aim of the study was not to study the intelligibility. In contrast, Uchanski et al. (2002) investigated the intelligibility of enhanced speech.

From the studies on spectro-temporal modification in different clinical population it can be surmised that children with temporal processing based language impairment showed improvement in language age when they were trained using spectro-temporally modified stimuli. In contrast, children with severe to profound sensori-neural hearing loss showed deterioration in speech perception when such a signal enhancement strategy was used. This highlight that perception of such a spectro-temporal enhancement strategy can be used in those with ANSD having temporal processing deficit but not in those having sensori-neural hearing loss.

From the studied reviewed in this chapter, it is evident that late onset ANSD is highly prevalent in India. The rehabilitative options available for these individuals are cochlear implants, hearing aids and FM systems. Although cochlear implantation is found to be the most successful rehabilitative option, their cost and invasive nature advocates the need for alternate options. Hence, research on hearing aids and speech signal processing strategies are suggested.

It is clear from the literature that usefulness of amplification is not systematically investigated in individuals with late onset ANSD. The impact of temporal and intensity processing on aided performance is not clearly understood. Studies that reported aided speech perception improvement in a few individuals with late onset ANSD attributed their findings to lesser severity of problem. The presence cortical auditory evoked potentials and good speech perception abilities was reasoned to be the indicators of lesser severity. Thus, evaluation of temporal processing abilities in these individuals might be a better indicator of aided performance. It has been hypothesized that knowledge on intensity processing in these individuals might give better understanding of their aided performance. Hence, obtaining a performance-intensity function might be helpful to predict aided speech perception improvement.

Many signal enhancement strategies have shown to improve speech perception in individuals with late onset ANSD. Time scale modification, envelope enhancement and spectro-temporal enhancement are a few of them. Stretching of certain acoustic elements of speech syllables were found to improve speech perception significantly. However, identification and modification of these acoustic elements in a running speech has several practical problems. Though envelope enhancement was found to be effective that did not improve perception of voicing in individuals with ANSD. Hence, research on other signal processing strategies is warranted in those with ANSD.

CHAPTER 3 - METHOD

The study was carried out with the aim to determine the effect of two signal enhancement strategies as well as PI-PB function and aided performance in 30 individuals with ANSD. The study was executed in the following four phases:

Phase I: Obtain speech identification scores using the following two stimulus modification procedures in individuals with ANSD:

(a) Duration-enhancement of stimuli (stretch),

(b) Spectro-temporal enhancement of speech stimuli in the frequency region of 1 to 4 kHz of the temporal envelope.

Phase II: Determine speech identification scores in individuals with ANSD using the following two procedures to manipulate intensity:

(a) PI-PB function at different sensation levels,

(b) Aided performance using two different hearing aid amplification strategies.

Phase III: Evaluate temporal processing ability using TMTF in normal hearing individuals and individuals with ANSD.

Phase IV: Grouping of participants with ANSD based on their temporal resolution abilities and PI-PB function.

Participants

Two groups of participants were included in the study, those having ANSD and those having normal hearing. The former group had 30 individuals (12 males & 18 females), and the latter had 40 individuals (23 males, 17 females). Among the 40 normal hearing individuals, 10 were recruited for the development of the stimuli and the remaining 30 were evaluated in the third phase of the study. The 30 participants with ANSD were evaluated in the first three phases of the study and based on their performance in Phases II and III, they were grouped in two different ways in Phase IV. The first grouping was done based on the temporal resolution abilities of the participants and the second was based on their PI-PB function.

The demographic and audiological findings of *participants with ANSD* who participated in the study are given in Table 3.1. The age of the participants ranged from 14 years to 42 years with the mean age being 21.4 years and standard deviation being 6 years 6 months. This age range was chosen as it has been reported that psycho-acoustic abilities reach a plateau in normal individuals by the age of 12 years (Lynne, Werner, & Gray, 1998). It was ensured that no participant reported of any history of ear infection. It was also ascertained that they had no speech and language problems other than difficulty in understanding speech, especially in the presence of noise. None of the participants had undergone any prior formal auditory training activities and had no earlier exposure to the stimuli used in the study. The participants were literate, with all having passed at least secondary school education. Additionally, all the participants were fluent speakers of Kannada, a South Indian language spoken in Karnataka.

Only those participants who required or could benefit from hearing aids were selected for the study. Hence, individuals with mild to moderately-severe degree of hearing loss were chosen since Jijo and Yathiraj (2013b) observed that aided performance was poor in those with severe to profound hearing loss. Those with less than a mild degree of hearing loss were not included, as they usually did not require amplification. All the participants selected were naive hearing aid users.

The pure-tone average of the participants, for the frequencies 500 Hz, 1 kHz, and 2 kHz, ranged from 30 dB HL to 66.6 dB HL in the right ear (mean = 52.1 dB HL; standard deviation = 10.8). Likewise, in the left ear the pure-tone average ranged from 35 dB HL to 66.6 dB HL (mean threshold = 51.7 dB HL; standard deviation = 9.1). Additionally, all the participants had bilateral symmetrical hearing loss, with the difference in threshold between the two ears not exceeding 10 dB HL in any frequency. The Speech Identification Scores (SIS) in sound field ranged from 0% to 96% with the mean being 32%. Furthermore, all the participants met the diagnostic criteria for ANSD given by Starr et al. (2000) and Berlin et al. (2005). Thus, all of them had 'A' type tympanogram with no ipsilateral and contralateral reflexes. ABR was absent in all the participants, even at 90 dB nHL. Normal cochlear amplification was confirmed by the presence of TEOAEs with amplitudes of > 6 dB. Clinical neurological examination revealed that none of them had any space-occupying lesion. The absence of any external or middle ear problems was ruled out by an otological evaluation carried out by an oto-rhino-laryngologist.

The forty *participants with normal hearing* were in the age range of 18 to 35 years. Their mean age was 22 years and standard deviation was 4 years. All the participants spoke Kannada fluently. It was established, based on a structured interview, that none of them had any history of speech, hearing and neurological problems. A screening pure-tone audiological evaluation confirmed that their hearing thresholds were within 15 dB HL in the octave frequencies 250 Hz to 8000 Hz. The presence of A-type tympanograms and acoustic reflexes in both the ears substantiated that these participants had normal middle ear function.

Table 3.1

Demographic and Audiological Findings from 30 Participants having ANSD

SI. No	**Age (yrs)**	**Gender**	**Age of onset**	**PTA(dB HL)**		**SIS**	**Tympanogram Type**	**Reflex**	**ABR**	**OAE**
				Right	**Left**					
1	14	F	12	51.6	58.6	18	A	NR	NR	P
2	19	M	17	38.3	43.3	24	A	NR	NR	P
3	38	M	20	51.6	51.6	16	A	NR	NR	P
4	16	F	12	65	60	8	A	NR	NR	P
5	24	M	20	30	35	12	A	NR	NR	P
6	22	F	21	60	60	9	A	NR	NR	P
7	19	M	18	45	42	8	A	NR	NR	P
8	19	M	18	36.6	36.6	16	A	NR	NR	P
9	19	F	18	40	45	17	A	NR	NR	P
10	21	F	18	40	43.3	18	A	NR	NR	P
11	22	M	10	36	36	3	A	NR	NR	P
12	15	F	12	50	53.3	4	A	NR	NR	P
13	22	M	18	53.3	51.6	8	A	NR	NR	P
14	35	F	30	48.3	43.3	10	A	NR	NR	P
15	18	F	18	33.3	40	6	A	NR	NR	P
16	22	M	10	53.3	48.3	8	A	NR	NR	P
17	16	M	15	51.6	55	5	A	NR	NR	P
18	24	M	12	65	55	7	A	NR	NR	P
19	20	F	15	65	55	8	A	NR	NR	P
20	21	F	11	66.6	66.6	0	A	NR	NR	P
21	20	M	18	60	50	2	A	NR	NR	P
22	42	F	40	65	65	10	A	NR	NR	P
23	14	F	10	51.6	55	6	A	NR	NR	P
24	19	F	15	65	65	0	A	NR	NR	P
25	27	M	17	55	55	2	A	NR	NR	P
26	18	F	12	58.3	58	0	A	NR	NR	P
27	18	F	13	65	65	2	A	NR	NR	P
28	25	F	21	60	60	2	A	NR	NR	P
29	19	F	16	45	45	0	A	NR	NR	P
30	14	F	13	58.3	56.3	5	A	NR	NR	P

Note. PTA = Pure-tone average; SIS = Speech Identification Score; NR = No Response; P = Present

Instrumentation

The following instruments were utilized in carrying out the study:

1. A two channel diagnostic audiometer (GSI - 61), with supra-aural headphones (TDH-39), bone vibrator (Radio ear B-71) and speakers (Martin Audio C-15) was used to estimate pure-tone thresholds and also to present stimuli for the pilot and main study. It was ensured that the audiometer was calibrated once in three months as per the recommendations of ANSI, S3.6 (2004), during the period of the data collection.
2. A middle ear analyzer (GSI-Tympastar) was used to perform tympanometry and reflexometry. The instrument was calibrated following the recommendations of ANSI, S3.39 (R1996).
3. An oto-acoustic emission analyzer (ILO - 292) was employed for recording otoacoustic emissions.
4. With a two channel auditory evoked potential system (Smart EP, Version 2.21 C), auditory brainstem responses were recorded.
5. A personal computer [HP Compaq Elite 8300 MT with Intel (R) core (TM) i5 3470 processor] was used to generate and play the stimuli for the study. The computer had a Sigma Tel High definition audio sound card and was loaded with MATLAB (Version 7), Adobe Audition (Version 3) and Apex (Version 3).
6. Two digital behind-the-ear hearing aids, having two channels were used to assess aided performance.
7. A hearing aid analyzer (FONIX 7000) was utilized to measure the electro-acoustic characteristics of the hearing aids.

Test Environment

A sound treated two-room suite was used to record the test material and to collect data. It was ensured that the room meets the standards stipulated by ANSI S3.1- (1999).

Materials

The participants with ANSD were evaluated using existing material as well as material developed as a part of the study. These materials were utilised to group the participants and to establish their speech perception abilities.

Existing material used. The existing material used included, a phonemically balanced word identification test developed by Yathiraj and Vijayalakshmi (2005). Additionally, amplitude modulated white noise developed by Narne (2008) was used to evaluate temporal resolution abilities. The material developed by Narne (2008) was based on the procedure described by Lorenzi et al. (2000). This material had two test stimuli in it, an un-modulated white noise and sinusoidal amplitude modulated white noise, both having 500 ms duration with a ramp of 20 ms. The material were designed to obtain responses using a three-interval forced-choice method with each triad having two un-modulated tokens and one modulated token. The modulated white noise was derived by multiplying the broadband noise by a DC shifted sine wave. The depth of modulation was varied by changing the amplitude of modulating sine wave. Modulation depth was varied between 0 to -30 dB (where 0 dB is equal to 100% modulation depth). Modulation depth was converted into decibels using equation 1. Figure 3.1 shows the sample waveform of modulated white noise having 100% or 0 dB modulation depth.

Modulation depth in dB = 20 log 10 (m) ....*Equation 1* where ‘m’ refers to the depth of modulation.

Seven different modulation frequencies were used (4 Hz, 8 Hz, 16 Hz, 32 Hz, 64 Hz, 128 Hz & 256 Hz). All the stimuli were generated using a 32 bit digital to analogue converter at a sampling frequency of 44.1 kHz.

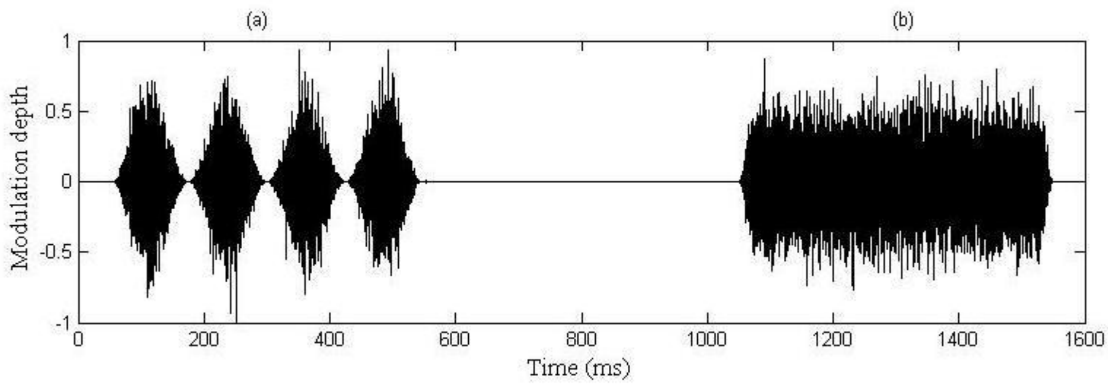


Figure 3.1. Sample of modulated wave (8 Hz) (a) and un-modulated white noise (b)

Material Development. Unprocessed (natural) stimuli that were recorded were used to develop processed stimuli. Using the unprocessed signal, two processed stimuli were developed one had enhancement in terms of duration and the other had enhanced amplitude in the 1 to 4 kHz region of the temporal envelope.

Recording of unprocessed syllables. Thirty natural VCV syllables comprising of 10 stop and liquid consonants (/p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪ /, /l/, /r/) in the context of three vowels (/a/, /i/ and /u/) were recorded to be used as the unprocessed stimuli. Classification of the above mentioned consonants based on their phonetic features is provided in Table 3.2. These consonants were chosen since earlier investigations demonstrated that individuals with ANSD had more difficulty in perceiving stops and liquids compared to fricatives, affricates and nasals (Narne & Vanaja, 2008; Ramirez &

Mann, 2005). The selected syllables were recorded by a female who was a native speaker of Kannada in a sound treated room. The speech tokens were recorded using a sampling frequency of 44.1 kHz and a resolution of 32 bit. A unidirectional microphone (AHUJA-AUD- 101 XLR), placed 6 cm from the mouth of the speaker, was connected to a personal computer loaded with Adobe audition (Version 3) software was utilised for recording. Three tokens of each stimulus, sequentially uttered at a normal vocal effort, were recorded. The middle token of each stimulus was selected as it had a flat intonation pattern. The selected tokens were normalised based on their RMS energy, using Adobe Audition (Version 3.0) software. A goodness test was carried out using the recorded stimuli on 10 normal hearing individuals. The participants, who heard the stimuli in a random order, were instructed to identify the syllables and to rate their quality. Those syllables that were reported to be unintelligible by 70% of the participants were re-recorded and again rated for their quality. Only those syllables that were correctly identified and rated as being intelligible were selected. Three lists, one for each vowel context, were constructed using the selected VCV syllables. Each list had ten VCV syllable and served as the unprocessed lists.

Table 3.2.

Classification of Consonants Based on their Phonetic Features

	/b/	/d/	/d̪/	/g/	/k/	/l/	/p/	/r/	/t/	/t̪/
Manner	s	s	s	s	s	l	s	l	s	s
Place	b	a	d	v	v	a	b	a	a	d
Voicing	+	+	+	+	-	+	-	+	-	-

Note. s = stop, l = liquid, b = bilabial, a = alveolar, d = dental, v = velar, + = present, - = absent

Development of duration enhanced syllables (temporal processed signals). For duration enhancement of the material, each stimulus from the unprocessed lists was stretched using a Pitch Synchronous Overlap and Add (PSOLA) algorithm (Moulines & Laroche, 1995), available in Adobe Audition (Version 3.0). This algorithm has been reported to preserve the formant transitions of the stop consonants and also have minimal digital artifacts compared to other time scaling algorithms (Malah, 1979). In addition, the algorithm preserves the pitch of the signal. Initially, the original signal was decomposed into short time signals based on pitch synchronous marks. The decomposed signal was duplicated based on predefined stretch factors (25%, 35% and 50%). The modified short-time signal was added to the duplicated signal to synthesis the stretched stimulus. Thus, the stimuli in each vowel context (/a/, /i/ and /u/) were enhanced using three stretch factors (25%, 35% and 50%), resulting in a total of 90 stimuli. Figure 3.2 provides sample waveforms of the stimulus /apa/, to depict the effect of the stretch factors. To check the intelligibility of the duration-enhanced stimuli, they were presented to 10 normal hearing adults, who had not been previously evaluated. It was found that there was no reduction in intelligibility of the stimuli enhanced by any of the three stretch factors.

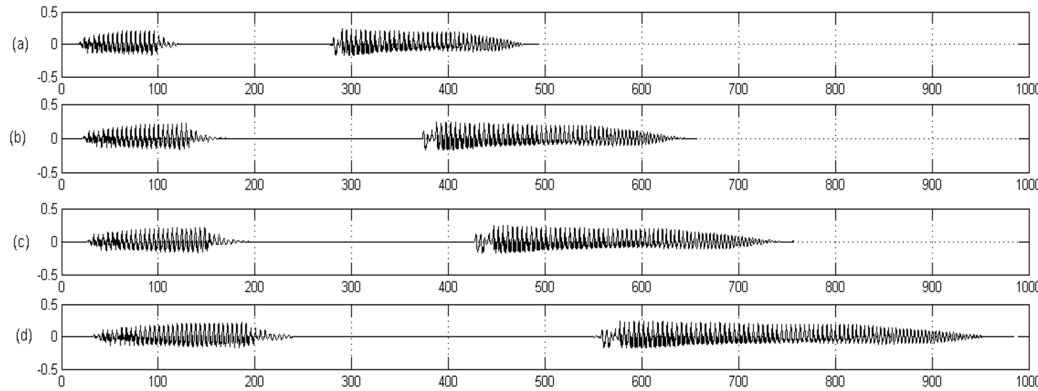


Figure 3.2. Unprocessed and the processed waveforms of the VCVsyllable /apa/ [(a) unprocessed, (b) stretched by 25%, (c) stretched by 35%, (d) stretched by 50%]

Selection of optimum duration enhancement. The quantum of duration enhancement of the speech signal that resulted in the highest speech identification scores was selected based on the findings of Jijo and Yathiraj (2013a). They evaluated eight individuals with ANSD using the four stretch condition stimuli (unprocessed signal, 50% stretched, 35% stretched, & 25% stretched). The SIS obtained for each stretch condition was compared with the unprocessed condition. The stretch condition that resulted in the highest speech identification improvement was considered as the optimum duration enhancement. They found that a stretch factor of 25% resulted in the highest speech identification score. Table 3.3 provided the duration of VCV syllables in three vowel contexts in the unprocessed and 25% stretched conditions.

Table 3.3

Duration of VCV syllables in Three Vowel Contexts in the Unprocessed and 25% Stretched Conditions

VCV syllable	Unprocessed			Stretched		
	/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/
/VpV/	464.00	444.00	441.00	613.00	577.00	583.00
/Vt̪V/	462.00	477.00	459.00	613.00	651.00	593.00
/VkV/	527.00	470.00	490.00	722.00	634.00	643.00
/VbV/	465.00	440.00	427.00	611.00	590.00	555.00
/VdV/	444.00	397.00	364.00	581.00	515.00	474.00
/VgV/	493.00	520.00	419.00	662.00	657.00	540.00
/VthV/	457.00	480.00	442.00	626.00	658.00	593.00
/Vd̪V/	470.00	424.00	430.00	620.00	564.00	559.00
/VlV/	448.00	408.00	389.00	608.00	527.00	508.00
/VrV/	452.00	409.00	408.00	598.00	540.00	527.00
Mean	**468.00**	**446.00**	**426.00**	**625.00**	**591.00**	**557.00**

Development of spectro-temporal enhanced syllables (spectro-temporal processed signals). Each stimulus was also enhanced spectro-temporally, as described by Nagarajan et al. (1998). This signal enhancement was carried out using MATLAB (Version 7) software. Initially, the speech signal was filtered into 20 band pass filters that were logarithmically spaced between 100 Hz to 10 k Hz. The output of these filter bands were subjected to Hilbert transform. The absolute values of the Hilbert transform provided information regarding the envelope of the speech signal for each of the bands.

The envelope in each band was then subjected to filtering using a second order Butterworth filter set between 3 Hz to 30 Hz. To avoid phase distortions, forward and backward filtering were carried out. The bands in the frequency region of 1 to 4 k Hz were provided a a gain of 15 dB. These spectral bands were added to produce the final output. A total of 30 enhanced stimuli were made from the unprocessed stimuli. It was ensured that the RMS energy of both unprocessed and enhanced stimuli were equal. Figure 3.3 provides sample waveforms and spectrograms of the unprocessed and the spectro-temporally modified stimulus /apa/.

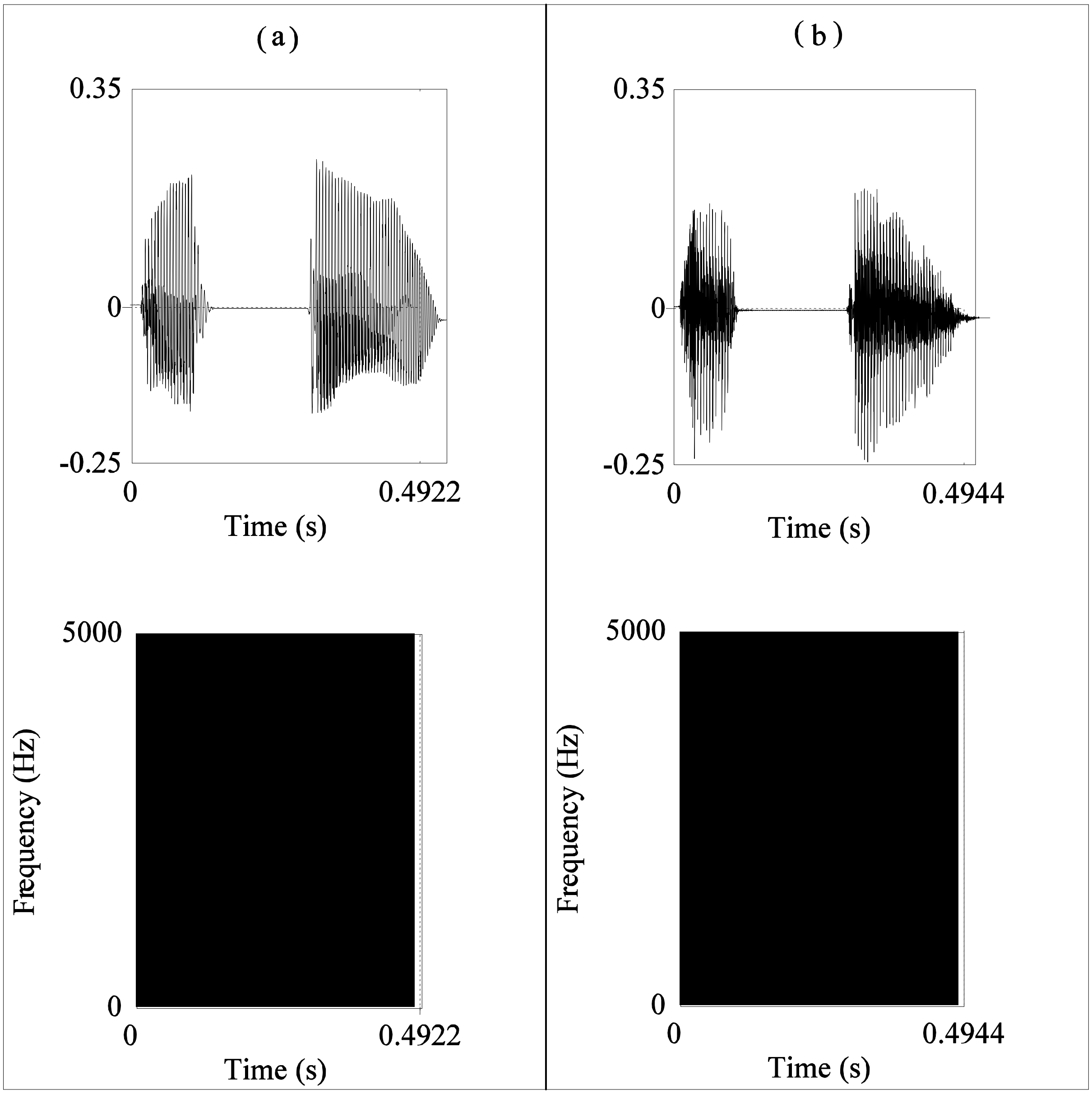


Figure 3.3. Waveforms and spectrogram of the unprocessed (a) and spectro-temporally enhanced (b) VCV syllable /apa/

Additionally, the temporal envelope of the unprocessed and spectro-temporally modified stimuli in four frequency bands are provided in Figure 3.4. Similar to the duration-enhanced stimuli, an intelligibility test was carried out that revealed no reduction in intelligibility for any of the stimulus that had spectro-temporal modification . However, the listeners reported of synthetic speech quality. It has been reported that filter bank emphasis of signal led to synthetic sounding speech output and shift in timbre (Nagarajan et al., 1998).

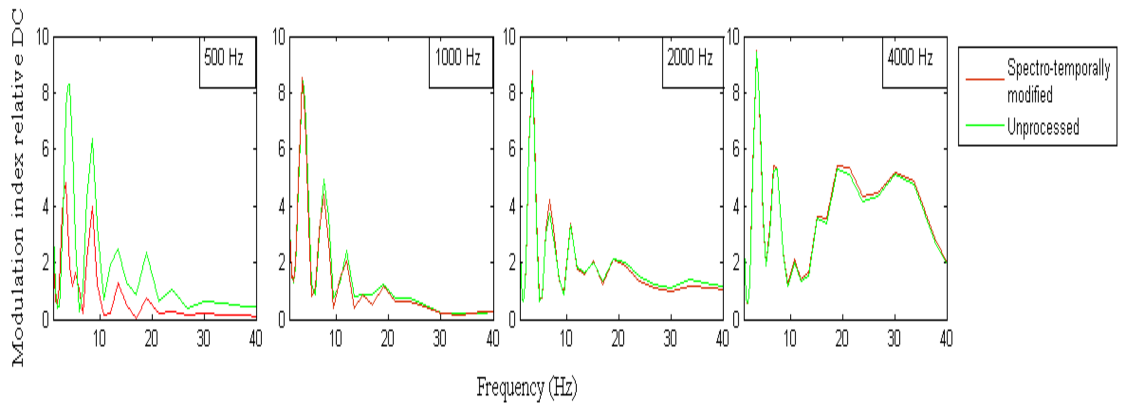


Figure 3.4: Envelope modulation spectra of unprocessed and spectro-temporally modified VCV syllable /apa/ analysed for four octave bands 500 Hz, 1 kHz, 2 kHz and 4 kHz presented in relation to energy at 0 Hz or DC.

Procedure

Initially, the participants were evaluated to ensure that they met the requirements to be included in the study. Those who met the requirements were subjected to further evaluations.

Procedure for selection of the participants. All the participants underwent routine audiological evaluation that included the following:

1. Pure-tone audiometric evaluation (air conduction and bone conduction) using modified version of Hughson and Westlake procedure (Carhart & Jerger, 1959),
2. Speech Recognition Threshold (SRT) was established using the Kannada paired-words developed at the All India Institute of Speech and Hearing, Mysore.
3. Word identification score was measured using bisyllabic words in Kannada developed by Yathiraj and Vijayalakshmi (2005).
4. Tympanograms were obtained bilaterally using a probe tone of 226 Hz at 85 dB SPL. Similarly, acoustic reflex thresholds were obtained in each ear at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.
5. Auditory brainstem responses were recorded using click stimuli, presented through an insert receiver (Etymotic Research - 3A) at 90 dBnHL. A total of 2000 stimuli were presented at a repetition rate if 11.1/sec. Responses collected from each channel were filtered using a band pass filter of 100 Hz to 3000 Hz and amplified one lakh times. In order to ensure the reproducibility of the waveform, the responses were recorded twice.
6. Transient evoked otoacoustic emissions were recorded using click stimuli presented at 80 dB + 5 dB peSPL in a non-linear fashion. A total of 260 stimuli were presented and the responses averaged over a period of 20 msec. OAEs were considered present only when the amplitude of the response was at least 5 dB SPL with a reproducibility of 75%.

7. All the participants underwent ENT examination to rule out any external or middle ear infection.

8. In addition, neurological evaluation was done to rule out peripheral neuropathy as well as any space-occupying lesion. As per the neurological report, all the clients had primary auditory neuropathy.

Procedure for the three phases of the study. Using the existing test material [PB wordlist (Yathiraj & Vijayalakshmi, 2005)]; TMTF stimuli (Narne, 2008) and the developed test material (VCV syllables), the participants with ANSD were evaluated. The three phases in which the data were obtained are described below. Investigations in Phase I and Phase II were carried out in a random order across the individuals with ANSD to avoid a test order bias. However, Phase III was always carried out after the first two phases to avoid any tester bias. In addition, to evaluating the participants with ANSD in the three phases, normal hearing individuals were evaluated in the third phase. The tests within each of the phases were also randomised. Following the completion of all the evaluations, the participants were grouped based on their test results.

Phase I: Procedure for evaluating the effect of temporal and spectro-temporal modification on speech perception. In this phase the effect of two different temporal enhancement strategies was investigated in the 30 individuals with ANSD. In the first investigation, perception of stimuli that were temporally stretched by 25% was investigated. In the second investigation, the perception of stimuli that were modified spectro-temporally was evaluated.

Effect of duration enhancement on speech perception. The set-up and procedure used to evaluate the performance of the participants with ANSD to duration enhanced signal was similar that used by Jijo and Yathiraj (2013a). The procedure involved presenting the unprocessed and stretched VCV syllables separately at SRT +40 dB HL to each participant. The unprocessed stimuli were used for the measurement of a baseline performance. The stimuli stretched by 25% were used to investigate the effect of temporal modification on perception. The unprocessed or temporally modified VCV lists were presented using a personal computer, via a calibrated diagnostic audiometer (GSI-61) to a loud speaker placed at 0^0 azimuth at 40 dB SL (ref SRT). Apex software (Version 3.0) was used to present the stimuli and also to generate stimulus-response confusion matrices. The 10 stimuli in a particular vowel context were presented thrice in a random order. It was ensured that the order of presentation of lists having different vowel environments (/a/, /i/, & /u/) varied across the participants. Closed-set responses were obtained from the participants by asking them to point to the syllables from a printed list of the stimuli. The next stimulus was presented after the participant responded. The SIS was calculated by counting the number of syllables correctly identified. Using a similar procedure, the scores obtained for the closed-set responses for the temporally modified stimuli in each vowel contexts were tabulated.

Effect of spectro-temporal enhancement on speech perception. The effect of spectro-temporally enhanced stimuli on speech perception was investigated using a set-up and procedure similar to that used for duration enhancement. The scores obtained from the unprocessed condition and spectro-temporally modified conditions in each vowel context were tabulated.

Phase II: Procedure for evaluating the effect of intensity on speech perception. The effect of intensity on speech perception was studied on 30 participants having ANSD through two different investigations. The set-up used was similar to that described earlier for investigating the effect stimulus modification in phase I. The first investigation in phase II involved obtaining speech identification scores at different sensation levels. The information from this performance-intensity function was used to group participants with ANSD later in Phase IV. The second investigation involved evaluating the aided performance of the participants using binaural digital hearing aids with and without compression. This evaluation was done to compare the effect of compression and linear amplification strategies, as the former strategy was reported to alter temporal envelope of speech whereas the latter was found to preserve it (Van Tassel, 1993).

Speech identification scores at different sensation levels. A performance-intensity function was obtained by presenting bisyllabic phonemically balanced words (Yathiraj & Vijayalakshmi, 2005) at different sensation levels. The CD version of the test, consisting of four lists having 25 words each, was played using the computer. The output of the computer was routed through a calibrated clinical audiometer (GSI-61) and presented through a loud speaker kept at a distance of 1 meter away from the client at 0^0 azimuth. A 1000 Hz calibration tone was presented and the VU meter dial was adjusted to 0 dB HL. The stimuli were presented at four to six different sensational levels (0, 10, 20, 30, 40, & 50 dB SL, ref: PTA), depending on the hearing thresholds of the participants. As the highest level of presentation was 90 dB HL, those with mild degree of hearing loss heard the stimuli at 5 different levels above their threshold. On the other hand, those with moderately-severe hearing loss received only 2 to 3 levels of presentation. It was ensured that the highest presentation level was always below the uncomfortable loudness level of each individual. The PI-PB function was obtained for all the participants, irrespective of their speech perception abilities. Although a few participants had 0% SIS at certain levels of the PI-PB function, none of them had 0% score at all the presentation levels.

In order to avoid any familiarity effect, the PB words were always presented in a random order. The participants were instructed to repeat the stimuli and their responses were noted by the experimenter. Each correct response was given a score of one and an incorrect response was given a score of zero. The speech recognition scores was calculated by counting the number of words correctly repeated. The PI-PB function was used to group the participants at a later stage, based on the rollover ratio (Phase IV). Grouping was not done at this stage to prevent the tester being influenced while carrying out further evaluations.

Aided Speech Identification Scores. Aided SIS was obtained from each participant with them wearing binaural hearing aids. This was carried out to investigate the relation between SIS obtained at different sensation levels and aided SIS. Their aided performance was obtained with them using two different programmes, one linear and the other non-linear.

The set-up for hearing aid performance was the same as that mentioned earlier for measuring SIS at different sensation levels. Prior to measuring the performance with the hearing aids, *unaided SIS* was obtained at 50 dB HL. The unaided performance was evaluated using two tests, the phonemically balanced Kannada word test (Yathiraj & Vijayalakshmi, 2005), using a list that had not been used earlier to evaluate the participants, and the unprocessed VCV syllables. A procedure, similar that used by Jijo and Yathiraj (2013a), as described earlier, was used to present the unprocessed VCV list.

The aided performance was obtained with the participants wearing binaural two channel digital behind-the-ear hearing aids, programmed using either a linear (DSL-Lin) or a non-linear (DSL=i/o) fitting formulae. All the participants were tested with both formulae, in a randomly order. Each digital hearing aid was programmed using a personal computer, in which NOAH software (Version 3) and the hearing aid specific software were installed. A HiPro, which was connected to the computer, provided an interface between the computer and the hearing aid to be programmed. Based on the pure-tone air conduction thresholds from 250 Hz to 8000 Hz of each ear, the first fit was generated using the DSL-i/o fitting formula. The hearing aids, programmed independently for each ear, were anchored to the ears of the participants using custom-made soft ear moulds. In order to obtain the preferred fit, the gain of each hearing aid was varied by 5 to 10 dB. The attack and release time of the hearing aids were adjusted to 5 ms and 40 ms respectively. With the hearing aids worn binaurally, loudness matching was carried out using the Ling six sounds test. After fitting the hearing aids binaurally, the stimuli (bisyllabic words & VCV syllables) were presented at 50 dB HL, in the same set-up as the unaided evaluation. The presentation level of 50 dB HL was chosen as the compression threshold of the hearing aid was 60 dB SPL. Similarly, the hearing aids were programmed using the DSL-Lin fitting formula before obtaining the SIS. Each correct response was given a score of one and an incorrect response was given a score of zero. The speech recognition score was calculated by counting the number of words / syllables correctly repeated.

Phase III: procedure for evaluation temporal processing ability. TMTF was used to investigate the temporal resolution abilities of individuals with ANSD. In order to avoid any tester bias TMTF was carried out after the completion of the other tests. Information from TMTF was later used to group the participants in Phase IV. Thirty individuals with ANSD and 30 normal hearing individuals were assessed to obtain their ability to detect rapid amplitude changes. This was assessed by determining the sensitivity to sinusoidally amplitude modulated broadband noise, as a function of modulation frequency.

The stimuli were played manually using a computer, the output of which was routed to a calibrated audiometer (GSI-61). The stimuli were presented through a loud speaker kept at a distance of 1 meter at 0^0 azimuth. Although the stimuli were presented at 40 dB SL (ref: SRT), the presentation level varied over a range of 10 dB at least for one modulation frequency. This was done to avoid the use of loudness as a cue for stimulus discrimination. A three-alternative forced-choice method was used, where un-modulated and modulated stimuli were randomly presented with an inter-stimulus interval of 500 ms. The participants were instructed to identify the stimulus that was different from the others. The Apex software (Version 3) was used to present the stimuli and obtain the plotted response.

Initially, the stimuli having 100% modulation (0 dB) was presented. The modulation depth was gradually decreased once the participant identified the modulated signal. A step size of 4 dB was used initially and then reduced to 2 dB after two reversals. This procedure has been estimated to provide the value of amplitude modulation necessary to obtain a 70.7% correct responses (Levitt, 1971). The mean of the last eight reversals in a block of 14 reversals was taken as the threshold.

Phase IV. Grouping of Participants with ANSD Based on Temporal Resolution Abilities and PI-PB function

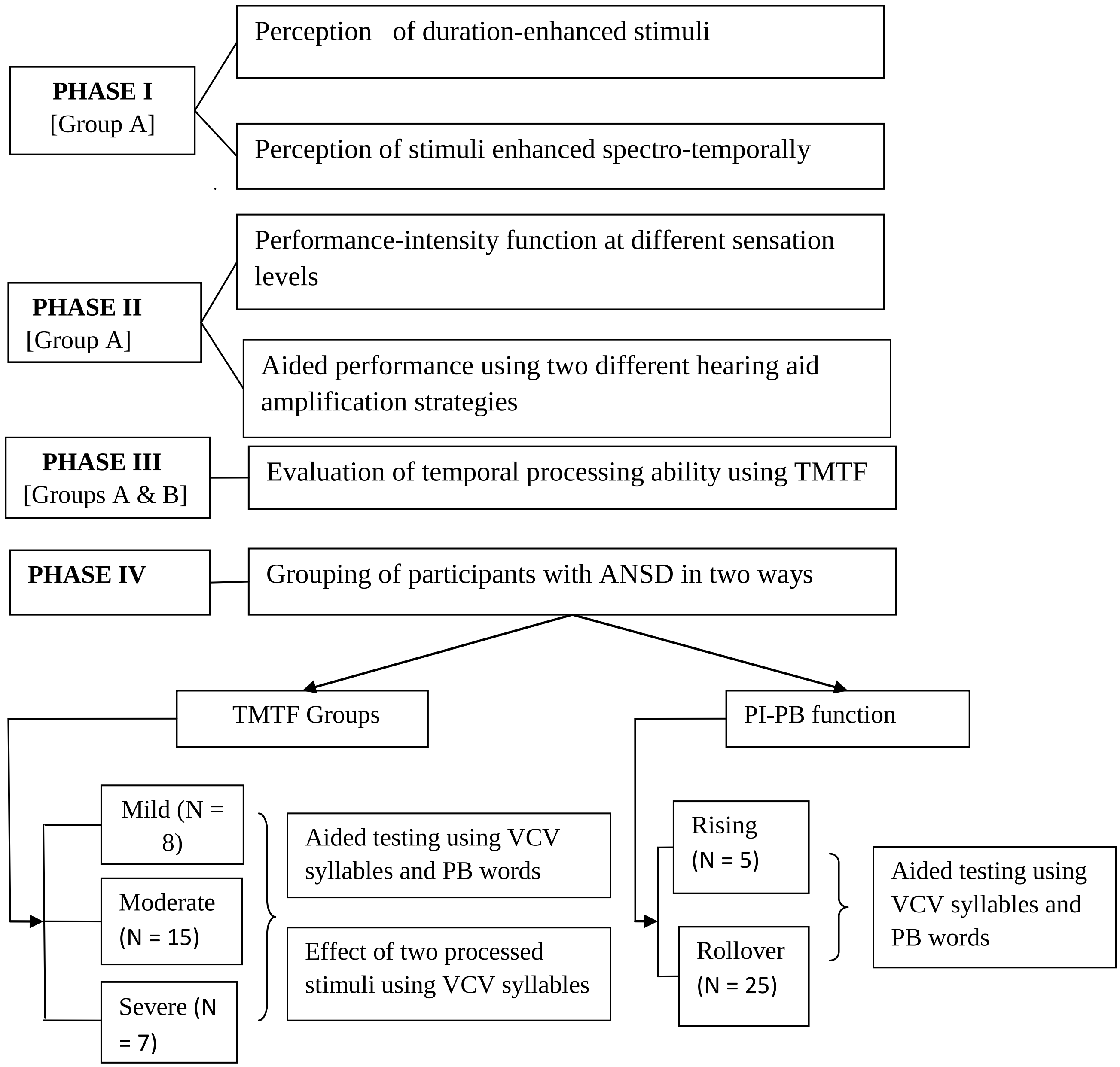
The 30 individuals with ANSD were grouped in two ways based on their temporal resolution abilities and PI-PB function. Their responses obtained in earlier phases of the study were used to group the participants.

Grouping of the based on their temporal resolution abilities was done using their peak modulation detection threshold ie, the best modulation detection threshold obtained at a particular frequency, obtained in Phase III. Using the peak modulation detection thresholds, the participants with ANSD were divided in to three groups having different levels of severity (mild, moderate, & severe), following the recommendations of Narne (2008). Those who had a mean peak modulation detection threshold of -16.20 dB were categorised in the mild group (N = 8). The moderate group (N = 15) had individuals with a mean peak modulation detection threshold of -10.70 dB and the severe group (N = 7) had individuals with a peak modulation detection threshold of -5.77 dB.

Grouping of the participants based on the PI-PB function was done using the criterion given by Jerger and Jerger (1971). In order to group the participants with ANSD, their SIS was plotted as a function of the presentation level. The PI-PB functions were noted to either have a rollover pattern or a rising pattern. As recommended by Jerger and Jerger those having a rollover index of greater than or equal to 0.45 were classified as having a rollover pattern, while those with a rollover index lesser than 0.45 was considered to have a rising function. The rollover index was calculated using equation 2 given below.

Rollover index (RI) = (PB max-PB min/PB max) ………….....*Equation 2*

where PB max was the level at which the maximum score in the PI-PB function was obtained and PB min was the level at which the lowest SIS was obtained beyond the level of the PB max. Among the 30 participants with ANSD, 25 exhibited rollover at high intensity levels. The remaining 5 had a rising pattern with slight reduction at higher levels. Figure 3.5 summarizes the procedure used in the study. It provides information regarding the four phases of the study, indicating the participants and the evaluations that were carried out at each phase



Note. Group A = 30 individuals with ANSD

Group B = 30 individuals with normal hearing

Figure 3.5. A flowchart depicting the four phases of the study, indicating the participants evaluated and the evaluations carried out

Analyses

The data collected were tabulated and subjected to statistical analyses using Statistical Package for the Social Sciences (Version 17). Prior to the statistical analyses the data obtained from each group were analyzed to check the assumptions for parametric statistics. The assumptions tested were the normality of the data and homogeneity of variance. In order to check normality, Shapiro Wilk test was performed in each TMTF group (mild, moderate and severe) for both the test conditions each having three conditions (unprocessed, spectro temporally modified & stretched; unaided, aided-linear & aided non-linear) conditions. It was noted that in each TMTF group the distribution of sample was significantly different from the normal distribution ($p > 0.05$). Leven's test also revealed that there was a significant difference in variance ($p > 0.05$). Additionally, the sample sizes were unequal in each of the TMTF groups. Similarly, the groups based on PI-PB function also did not meet the assumptions for parametric statistics. Hence, non-parametric statistics was carried out.

Both descriptive and inferential statistics were used to analyze the data. The mean, median and standard deviation of speech identification scores were calculated from the unprocessed and two modified stimuli (VCV syllables) as well as the unaided and two aided conditions (VCV syllables & PB words). This was obtained in participants who were grouped based on TMTF and PI-PB function. The following inferential statistics were carried out in those individuals who were grouped based on their TMTF and PI-PB function:

Non-parametric Kruskal-Wallis test was carried out to analyze the overall significant difference in word identification scores across the TMTF severity groups.

Further, stimuli modified conditions (unprocessed & two modified stimuli) and amplification conditions (unaided & two aided conditions) were also compared across the TMTF groups. This was followed by Mann-Whitney U test to compare pairs of groups, provided a significant difference was obtained in the Kruskal-Wallis test.

Non-parametric Friedman test was carried out to compare the performance across the stimulus modified (unprocessed and two modified stimuli) and amplification conditions (unaided and two aided conditions) within each of the TMTF severity groups. This was followed by Wilcoxon Signed ranks test to compare pairs of stimuli, if an overall significant difference was seen. Using a similar procedure performance across vowel contexts were also evaluated.

In a similar manner, the data obtained from individuals who were grouped based on PI-PB function were analyzed. Non-parametric Friedman test was carried out in each PI-PB function group, to compare across amplification conditions (unaided & two aided) and vowel context. This was followed by Wilcoxon Signed Ranks test to compare between pairs, is an overall significant difference was seen in the Friedman test.

Mann-Whitney U test was carried out to analyze the difference between PI-PB groups in the unaided and two aided conditions.

Information transmitted for the consonantal features was calculated using Sequential information analysis (SINFA) in both the test conditions (stimulus modified and amplification conditions) in participants grouped based on TMTF as well as PI-PB function. Statistical analysis of the same was carried using Friedman test followed by Wilcoxon Signed Ranks test.

Additionally, Spearman's rank correlation was performed to analyze the relation between PI-PB function, rollover ratio obtained from PI-PB function, TMTF peak threshold and the word identification scores in three amplification conditions (unaided, aided-linear aided non-linear).

CHAPTER 4 – RESULTS

The study aimed to investigate the effect of two signal enhancement strategies as well as PI-PB function and aided performance in 30 individuals with ANSD. The major independent variables were temporal processing severity, PI-PB function, speech modification strategies (stretch & spectro-temporal modification) and amplification conditions (linear & non-linear). The dependent variables included, speech identification scores obtained using phonemically balanced words as well as vowel-consonant-vowel (VCV) syllables. The dependent variables were measured within and across the independent variables. The data obtained from the participants having ANSD, grouped in terms of their temporal processing abilities and PI-PB function responses, were analysed using the below mentioned statistics.

1. Descriptive statistics was carried out for all the parameters evaluated.
2. To evaluate the overall effect of the dependent variables across the participant groups, non-parametric Kruskal-Wallis test was performed. This was followed by Mann-Whitney test to obtain a pair-wise comparison, if a significant difference was seen in the Kruskal-Wallis test. In order to balance between type I and type II errors, adjustments for multiple comparisons were not carried out in the Mann-Whitney test, as recommended by Rothman (1990).
3. To obtain an overall effect of the dependent variables within each participant groups, non-parametric Friedman test was administered. If a significant difference was found in the Friedman test, Wilcoxon Signed Ranks test was done to determine the difference between pairs of dependent variables. Adjustments for multiple comparisons were not performed in the Wilcoxon Signed Ranks test in

order to counter balance the effects of type I and type II errors, based on the findings of Rothman (1990).

4. Information transfer for the consonantal features was carried out using sequential information transfer analysis (SINFA). In order to investigate the statistical significance of consonantal features transmitted, Friedman test was carried out. If a significant difference was found, Wilcoxon Signed Ranks test was performed. However, adjustment for multiple comparisons were not performed (Rothman, 1990).
5. Spearman's rank correlation was performed to analyze the relation between SIS obtained at different intensity levels of the PI-PB function, Temporal Modulation Transfer Function (TMTF) peak modulation detection thresholds, PI-PB function rollover index and three amplification conditions (unaided, aided linear, & aided non-linear), and
6. To compare the temporal modulation detection thresholds of the normal hearing individuals and those with ANSD, Mann-Whitney test was performed at each modulation frequency. Kruskal-Wallis test was used to compare modulation thresholds of the normal hearing individuals with the 3 ANSD severity groups. This was followed by Mann-Whitney test for pair-wise comparison. Adjustments for multiple comparisons were not performed in the Mann-Whitney test (Rothman, 1990).

The outcomes obtained from the above statistical evaluations are provided under the following headings:

1. Effect of temporal processing severity and performance-intensity function on word identification scores in individuals with ANSD.

2. Effect speech modification strategies (stretch & spectro-temporal modification) on speech identification in participants grouped based on their temporal processing difficulty,

    2.1. Comparison of stimulus modified conditions (unprocessed, spectro-temporally modified, & stretched) and vowel context (/a/, /i/ & /u/) within a temporal processing severity group.

        2.1.1. Comparison across and within stimulus modified conditions in individuals having mild temporal processing deficit.

        2.1.2. Comparison across and within stimulus modified conditions in individuals having moderate temporal processing deficit.

        2.1.3. Comparison across and within stimulus modified conditions in individuals having severe temporal processing deficit.

    2.2. Comparison of stimulus modified conditions, across temporal processing severity groups.

    2.3. Comparison of information transfer in three temporal processing severity groups for three stimulus modified conditions and vowel contexts.

3. Effect of types of amplification (linear & non-linear) on speech identification in participants grouped based on their temporal processing difficulty,

3.1. Comparison of amplification conditions (unaided, aided linear, & aided non-linear) and vowel context (/aCa/, /iCi/ & /uCu/) within a temporal processing severity group.

3.1.1. Comparison across and within amplification conditions in individuals having mild temporal processing deficit.

3.1.2. Comparison across and within amplification conditions in individuals having moderate temporal processing deficit.

3.1.3. Comparison across and within amplification conditions in individuals having severe temporal processing deficit.

3.2. Comparison of amplification conditions, across temporal processing severity groups.

3.3. Comparison of information transfer in three temporal processing severity groups for three amplification conditions and vowel contexts.

4. Effect of types of amplification (linear & non-linear) on speech identification in participants grouped based on the PI-PB function responses,

4.1. Comparison across amplification conditions and vowel context within a PI-PB function severity group (rising & rollover),

4.1.1. Comparison across amplification conditions

4.1.2. Comparison across vowel contexts

4.2. Comparison of amplification conditions between PI-PB function groups.

4.3. Comparison of information transfer in two PI-PB function groups for three amplification conditions and vowel contexts.

5. Relation between PI-PB function / PI-PB rollover index / TMTF threshold with amplification Conditions.

6. Comparison of peak modulation detection thresholds of the normal hearing individuals and those with ANSD, grouped based on their temporal processing ability.

The results, after statistical analyses, are provided in detail under the headings mentioned above. Within the subheadings, information regarding the performance of subgroups of participants to stimuli in different vowel environments is given.

1. Effect of Temporal processing Severity and Performance-Intensity Function on Word Identification Scores in Individuals with ANSD

Temporal modulation transfer function, a graphical representation of modulation detection threshold as a function of modulation frequency, was analysed for the individuals with ANSD. Figure 4.1 depicts the mean TMTF threshold along with the standard deviation at different modulation frequencies. The mean TMTF threshold at a particular frequency was calculated after eliminating those who got a modulation threshold of 0 dB (100% modulation). Thus, the number of participants varied depending on the frequency, as shown in Figure 4.1. Although, all the participants with ANSD could detect the modulations at lower frequencies (4 Hz & 8 Hz), the number of participants who could detect modulations decreased as the frequency increased beyond 8 Hz. At 256 Hz, none of those with ANSD could detect even the maximum amount of modulation (100%). At the lower modulation frequencies, the variability in scores was much higher (4 Hz, 8 Hz, 16 Hz, & 32 Hz) than the higher frequencies (64 Hz & 128 Hz).

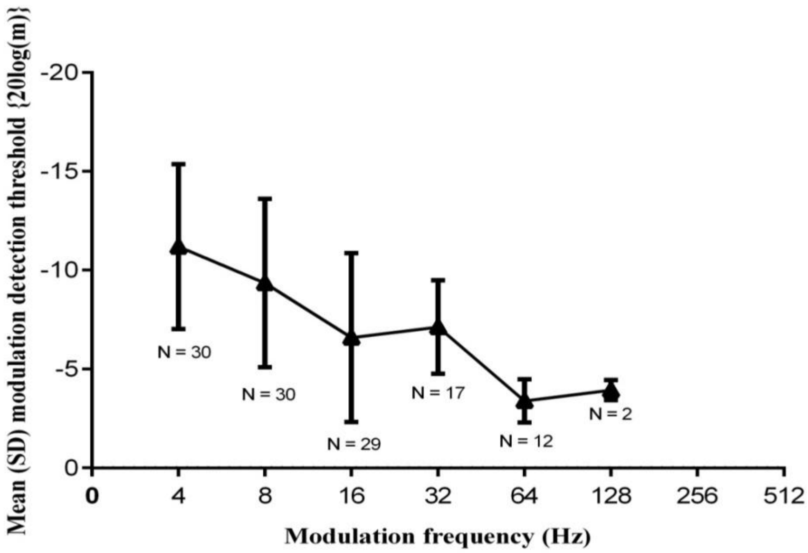


Figure 4.1. Mean and SD of modulation detection threshold in individuals with ANSD

To determine if there existed a difference in performance of the participants when grouped based on their TMTF performance, further analysis was carried out. The mean and SD of the modulation detection thresholds at different modulation frequencies in the three temporal processing deficit groups (mild, moderate, & severe) are depicted in Figure 4.2. It can be noted that the modulation detection thresholds in all three temporal processing deficits groups deteriorated as the modulation frequencies increased. The number of people who could detect the modulations also reduced at higher frequencies. In the mild group, the participants could detect modulations till 128 Hz, whereas the severe group could detect only till 32 Hz.

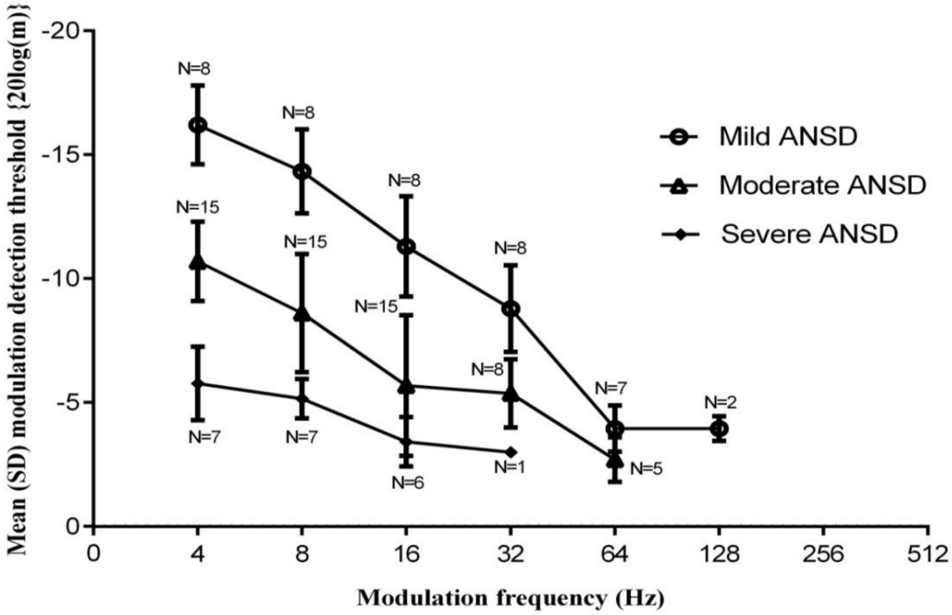


Figure 4.2. Mean and SD of threshold of modulation detection three groups of individuals with ANSD

Comparison of *word identification scores* across the ANSD *severity groups* indicated that as the severity increased the scores decreased. While the mild group got a mean score of 61% with a standard deviation of 20, the moderate and severe groups got mean scores of 38% and 8%, with a standard deviation of 16 and 4 respectively. Non-parametric Kruskal-Wallis test, performed to investigate if there existed an overall significant difference in SIS between the three temporal processing severity groups, showed the presence of a significant difference [H (2) = 17.12, $p < 0.05$]. Further, Mann-Whitney test, performed to check for differences between pairs of groups, revealed a significant difference in SIS between the mild and moderate groups (U = 21.5, $p < 0.05$), moderate and severe groups (U = 7.5, $p < 0.05$) and mild and severe groups (U = 0, $p < 0.05$). The groups with greater severity performed significantly poorer than those with lesser severity.

The mean and SD of the word identification scores obtained in participants with ANSD, grouped as having *rising and rollover PI-PB function*, are provided in Figures 4.3 and 4.4. The figures depict the mean and standard deviation of SIS obtained at different intensity levels in individuals who exhibited rising (N = 5) and rollover (N = 25) patterns, respectively. In the rising group, SIS increased as the presentation level increased till 30 dB SL and reached a plateau at higher presentation levels. In contrast, in the rollover group the SIS declined as the presentation level increased.

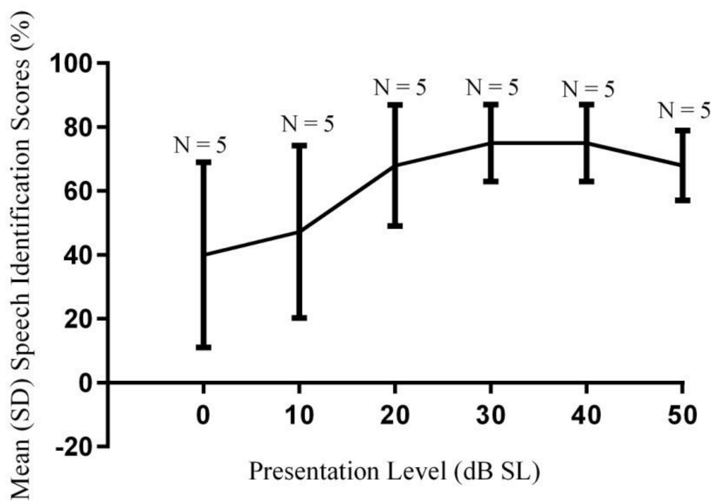


Figure 4.3. Mean and SD of SIS obtained as a function of presentation level in individuals with ANSD exhibiting a rising pattern. (*Note*. N = number of participants)

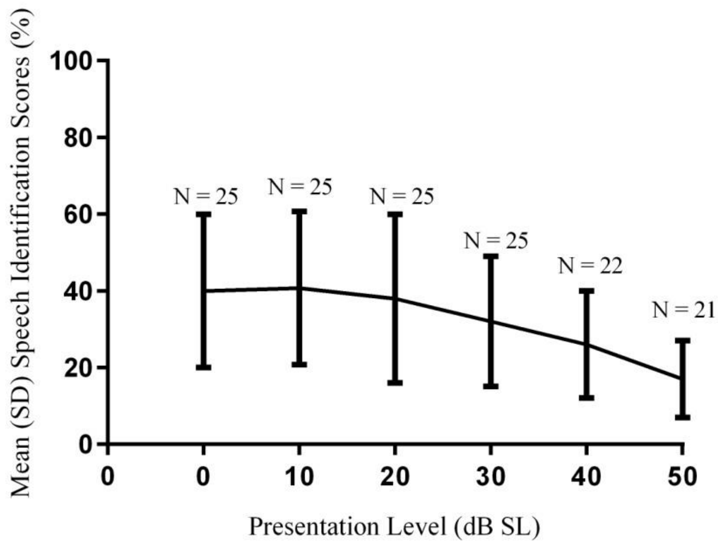


Figure 4.4. Mean and SD of SIS obtained as a function of presentation level in individuals with ANSD exhibiting a rollover pattern. (*Note.* N = number of participants)

In order to compare the SIS in the rising and rollover groups at each sensation level, Mann-Whitney test was performed. No significant difference between the two groups was obtained at the lowest two sensation levels [0 dB SL ($U = 54.0$, $p > 0.05$); & 10 dB SL ($U = 47.0$, $p > 0.05$)]. However, the rising group obtained significantly higher scores than the rollover group in the four higher sensation levels [20 dB SL ($U = 21.5$, $p < 0.05$); 30 dB SL ($U = 4.0$, $p < 0.05$); 40 dB SL ($U = 0.5$, $p < 0.05$); & 50 dB SL ($U = 0$, $p < 0.05$)].

To determine the overall effect of intensity on SIS, in each of the PI-PB function groups (rising & rollover), Friedman test was performed. In the *rising pattern group*, a significant effect of intensity on SIS was obtained [χ^2 (6) = 20.56, $p < 0.001$]. Further, to obtain information regarding the significance of difference between performance across pairs of intensities, Wilcoxon sign rank test was done. The results revealed a significant difference in SIS between the lower 2 adjacent levels (0 dB SL & 10 dB SL as well as 10 dB SL & 20 dB SL). However, no significant difference was obtained between the adjacent presentation levels above 20 dB SL (i.e. 20 dB SL & 30 dB SL, 30 dB SL & 40 dB SL, 40 dB SL & 50 dB SL), as can be seen in Table 4.1. Friedman test in the *rollover group* also showed a significant overall effect of intensity on SIS (χ^2 (6) = 67.03, $p < 0.05$). The pair-wise comparison obtained using Wilcoxon sign rank test (Table 4.1) indicated a significant difference between adjacent pairs of sensation levels (0 dB SL & 10 dB SL, 10 dB SL & 20 dB, 20 dB SL & 30 dB SL, 30 dB SL & 40 dB SL, 40 dB SL & 50 dB SL). Each 10 dB increment in presentation level resulted in a significant deterioration in SIS.

Table 4.1
Comparison of SIS between Adjacent Pairs of Intensity Levels in Those with ANSD having Rising and Rollover Patterns of PI-PB function. Z value, p value and Levels of Significance are Given

	0 vs 10		10 vs 20		20 vs 30		30 vs 40		40 vs 50	
PI-PB function groups	$\lvert z \rvert$	P	$\lvert z \rvert$	P	$\lvert z \rvert$	P	$\lvert z \rvert$	P	$\lvert z \rvert$	P
Rising	2.02	0.04* ↑	2.03	0.04*↑	1.09	0.273	.272	.785	1.84	.07
Rollover	3.39	0.001***↓	1.99	0.046↓	2.54	0.011*↓	3.65	0.00***↓	4.0	0.00***↓

Note. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$; Upward arrow (↑) shows significant improvement of the second level over the first; Downward arrow (↓) shows significant deterioration of the second level over the first.

2. Effect of Stimuli Modification in Participants Grouped Based on the Severity of Temporal Processing Problem

The mean, median and standard deviation of the VCV syllable scores obtained from three temporal processing severity groups are shown in Table 4.2. The table provides information regarding the perception of the unprocessed, spectro-temporally modified and stretched stimuli in the three different vowel contexts. It can be noted from the table that VCV syllable perception became poorer as the temporal processing ability deteriorated. Higher and similar scores were found for the VCVs having the vowel contexts /a/ and /u/ compared to the context of /i/. The spectro-temporally modified stimuli either resulted in a drop in performance or did not improve speech perception in any of the temporal processing severity groups, in any vowel context. In contrast, stretching the stimuli improved perception, irrespective of the severity of temporal processing and vowel context.

Table 4.2

Mean, Median and SD of Consonant Perception in Three Different Stimulus Modified Conditions (Unprocessed, Spectro-temporally modified, & Stretched) and Vowel Contexts (/a/ /i/ /u/) in Three Groups of ANSD

		Stimulus modified conditions								
		Unprocessed			Spectro-temporally modified			Stretched		
TMTF severity groups	VCV syllables	Mean #	Median	SD	Mean #	Median	SD	Mean #	Median	SD
Mild	/aCa/	19.25	19.5	4.13	18.75	18.0	4.49	23.25	22.5	3.10
	/iCi/	16.25	17.0	2.65	15.62	16.0	2.82	19.00	18.0	2.44
	/uCu/	20.12	21.5	3.79	19.37	20.0	4.06	22.3	23.0	4.47
Moderate	/aCa/	15.6	14.0	5.05	13.26	14.0	4.81	18.00	17.0	4.91
	/iCi/	12.73	14.0	3.51	10.66	11.0	3.13	14.93	14.0	4.13
	/uCu/	15.0	14.0	3.85	12.06	13.0	4.39	18.26	19.0	3.73
Severe	/aCa/	12.14	10.0	2.91	9.00	9.00	2.44	14.42	14.0	2.50
	/iCi/	10.85	10.0	1.46	8.57	8.0	1.13	12.71	13.0	2.36
	/uCu/	11.71	12.0	2.05	9.71	9.0	2.13	13.14	12.0	1.77

Note. # Maximum possible score = 30; VCV = Vowel-Consonant-Vowel; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / ṯ /, /ḏ/, /l/, /r/.

2.1. Comparison of stimulus modified conditions and vowel context, within a temporal processing severity group. The comparison across stimulus modified conditions was done within each of the temporal processing severity groups (mild, moderate, & severe). Friedman test was carried out to analyze the overall effect of stimulus modified conditions (unprocessed, spectro-temporally modified, & stretched). This test was done separately for each of the three vowel contexts. If a significant difference was found between the stimulus modified conditions, Wilcoxon Signed Ranks test was done to check for the presence of any significant difference between pairs of stimulus modified conditions. Using the similar sequence of statistical procedures, a comparison was made across the vowel contexts (/a/, /i/ and /u/) within each stimulus modified condition. Furthermore, the overall effect of consonantal features transmitted (manner, place, &voicing) were analysed using Friedman test for the three stimulus modified conditions, for each of the vowel contexts. This was then followed by Wilcoxon Signed Ranks test, in case an overall significant difference was present. These were carried out separately for each temporal processing deficit group.

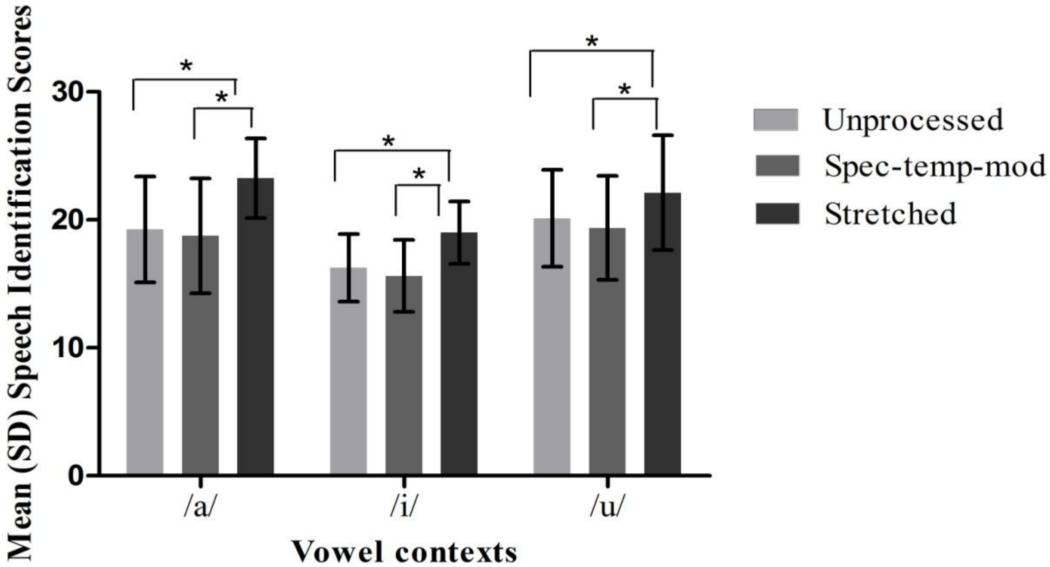
2.1.1. Comparison across and within stimulus modified conditions in individuals having mild temporal processing deficit. In the mild group, there was a significant difference *across stimulus modified conditions*, in the context of */a/* [χ^2 (2) = 12.00, $p < 0.05$], */i/* [χ^2 (2) = 12.07, $p < 0.05$] and */u/* [χ^2 (2) = 9.93, $p < 0.05$]. The results were further analysed using Wilcoxon Signed Ranks test (Table 4.3), which showed that in the context of /a/, the stretched stimuli resulted in significantly higher perception compared to the unprocessed and spectro-temporally modified stimuli. However, there was no significant difference between the unprocessed and the spectro-temporally modified stimuli. Similar results were observed in the context of /i/ and /u/ (Figure 4.5).

Table 4.3

Pair-wise Comparison and Levels of Significance of Stimulus Modified Conditions in Different Vowel Contexts in Individuals with Mild, Moderate, and Severe Temporal Processing Deficits

		Stimulus modified condition pairs					
		Unprocessed vs Spectro-temporally modified stimuli		Unprocessed vs Stretched stimuli		Spectro-temporally modified vs Stretched stimuli	
TMTF severity groups	VCV syllables	|z|	p value	|z|	p value	|z|	p value
Mild	/aCa/	1.41	0.157	2.37	0.018* ↑	2.38	0.017* ↑
	/iCi/	1.66	0.096	2.38	0.017* ↑	2.38	0.017* ↑
	/uCu/	1.89	0.058	2.12	0.034* ↑	2.37	0.018* ↑
Moderate	/aCa/	3.21	0.001*** ↓	3.01	0.003** ↑	3.41	0.001*** ↑
	/iCi/	3.32	0.001*** ↓	2.82	0.005** ↑	3.41	0.001*** ↑
	/uCu/	3.31	0.001*** ↓	3.42	0.001*** ↑	3.42	0.001*** ↑
Severe	/aCa/	2.38	0.017* ↓	2.21	0.027* ↑	2.37	0.018* ↑
	/iCi/	2.41	0.016* ↓	1.96	0.050* ↑	2.37	0.018* ↑
	/uCu/	2.22	0.026* ↓	1.38	0.167	2.38	0.017* ↑

Note. * = p < .05, ** = p < .01, *** = p < .001; VCV = Vowel-Consonant-Vowel; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/. Upward arrow (↑) shows significant improvement of the second condition over the first, Downward arrow (↓) shows significant deterioration of the second condition over the first.



Note. Maximum possible score = 30; Spec-temp mod = Spectro-temporal modification;
* = p < 0.05

Figure 4.5. Mean speech identification scores and 1 SD in different stimulus modified conditions (unprocessed, spectro-temporally modified, & stretched) for different vowel contexts in those with mild temporal processing deficit.

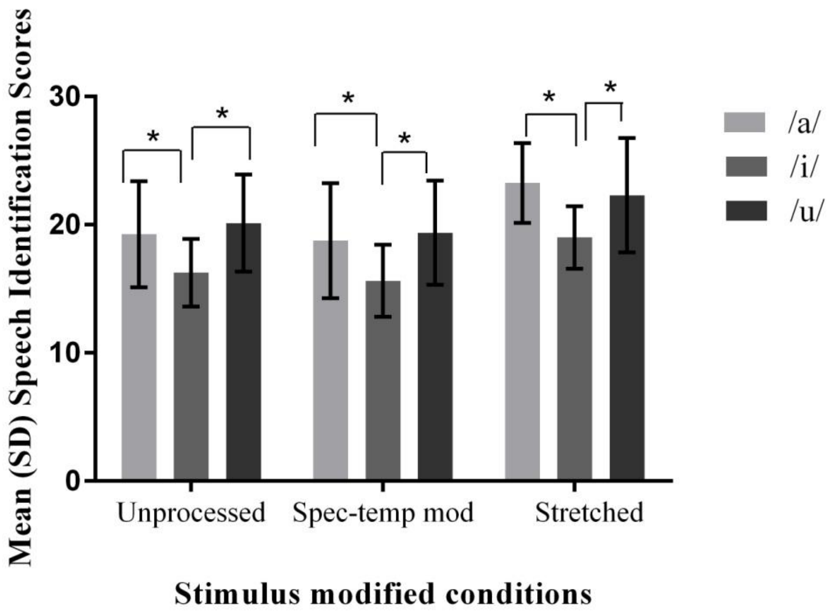
Comparison across *vowel contexts (*/a/, /i/, & /u/) in the mild group using Friedman test revealed a significant difference between them in the *unprocessed condition* (χ^2 (2) = 7.03, $p < 0.05$), *spectro-temporally modified condition* (χ^2 (2) = 7.51, $p < 0.05$) and *stretched condition* (χ^2 (2) = 8.46, $p < 0.05$). Further, Wilcoxon Signed Ranks test (Table 4.4) showed that consonant perception in the context of /a/ and /u/ was significantly higher than that of /i/. However, no significant difference was found between /a/ and /u/ in any of the stimulus modified conditions (Figure 4.6).

Table 4.4

Pair-wise comparison and level of significance between vowel contexts in different stimulus modified conditions in those with mild and moderate temporal processing deficit

Vowel context pairs							
		/aCa/ vs /iCi/		/aCa/ vs /uCu/		/iCi/ vs /uCu/	
TMTF severity group	Stimulus modified conditions	|z|	p value	|z|	p value	|z|	p value
Mild	Unprocessed	2.03	0.042*↓	0.17	0.856	2.31	0.020*↑
	Spectro-temporally modified	2.20	0.028*↓	0.40	0.684	2.39	0.017*↑
	Stretched	2.38	0.017*↓	0.43	0.667	2.03	0.042*↑
Moderate	Unprocessed	2.95	.003* ↓	0.07	0.944	2.13	0.033*↑
	Spectro-temporally modified	3.21	0.001***↓	1.45	0.146	1.72	0.085
	Stretched	3.13	0.002**↓	0.26	0.788	2.64	0.008**↑

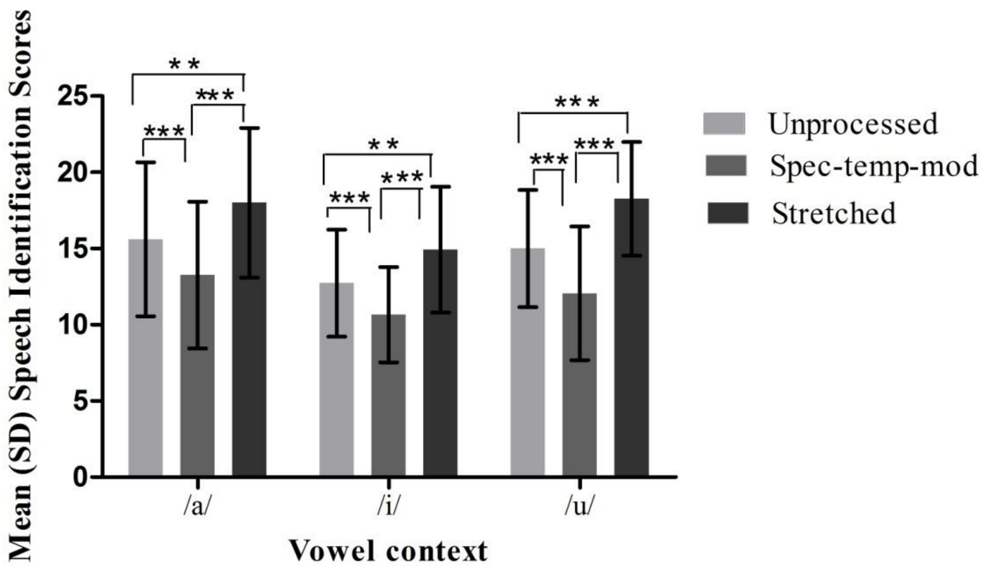
Note. * = p < .05; ** = p < .01; *** = p < .001; C = Consonants; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/; Upward arrow (↑) shows significant improvement of the second condition over the first, Downward arrow (↓) shows significant deterioration of the second condition over the first.



Note. Maximum possible score = 30; Spec-temp mod = Spectro-temporal modification;
* = $p < 0.05$

Figure 4.6. Mean speech identification scores and 1 SD in different stimulus modified conditions (unprocessed, spectro-temporally modified, & stretched) for different vowel contexts in individuals with mild temporal processing deficit.

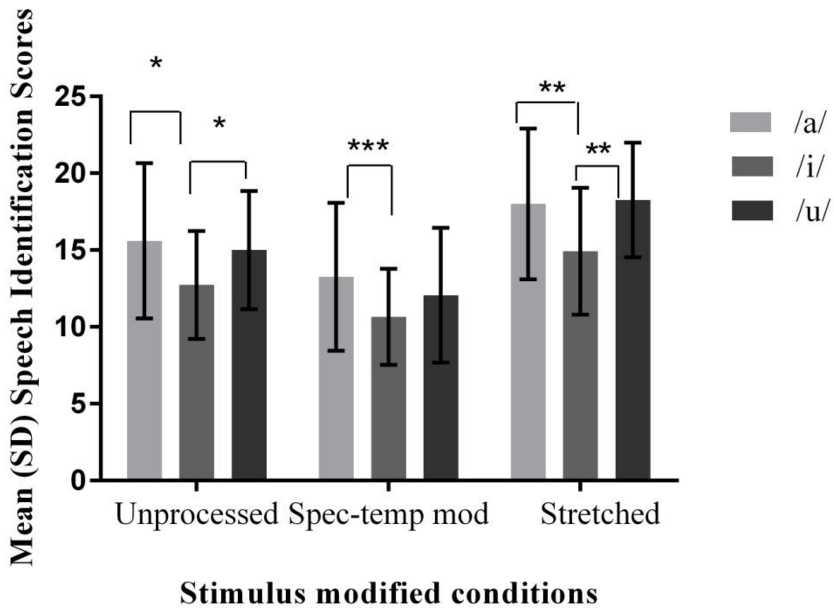
2.1.2. ***Comparison across and within stimulus modified conditions, in individuals having moderate temporal processing deficit.*** In the group with moderate temporal processing deficit, Friedman test indicated that there was a significant difference *across stimulus modified conditions* in the context of the vowel */a/* [χ^2 (2) = 26.14, $p < 0.05$], */i/* [χ^2 (2) = 26.46, $p < 0.05$], and */u/* [χ^2 (2) = 29.52, $p < 0.05$]. Further, analysis using Wilcoxon Signed Ranks test (Table 4.3) showed significantly higher scores in the temporally stretched stimuli relative to the unprocessed as well as the spectro-temporally modified stimuli. However, the spectro-temporally modified stimuli resulted in significantly poorer perception scores compared to the unprocessed stimuli (Figure 4.7 & Table 4.3). This was observed in all three vowel-contexts.



Note. Maximum possible score = 30; Spec-temp mod = Spectro-temporal modification;
* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$

Figure 4.7. Mean speech identification scores and 1 SD in different stimulus modified conditions for different vowel context in those with moderate temporal processing deficit.

There was a significant difference *between the vowel contexts*, as per the findings of Friedman's test in the *unprocessed* [χ^2 (2) = 11.11, $p < 0.05$], *spectro-temporally modified* [χ^2 (2) = 12.47, $p < 0.05$] and *stretched* [χ^2 (2) = 12.49, $p < 0.05$] conditions. Further, Wilcoxon Signed Ranks test (Table 4.4), done to compare vowel pairs in each stimulus modified condition, showed significantly lower scores in the context of /i/ compared to the vowel contexts /a/ as well as /u/. However, no significant difference was found between /a/ and /u/ in any of the stimulus modified conditions. This is depicted in Figure 4.8 and Table 4.4.

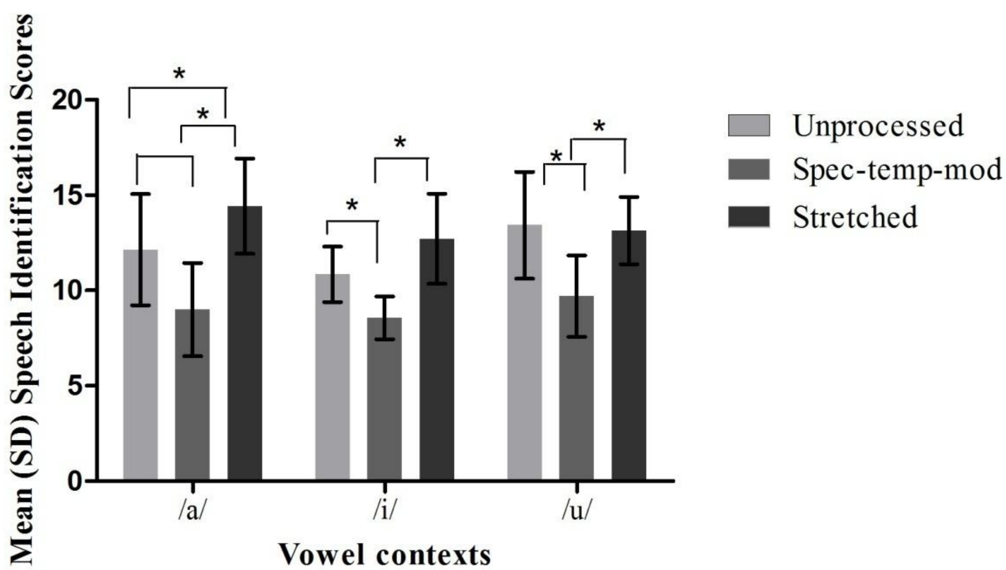


Note. Maximum possible score = 30; Spec-temp mod = Spectro-temporal modification;
* = p < 0.05; ** = p < 0.01; *** = p < 0.001

Figure 4.8. Mean speech identification scores and 1 SD in different vowel contexts for unprocessed, spectro-temporal modified and stretched conditions in individuals with moderate temporal processing deficit

2.1.3. Comparison across and within stimulus modified conditions, in individuals having severe temporal processing deficit. Comparison *across stimulus modified condition* within each vowel context using Friedman test indicated the presence of an overall significant difference between stimulus modified conditions in the context of the vowels */a/* [χ^2 (2) = 13.55, $p < 0.05$], */i/* [χ^2 (2) = 12.07, $p < 0.05$], and */u/* [χ^2 (2) = 10.23, $p < 0.05$]. In the context of /a/ and /i/, stretched stimuli resulted in significantly higher perception compared to the unprocessed and spectro-temporally modified stimuli conditions, as seen in the outcome of the Wilcoxon Signed Ranks test (Table 4.3). In contrast, the spectro-temporally modified stimuli led to significant deterioration in performance compared to the unprocessed stimulus condition. In the vowel context /u/, there was no significant difference between the unprocessed and stretched conditions.

However, stretching the stimuli led to significant improvement compared to spectro-temporally modifying the stimuli. Further, similar to what was seen in the context of the vowels /a/ and /i/, the spectro-temporally modified stimuli were perceived significantly poorer than the unprocessed stimuli in the context of /u/ (Figure 4.9 & Table 4.4). Comparison *across vowel context,* within each stimuli condition, showed no significant difference between the three vowel contexts (/a/, /i/, & /u/), in any of the stimulus modified conditions.



Note. Maximum possible score = 30; Spec-temp mod = Spectro-temporal modification;
* = $p < 0.05$

Figure 4.9. Mean speech identification scores and 1 SD in different stimulus modified conditions for different vowel context in those with severe temporal processing deficit.

From the above results it was noted that spectro-temporally modified stimuli did not improve speech perception in individuals with ANSD. In order to further investigate the reason for the lack of improvement using spectro-temporally modified stimuli, an envelope modulation spectra was generated. Additionally, spectro-temporally modified stimuli, generated using PRAAT was developed, as this has been shown by Narne and

Vanaja (2008) to bring about an improvement in individuals with ANSD (Appendix A). The envelope modulation spectra of spectro-temporally modified stimuli used in the presents study were compared with the unprocessed stimuli and stimuli that were enhanced using a similar algorithm that was developed by Nagarajan et al. (1998) to improve speech perception in individuals with ANSD. It can be observed from the spectra (Appendix A) that there are certain major changes in the envelope spectrum of the three stimuli. In the lower centre frequencies (500 Hz & 1 kHz) the envelope spectrum were found to be similar. However, at higher centre frequencies, especially at 4 kHz, the envelope of the stimuli that were enhanced using PRAAT had higher energy compared to the algorithm used in the present study.

2.2. Comparison of stimulus modified conditions across temporal processing severity groups. Kruskal-Wallis test was performed to assess the significance of difference between the three stimulus modified conditions (unprocessed, spectro-temporally modified, & stretched stimuli) across the three temporal processing severity groups (mild, moderate, & severe). In each stimulus modified conditions, the evaluation was carried out in three vowel contexts (/a/, /i/, & /u/). The results shown in Table 4.5 revealed that there was a significant difference between the temporal processing severity groups in each of the nine stimulus modified conditions.

Table 4.5

Significance of Difference Between Temporal Severity Groups for Each Stimulus Modified Condition and Vowel Context, with the Three Groups Combined

Stimulus modified condition →	Unprocessed	Spectro-temporally modified	Stretched

VCV syllables →	/aCa/	/iCi/	/uCi/	/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/
H	8.36	9.57	11.02	13.09	13.90	12.24	12.93	9.18	13.41
df	2	2	2	2	2	2	2	2	2
p value	0.015*	.008**	.004**	.001***	.001***	.002**	.002**	.010**	.001***

Note. * = p < .05, ** = p < .01, *** = p < .001; VCV = Vowel-Consonant-Vowel; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/.

Mann-Whitney test was performed to compare the temporal processing severity groups, in each of the three stimulus modified conditions (Table 4.6). The performance of the mild group with the *unprocessed stimuli* was significantly higher than the moderate and severe groups, in all three vowel-contexts. However, there was no significant difference between the moderate and severe groups. Similarly, with the *spectro-temporally modified stimuli*, the mild group had significantly higher speech perception than the moderate and severe groups, in all three vowel-contexts. The moderate and the severe groups continued to demonstrate no significant difference in performance, except in the context of the vowel /a/. With the *stretched stimuli*, the mild group had significantly higher scores compared to the moderate and severe groups in all three vowel-contexts. In contrast, comparison between the moderate and severe groups showed that there was no significant difference between them in the vowel contexts /a/ and /i/, but were different in the context of /u/.

Table 4.6
Pair-wise Comparison of Temporal Processing Severity Groups and Levels of Significance for the Three Stimulus Modified Conditions and Vowel Contexts

Stimulus modified conditions	VCV syllables	Temporal processing severity groups: Mild vs Moderate		Mild vs Severe		Moderate vs Severe	
		U	p value	U	p value	U	p value
Unprocessed	/aCa/	31.5	.065	4.5	.004** ↓	30	.110
	/iCi/	29.5	.047* ↓	1	.001*** ↓	33	.163

	/uCu/	24	.019* ↓	4	.005** ↓	25.5	.053
Spectro-temporally modified	/aCa/	22	.013* ↓	0	.001***↓	24.5	.047*↓
	/iCi/	14	.002**↓	0	.001***↓	32	.143
	/uCu/	15	.004**↓	2	.002** ↓	36	.241
Stretched	/aCa/	19.5	.009**↓	0	.001***↓	28	.083
	/iCi/	28	.038* ↓	0.5	.001***↓	39	.337
	/uCu/	24	.019* ↓	4.5	.004** ↓	12	.004**↓

Note. * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; VCV = Vowel-Consonant-Vowel; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/; Downward arrow (↓) shows significant deterioration of the second group over the first.

The *change in speech perception scores as a result of signal modification* was calculated by computing the difference between the SIS obtained using modified stimuli and unprocessed stimuli in each vowel context (stretched SIS minus unprocessed SIS & spectro-temporally modified SIS minus unprocessed SIS). The mean difference score between stretched and unprocessed stimuli was highest in the mild group followed by moderate and severe respectively, in all three vowel contexts. However, the mean of the difference score between spectro-temporally modified and unprocessed stimuli was highest in the severe group followed by moderate and mild in all three vowel contexts. Kruskal-Wallis test was performed to assess the significance of difference in the change in scores obtained by stretching the VCV signals (stretched SIS minus unprocessed SIS) across the three temporal processing deficits groups. The results showed no significant difference across the temporal processing deficits groups for the difference score in the context of /a/ [$H(2) = 2.0$, $p > 0.05$], and /i/ [$H(2) = .98$, $p > 0.05$] and /u/ [$H(2) = 4.6$, $p > 0.05$]. In contrast, the change in scores obtained by spectro-temporally modifying the VCV signals (spectro-temporally modified SIS minus unprocessed SIS) showed significant difference across temporal processing deficits in the context of /a/ [$H(2) = 10.0$, $p < 0.05$], and /i/ [$H(2) = 9.1$, $p < 0.05$] and /u/ [$H(2) = 7.6$, $p < 0.05$]. Further, Mann-Whitney test showed significant differences between the mild and moderate groups as well as mild and severe groups in all three vowel context ($p < 0.05$). However, no significant difference was found between the moderate vs. severe groups ($p > 0.05$).

2.3. Comparison of information transfer in three temporal processing severity groups for three stimulus modified conditions and vowel contexts. Sequential information analysis was carried out to determine the amount of information transferred for the phonetic features (manner, place, & voicing). The stimulus-response matrices obtained from three temporal processing deficit groups for three stimulus modified conditions, in three vowel contexts were analysed separately.

It can seen in Table 4.7 that irrespective of the temporal processing deficit group, stimuli condition and vowel context, information regarding manner of articulation was transmitted the highest followed by place and voicing. In the *mild temporal processing deficit group*, compared to the unprocessed stimuli, perception of manner improved in both spectro-temporally modified and stretched stimuli in all three vowel contexts. Among the three vowel contexts, the highest improvement in manner was obtained in the context of /a/ followed by /u/, while it was least in the context of /i/. Similar results were noted for the perception of place and voicing. However, most of these differences were not significant ($p > 0.05$), except in a few stimulus modified conditions and vowel contexts (Appendix B).

In both *moderate and severe temporal processing deficit groups*, stretching the stimuli resulted in improvement in perception of manner, place and voicing information in all three vowel contexts. In contrast, in these two severity groups, spectro-temporally modified stimuli resulted in deterioration in the perception of manner, place and voicing in all three vowel contexts. However, except for a few stimulus modified conditions and vowel contexts, the results were insignificant (p > 0.05) as shown in Appendix B.

Table 4.7

Information Transmitted in Bits for the Three Consonantal Features in Three Different Stimulus Modified Conditions and Vowel Contexts in Three Temporal Processing Deficit Groups

TMTF severity Groups	Features ↓ / Vowel contexts →	Stimuli conditions								
		Unprocessed			Spectro-temporally modified			Stretched		
		/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/
Mild	Manner	0.72	0.64	0.90	0.83	0.72	0.90	1.00	0.94	0.90
	Place	0.56	0.41	0.49	0.53	0.41	0.47	0.64	0.53	0.53
	Voicing	0.31	0.28	0.47	0.19	0.24	0.37	0.56	0.50	0.49
Moderate	Manner	0.71	0.53	0.72	0.56	0.46	0.51	0.80	0.81	0.76
	Place	0.33	0.25	0.26	0.28	0.19	0.26	0.41	0.30	0.36
	Voicing	0.24	0.24	0.24	0.16	0.16	0.16	0.27	0.28	0.34
Severe	Manner	0.44	0.40	0.54	0.36	0.33	0.38	0.68	0.68	0.59
	Place	0.22	0.27	0.27	0.21	0.16	0.23	0.32	0.28	0.32
	Voicing	0.19	0.16	0.20	0.17	0.10	0.15	0.21	0.20	0.21

Note. C = consonants; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/.

The statistical analysis of perception of phonetic features using Friedman test showed an overall significant difference between the *three consonantal features* (manner, place, voicing). Pair-wise comparison, done using Wilcoxon Signed Rank test (Table

4.8), revealed that perception of manner was significantly higher than place ($p < 0.05$). Similarly, place cues were transmitted significantly higher than voicing ($p < 0.05$). This significant difference was observed for all three stimulus modified conditions, and vowel contexts, in all the temporal processing deficit groups.

Table 4.8
Significance of Difference for Information Transmitted for the Three Consonantal Features in Three Different Stimulus Modified Conditions and Vowel Contexts in Three Temporal Processing Deficit Groups

Note. Downward (↓) arrow shows significant deterioration of the second feature over the first

TMTF severity Groups	Stimulus conditions	Vowel context	Manner vs. Place ↓		Manner vs. Voicing ↓		Place vs. Voicing ↓	
			z value	p value	z value	p value	z value	p value
Mild	Unprocessed	/a/	2.3	.01	2.5	.01	2.5	.01
		/i/	2.5	.01	2.5	.01	1.8	.05
		/u/	2.5	.01	2.5	.01	2.3	.01
	Spectro-temporally modified	/a/	2.5	.01	2.5	.01	2.5	.01
		/i/	2.5	.01	2.5	.01	2.2	.02
		/u/	2.3	.01	2.5	.01	2.2	.02
	Stretched	/a/	2.5	.01	2.5	.01	2.4	.01
		/i/	2.5	.01	2.5	.01	2.3	.01
		/u/	2.5	.01	2.5	.01	2.1	.03
Moderate	Unprocessed	/a/	3.4	.001	3.4	.001	3.3	.001
		/i/	3.3	.001	3.4	.001	3.5	.000
		/u/	3.4	.001	3.4	.001	3.2	.001
	Spectro-temporally modified	/a/	3.4	.001	3.4	.001	3.1	.002
		/i/	3.4	.001	3.4	.001	3.5	.000
		/u/	3.3	.001	3.4	.001	3.3	.001
	Stretched	/a/	3.4	.001	3.4	.001	3.4	.001
		/i/	3.4	.001	3.4	.001	3.4	.001
		/u/	3.3	.001	3.4	.001	3.3	.001
Severe	Unprocessed	/a/	2.4	.01	2.4	.01	2.2	.02
		/i/	2.2	.02	2.4	.01	2.2	.02
		/u/	2.3	.01	2.4	.01	2.4	.01
	Spectro-temporally modified	/a/	2.4	.01	2.4	.01	2.3	.01
		/i/	2.6	.008	2.5	.011	2.5	.011
		/u/	2.4	.01	2.4	.01	2.1	.03
	Stretched	/a/	2.4	.01	2.3	.01	2.4	.01
		/i/	2.4	.01	2.4	.01	2.4	.01
		/u/	2.3	.01	2.3	.01	2.4	.01

↓

In order to investigate the spectral differences between consonants in different vowel contexts, spectrographic analyses of VCV syllables were carried out. The change in frequencies in the second formant transitions of VCV syllables in the context of vowel

/i/ was greater than 200 Hz in a time interval of 25 to 30 ms. In the other two vowel contexts the second formant transition had a change less than 40 Hz in 30 ms. Hence the F2 transitions observed in the context of /i/ was considered to be steeper compared to that of vowel context /a/ and /u/ (Kumar & Jayaram, 2011). An example of a spectrographically analyzed stimuli is provided in Appendix C.

3. Effect of Amplification Conditions in Participants Grouped Based on their Severity of Temporal Processing Problem

The mean, median and standard deviation for the VCV syllables and word identification scores obtained for three amplification conditions (unaided, aided linear, & aided non-linear) and vowel contexts (/a/, /i/ & /u/) are given in Table 4.9. It can be noted from the table that the perception of VCV syllables and words deteriorated as the temporal processing ability became more severe. In all three temporal-processing-severity groups, consonant perception in the context of /a/ and /u/ led to similar but higher perception compared to consonants in the context of the vowel /i/. In the mild and severe temporal processing deficit groups, both the aided conditions resulted in slight improvement in speech identification scores in all three vowel contexts. In contrast, in the moderate group, speech perception in the aided conditions was poorer than their unaided performance in all three vowel contexts. A similar trend was observed for word identification scores. The responses obtained from the participants were subjected to further statistical analyses to see if there existed a significant difference between the severity groups within and between vowel contexts.

Table 4.9.

Mean, Median, and SD of Speech Identification Scores for PB Words and VCV Syllables in Three Different Amplification Conditions (Unaided, Aided linear, Aided non-linear) in the Three Temporal Processing Severity Groups

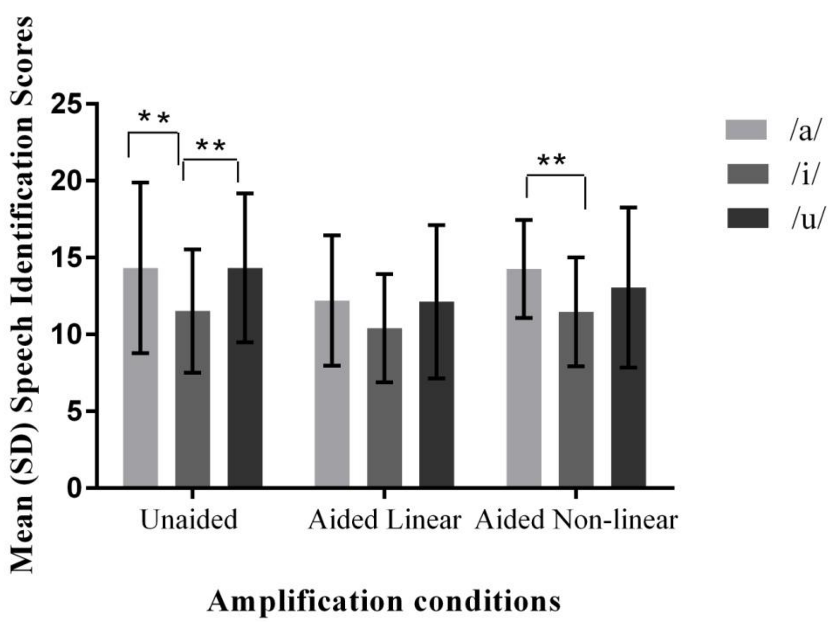
	Amplification Conditions									
		Unaided scores			Aided scores with linear hearing aids			Aided scores with non-linear hearing aids		
TMTF groups	VCV syllables / PB words	Mean #	Median	SD	Mean #	Median	SD	Mean #	Median	SD
Mild	/aCa/	15.87	16.5	4.58	19.25	19.0	2.60	18.37	18.0	3.29
	/iCi/	14.25	15.5	4.49	16.62	16.0	2.38	16.62	16.0	3.02
	/uCu/	14.62	13.0	4.77	18.00	17.5	4.24	18.25	16.5	4.20
	PB words	14.12	14.00	7.05	15.87	15.5	4.58	15.87	16.00	4.45
Moderate	/aCa/	13.93	13.0	5.48	12.20	12.0	4.24	14.26	15.0	3.19
	/iCi/	11.23	10.0	3.91	10.40	10.0	3.52	11.46	12.0	3.54
	/uCu/	13.86	14.0	4.43	12.13	13.0	4.99	13.06	12.0	5.21
	PB words	9.80	9.00	4.14	9.80	8.00	5.39	9.53	7.00	4.96
Severe	/aCa/	6.28	6.0	6.77	8.71	8.0	3.61	8.2	8.0	2.42
	/iCi/	5.71	9.0	5.41	8.42	9.0	2.29	8.42	8.0	2.76
	/uCu/	5.00	6.0	5.19	9.14	9.0	1.21	8.71	8.0	1.38
	PB words	2.57	2.00	3.59	4.57	4.00	2.22	4.57	4.00	0.97

Note. #Maximum possible score for VCV syllables = 30; Maximum possible score for PB words = 25; VCV = Vowel-Consonant-Vowel; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, /t̪/, /d̪/, /l/, /r/.

3.1. Comparison across amplification conditions, and vowel context within a temporal processing severity group. The comparison across amplification conditions (unaided, aided linear, & aided non-linear) was done, within those having mild, moderate and severe temporal processing problems. This was done using VCV syllables within each of the three vowel contexts as well as between the three vowel contexts. In addition, word identification scores were also compared within each temporal processing deficit group. In order to investigate the combined effect of three amplification conditions, Friedman test was carried out in each vowel context separately. Further, Wilcoxon Signed Ranks test was performed to obtain the significant difference between pairs of amplification conditions, if a significant effect was seen using Friedman test. Using similar statistical procedures, comparison across vowel contexts (/a/, /i/, & /u/) were carried out within each amplification condition, as well as for comparing phonetic features transmitted (manner, place, &voicing) in each amplification condition, for each of the vowel contexts. These were carried out separately for each temporal processing deficit group.

3.1.1. Comparison across and within amplification conditions in individuals having mild temporal processing deficit. In the group with mild temporal processing deficit, *comparison across amplification conditions* using Friedman test revealed no significant difference between amplification conditions for VCVs in the context of */a/* [χ^2 (2) = 4.07, $p > 0.05$], */i/* [χ^2 (2) = 3.92, $p > 0.05$] and */u/* [χ^2 (2) = 4.03, $p > 0.05$]. Similarly, the scores obtained across amplification condition did not vary significantly for *word identification* [χ^2 (2) = 1.18, $p > 0.05$]. In addition, *comparison across vowels within an amplification condition*, using Friedman test, indicated that there was no significant difference across vowel contexts in the *unaided* [χ^2 (2) = 5.40, $p > 0.05$], *aided linear* [χ^2 (2) = 4.00, $p > 0.05$] and *aided non-linear* [χ^2 (2) = 3.2, $p > 0.05$] amplification conditions.

3.1.2. Comparison across and within amplification conditions in individuals having moderate temporal processing deficit. Among those with moderate temporal processing defect, as per the findings of a Friedman test, *perception across amplification conditions* did not lead to a significant difference in perception of VCV stimuli, in the context of */a/* [χ^2 (2) = 4.44, p > 0.05], */i/* [χ^2 (2) = 2.34, p > 0.05] and */u/* [χ^2 (2) = 2.71, p > 0.05]. Likewise, the scores were not significantly difference across amplification conditions for *word identification* (χ^2 (2) = .50, p > 0.05). *Comparison across vowel context within an amplification condition* revealed significant differences in the *unaided* [χ^2 (2) = 11.14, p < 0.05] and *aided non-linear* condition [χ^2 (2) = 6.03, p < 0.05]. However, in the *aided linear* condition there was no significant difference across the three vowels [χ^2 (2) = 5.44, p > 0.05]. Further, Wilcoxon Signed Ranks test indicated that in the unaided condition, significantly higher consonant perception occurred in the environment of /a/ as well as /u/ when compared to /i/. On the other hand, no significant difference was found between /a/ and /u/ in the unaided condition. In the aided non-linear condition, though the perception in the context of the vowel /a/ was significantly higher than in the context of /i/, no significant difference was found between /a/ and /u/ as well as / i/ and /u/. This can be seen in the in Figure 4.10 and Table 4.10.



Note. Maximum possible score = 30; ** = p < 0.01

Figure 4.10. Mean speech identification scores and 1 SD in different amplification conditions for different vowel context in those with moderate temporal processing deficit.

Table 4.10

Pair-wise Comparison of Vowel Contexts and Levels of Significance in Different Amplification Conditions in the Moderate Temporal Processing Deficit Group

		Vowel context pairs					
		/aCa/ vs /iCi/		/aCa/ vs /uCu/		/iCi/ vs /uCu/	
TMTF group	Amplification conditions	|z|	p value	|z|	p value	|z|	p value
Moderate	Unaided	2.67	.007**↓	0.071	0.944	3.07	0.002**↑
	Aided non-linear	2.87	0.004**↓	1.16	0.246	1.37	0.169

Note. ** = $p < 0.01$; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/. Downward arrow (↓) shows significant deterioration. Upward arrow (↑) shows significant improvement in the second vowel context over the first.

3.1.3. Comparison across and within amplification conditions in individuals having severe temporal processing deficit. Friedman, used to compare *across amplification conditions*, showed no significant difference in vowel context */a/* [χ^2 (2) = 1.04, p > 0.05], */i/* [χ^2 (2) = 0.609, p > 0.05] and */u/* [χ^2 (2) = 5.20, p > 0.05]. Similarly, the *scores* across amplification condition did not vary significantly for *word identification* [χ^2 (2) = 5.55, p > 0.05]. Likewise, there was no significant difference observed across *vowel contexts within the amplification condition*s of the *unaided* [χ^2 (2) = 1.85, p > 0.05], *aided linear* [χ^2 (2) = .560, p > 0.05] and *aided non-linear* [χ^2 (2) = .560, p > 0.05] conditions.

It was found that there was no significant difference in consonant perception across the three amplification conditions and three temporal processing deficit groups. Further, stimuli in each amplification conditions were analysed to check for any change in temporal envelope. The Envelope Difference index (EDI) was calculated using a procedure given by Fortune, Woodruff, and Preves (1994). This was done to obtain a precise quantification of the temporal envelope contrast that exists between two waveforms. In comparison with the EDI range of values given by Fortune et al. (0 representing perfect correspondence between the envelopes, & 1 representing no correspondence between the envelopes), a value of 0.03 was obtained between the two aided conditions (linear & non-linear) used in the current study. This indicated that the envelope was preserved in the linear and non-linear amplification conditions. The temporal envelope of a sample stimulus in two amplification conditions is provided in Appendix D. It can be observed that the linear and non-linear amplification conditions did not alter the temporal envelope of the stimuli to a greater extend.

3.2. Comparison of amplification conditions across temporal processing severity groups. Kruskal-Wallis test was performed to assess the significance of difference in amplification conditions (unaided, aided linear, & aided non-linear stimuli) across the three temporal processing deficits groups (mild, moderate, & severe). This was done for the VCV syllables in three vowel contexts as well as word identification scores. There was a significant difference between the temporal processing deficits groups in all three vowel environments (/a/, /i/, /u/) within each of the three conditions (Table 4.11). Similarly, the word identification scores in the unaided condition [$H(2) = 12.75$, $p < 0.05$], aided linear condition [$H(2) = 13.15$, $p < 0.05$], and aided non-linear condition [$H(2) = 16.60$, $p < 0.05$] varied significantly between the temporal processing severity groups.

Table 4.11

Significance of Difference between Temporal Processing Severity Groups for each Amplification Condition and Vowel Context, with the Three Groups Combined

	Amplification conditions								
	Unaided			Aided linear			Aided non-linear		
	Vowel contexts								
	/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/
H	10.14	15.24	12.57	14.95	14.46	11.21	17.01	14.01	12.80
Df	2	2	2	2	2	2	2	2	2
p value	0.006**	0.000***	.002**	.001**	.001**	.004**	.000***	.001**	.002**

Note. ** = $p < 0.01$; *** = $p < 0.001$; C =Consonants; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/.

Further, Mann-Whitney test was performed to obtain a pair-wise comparison of the temporal processing deficit groups for VCVs and word identification. It can be observed from Table 4.12 that for VCVs *in the unaided condition*, the mild group had significantly higher speech perception scores than the moderate group in the context of vowel /i/. In the contrary, no such difference between these participant groups was noted in the context of /a/ and /u/. In *both the aided conditions* and in all three vowel contexts, the mild group had significantly higher VCV perception scores than the moderate group. A comparison between the mild and severe groups highlighted the presence of significantly higher VCV perception in the former group in all three stimulus modified conditions and vowel contexts. Among those with moderate and severe deficits, in the unaided condition, significantly higher scores were obtained in those with lesser severity (moderate group) in all three vowel contexts. However, no significant difference was found between these two groups in the aided linear condition. In the aided non-linear condition, in the context of vowel context /a/ and /u/, the moderate group had significantly higher speech perception than the severe group. On the other hand, no significant difference was found between the two groups in the context of the vowel /i/.

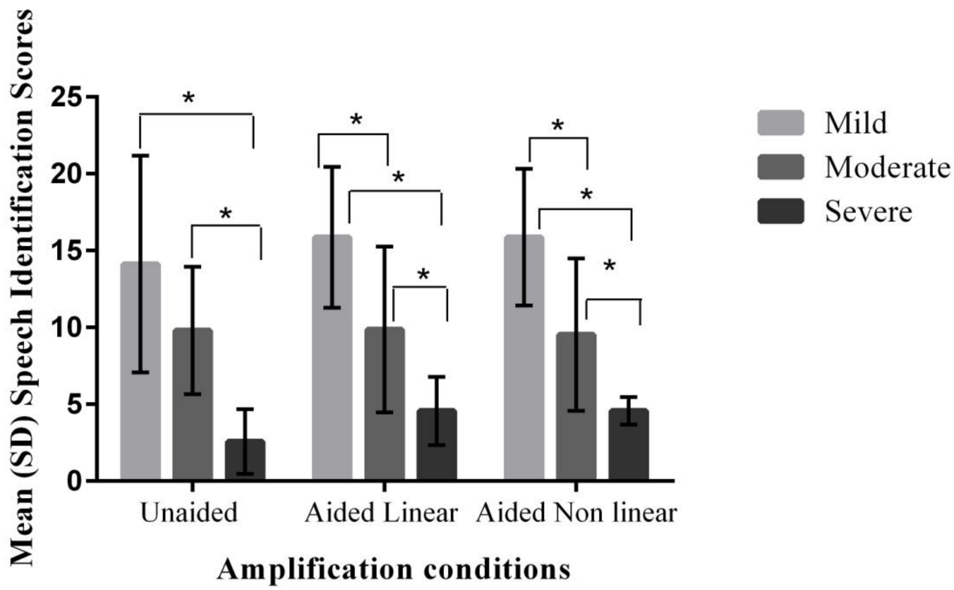
Table 4.12

Pair-wise Comparison between Temporal Processing Deficit Groups and the Level of Significance, in Different Amplification Conditions

Amplification conditions	VCV syllables/PB words	Temporal processing severity groups					
		Mild vs Moderate		Mild vs Severe		Moderate vs Severe	
		U	p value	U	p value	U	p value
Unaided	/aCa/	33	.080	3.5	.004** ↓	21	.026* ↓
	/iCi/	15.5	.004** ↓	0	.001*** ↓	21	.026* ↓
	/uCu/	45	.326 ↓	1.5	.002** ↓	9.5	.002** ↓
	PB words	39.00	0.174 ↓	2.5	0.003** ↓	9	0.002** ↓
Aided linear	/aCa/	11.5	.002** ↓	1	.002*** ↓	26	.061
	/iCi/	10.5	.001*** ↓	0	.001*** ↓	35.5	.227
	/uCu/	24	.019** ↓	0	.001*** ↓	32.5	.155
	PB words	25.5	0.025* ↓	0	0.001*** ↓	20	0.001*** ↓
Aided non-linear	/aCa/	20.5	.010** ↓	0	.001*** ↓	8.5	.002** ↓
	/iCi/	16	.004** ↓	0.5	.001*** ↓	26	.059
	/uCu/	27	.033* ↓	0	.001*** ↓	20	.022* ↓
	PB words	22	0.014* ↓	0	0.001*** ↓	9.50	0.002** ↓

Note. * = p < 0.05; ** = p < 0.01; *** = p < 0.001; VCV = Vowel-Consonant-Vowel; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/; Downward arrow (↓) shows significant deterioration of the second group over the first.

A pair-wise comparison of the word identification scores obtained by the three temporal processing severity groups using Mann-Whitney test are provided in Table 4.12. Comparison between the mild and moderate groups showed that in the *unaided condition*, there was no significant difference between the two groups. However, in the *aided linear* and *aided non-linear* conditions, the mild group obtained significantly higher perception scores. Among the mild and severe groups as well as moderate and severe groups, significantly lower perception scores were obtained by the severe group, in all three amplification conditions (Figure 4.11).



Note. Maximum possible score = 25
Figure 4.11. Mean word identification scores and 1 SD in different amplification conditions in the three temporal processing deficit groups.

The aided benefit across temporal processing severity groups was estimated by calculating the difference between the aided and unaided scores. This was done separately for the aided linear and aided non-linear for the VCV syllables identification as well as word identification scores. Kruskal-Wallis test was performed to assess the significance of difference in aided benefit across the three temporal processing deficits groups. The results showed no significant difference in VCV identification, across these groups for linear amplification in the context of /a/ [H (2) = 5.8, p > 0.05], and /i/ [H (2)

= 5.3, $p > 0.05$]. Likewise, no significant difference was noted with non-linear amplification in the context of /a/ [H (2) = .995, $p > 0.05$], and /i/ [H (2) = 2.5, $p > 0.05$]. However, in the context of /u/ there was a significant difference found across groups using linear [H (2) = 11.7, $p < 0.05$] and non-linear amplification [H (2) = 7.7, $p < 0.05$]. Further, Mann-Whitney test in the context of /u/ showed significant differences between the mild and moderate groups, mild and severe groups as well as the moderate and severe groups ($p < 0.05$) for both linear and non-linear amplification. Similarly, no significant difference across the temporal processing deficits groups for the aided benefit obtained using linear [H (2) = 3.4, $p > 0.05$], as well as non-linear [H (2) = 4.2, $p > 0.05$], amplification using PB words.

3.3. Comparison of information transfer in three temporal processing severity groups for three amplification conditions and vowel contexts. The amount of information transmitted for the phonetic features (manner, place, & voicing) were calculated using sequential information analyses. This was calculated separately for the three temporal processing deficit groups for three amplification conditions each in three vowel contexts.

In the *mild temporal processing deficit group*, compared to the unaided condition both aided linear and aided non-linear conditions resulted in improvement in transfer of manner place and voicing information in all three vowel contexts (Table 4.13). The vowel context /i/ resulted in the lowest manner and place transfer compared to /a/ and /u/. In contrast, the *moderate and severe temporal processing deficit groups*, transfer of manner, place and voicing deteriorated in both the aided conditions, in all three vowel contexts. However, these were not significant ($p > 0.05$) for majority of the amplification conditions and vowel context (Appendix E)

Table 4.13

Information Transmitted in Bits for the Three Consonantal Features in Three Different Amplification Condition and Vowel Contexts in Three Temporal Processing Deficit Groups

TMTF severity Groups	*Features* ↓ / *VCV syllables* →	*Amplification conditions*								
		Unaided			*Aided Linear*			*Aided-Non-linear*		
		/aCa/	*/iCi/*	*/uCu/*	*/aCa/*	*/iCi/*	*/uCu/*	*/aCa/*	*/iCi/*	*/uCu/*
Mild	*Manner*	0.70	0.70	0.78	0.80	0.74	0.78	0.80	0.74	0.78
	Place	0.46	0.44	0.41	0.49	0.45	0.44	0.53	0.44	0.42
	Voicing	0.32	0.23	0.32	0.34	0.24	0.32	0.33	0.26	0.33
Moderate	*Manner*	0.49	0.43	0.66	0.45	0.41	0.55	0.48	0.41	0.51
	Place	0.27	0.21	0.28	0.23	0.16	0.21	0.25	0.18	0.20
	Voicing	0.25	0.16	0.26	0.17	0.14	0.17	0.22	0.16	0.17
Severe	*Manner*	0.44	0.41	0.44	0.41	0.38	0.37	0.45	0.41	0.33
	Place	0.19	0.17	0.20	0.17	0.15	0.20	0.16	0.17	0.20
	Voicing	0.14	0.15	0.16	0.14	0.15	0.14	0.13	0.10	0.10

Note. VCV = Vowel-Consonant-Vowel; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/.

The results of Friedman test showed a significant overall difference between the three *consonantal features transmitted* (manner, place and voicing). Further, Wilcoxon Signed Rank test (Table 4.14) revealed a significant difference between manner and place, manner and voicing as well as place and voicing in all three amplification conditions for each vowel context. This was observed in all three temporal processing deficit groups.

Table 4.14.

Significance of Difference for Information Transmitted for the Three Consonantal Features in Three Different Amplification Conditions and Vowel Contexts in Three Temporal Processing Deficit Groups.

TMTF severity groups	Amplification conditions	Vowel context	Manner vs. Place ↓		Manner vs. Voicing ↓		Place vs. Voicing ↓	
			Z value	p value	Z value	p value	Z value	p value
Mild	Unaided	/a/	2.1	.03	2.5	.01	2.3	.01
		/i/	2.3	.01	2.5	.01	2.2	.02
		/u/	2.4	.01	2.5	.01	2.5	.01
	Aided linear	/a/	2.5	.01	2.5	.01	2.5	.01
		/i/	2.3	.01	2.5	.01	2.0	.03
		/u/	2.5	.01	2.5	.01	2.5	.01
	Aided non-linear	/a/	2.5	.01	2.5	.01	2.2	.02
		/i/	2.5	.01	2.5	.01	2.5	.01
		/u/	2.2	.02	2.5	.01	2.5	.01
Moderate	Unaided	/a/	3.4	.001	3.4	.001	3.2	.001
		/i/	3.3	.001	3.4	.001	2.9	.004
		/u/	3.4	.001	3.4	.001	3.2	.001
	Aided linear	/a/	3.3	.001	3.4	.001	2.9	.003
		/i/	3.4	.001	3.4	.001	3.3	.001
		/u/	3.5	.000	3.4	.001	3.3	.001
	Aided non-linear	/a/	3.3	.001	3.4	.001	3.3	.001
		/i/	3.4	.001	3.4	.001	3.4	.001
		/u/	3.3	.001	3.4	.001	3.3	.001
Severe	Unaided	/a/	2.4	.01	2.3	.01	2.2	.02
		/i/	2.3	.02	2.4	.01	2.1	.03
		/u/	2.3	.01	2.4	.01	2.2	.02
	Aided linear	/a/	2.2	.02	2.3	.01	2.3	.01
		/i/	2.6	.008	2.5	.01	2.5	.011
		/u/	2.4	.01	2.4	.01	2.2	.02
	Aided non-linear	/a/	2.3	.01	2.3	.01	2.4	.01
		/i/	2.4	.01	2.3	.01	2.4	.01
		/u/	2.4	.01	2.3	.01	2.2	.02

Note. Downward arrow (↓) shows significant deterioration of the second feature over the first

4. Effect of Types of Amplification (linear & non-linear) on Speech Identification in Participants Grouped Based on the PI-PB Function Responses

The mean, median and standard deviation of the SIS obtained using VCV syllables and PB-words in the two PI-PB function groups are given in Table 4.15. The scores were obtained in three amplification conditions (unaided, aided linear, & aided non-linear). For the VCVs, it can be noted that both rising and rollover groups performed similarly in the unaided condition. On the other hand, in both the aided conditions, the rising group outperformed the rollover group. In the rising group, the scores in both the aided conditions were better than the unaided condition for all three vowel contexts. In contrast, in the rollover group, VCV perception in the aided conditions was poorer than their unaided performance. It can be seen that higher but similar perception was obtained in the context of vowel /a/ and /u/ whereas in the context of /i/ poorer perception was attained.

Table 4.15
Mean, Median, and SD of Speech Identification Scores for VCV syllables and PB Words in the Amplification Conditions in the two PI-PB Function Groups

	Amplification conditions									
		Unaided			Aided linear			Aided non-linear		
PI-PB function group	VCV syllables/PB words	Mean#	Median	SD	Mean#	Median	SD	Mean#	Median	SD
Rising	/aCa/	12.4	11	4.5	19	19	3.6	17.4	16	1.9
	/iCi/	11.2	10	4.3	15.8	16	3.6	16	16	2.9
	/uCu/	12.6	11	4.8	17	15	4.3	17.4	17	3.2
	PB words	10	11.8	6.9	17	17.4	4.0	16	17.4	4.8
Rollover	/aCa/	12.7	12	6.9	12.1	12	4.9	13.2	13	4.7
	/iCi/	10.6	10	5.5	10.76	10	3.9	11.3	11	4.2
	/uCu/	11.8	12	6.3	12.2	10	5.1	12.6	11	5.4
	PB words	8	8.7	6.2	8	8.8	5.3	7	8.6	4.8

Note. #Maximum possible score for VCV syllables = 30; Maximum possible score for PB words = 25; VCV = Vowel-Consonant-Vowel; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/.

The word identification scores in the unaided and two aided conditions were also found to differ in the two PI-PB function groups (Table 4.15). In the rising group, both the aided conditions resulted in higher speech identification score than the unaided. In contrast, there no such trend found in the rollover group.

4.1. Comparison across amplification conditions and vowel context within a PI-PB function severity group. Non-parametric Friedman test was carried out to investigate the combined effect of amplification conditions (unaided, aided linear, & aided non-linear) for each vowel context. This was done separately for each PI-PB function group. Similarly, word identification scores were compared across the amplification conditions. If a significant difference was observed in the Friedman test, Wilcoxon signed rank test was done to obtain the significance of difference between pairs of amplification conditions. Similar statistical procedures were used to compare performance across vowel context in each amplification condition and also to compare the consonantal feature transmitted.

4.1.1. Comparison across amplification conditions

In the *rising PI-PB function group*, Friedman test indicated that for the VCV stimuli there was a significant difference between the amplification conditions in the context of */a/* [$\chi^2 = 7.41$, df = 2, $p < 0.05$] and */u/* [$\chi^2 = 7.89$, df = 2, $p < 0.05$]. Unlike what was observed in the context of /a/ and /u/, in the context of */i/* there was no significant difference between the amplification conditions [$\chi^2 (2) = 4.11$, $p > 0.05$]. Further analysis of perception in the two vowel contexts /a/ and /u/ using Wilcoxon signed rank test showed significantly higher perception in both the aided conditions than the unaided condition. However, between the two aided conditions there was no significant difference (Table 4.16).

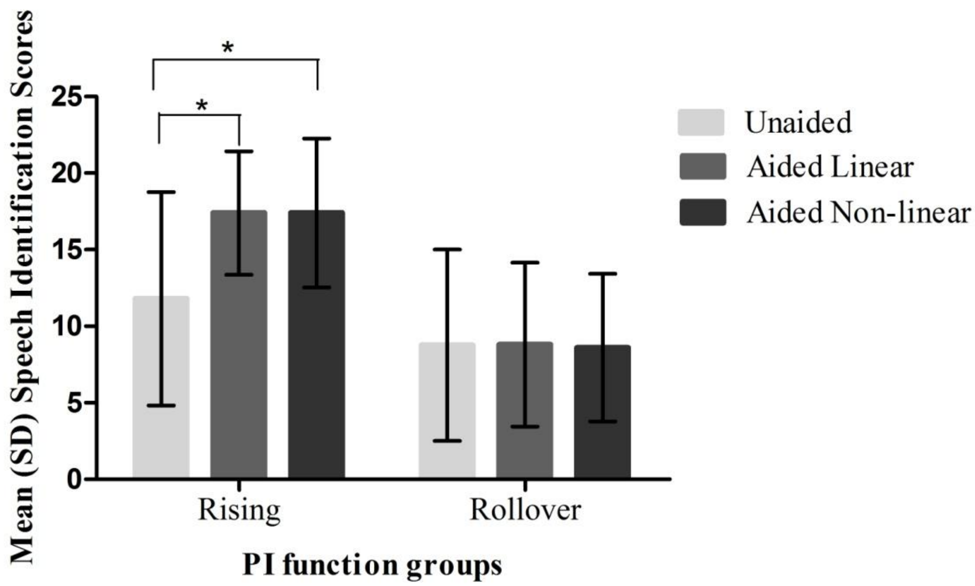
The word identification scores in the *rising* group, analysed using Friedman test, varied significantly across the three amplification conditions ($\chi^2 = 7.89$, df = 2, $p < 0.05$). Pair-wise comparison using Wilcoxon signed rank test (Figure 4.12) revealed that both aided linear ($|z| = 2.03$, $p < 0.05$) and aided non-linear conditions ($|z| = 2.03$, $p < 0.05$) were significantly higher than the unaided condition. However, no significant difference was noted between the two aided conditions ($|z| = 0.00$, $p > 0.05$).

Table 4.16
Pair-wise comparison of amplification conditions in different vowel contexts and the levels of significance

		Amplification condition pairs					
		Unaided vs Aided linear		Unaided vs Aided-non-linear		Aided linear vs Aided non- linear	
PI function group	Vowel context	|z|	p value	|z|	p value	|z|	p value
Rising	/aCa/	2.02	0.043* ↑	1.99	0.044* ↑	1.06	0.285
	/uCu/	2.02	0.042* ↑	2.03	0.042* ↑	0.552	0.581

Note. * = $p < 0.05$; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/. Upward arrow (↑) shows significant improvement in the second vowel context over the first.

Comparison across amplification conditions in the *rollover PI-PB function group*, showed no significant difference in the context of */a/* [$\chi2$ =1.42, df = 2, $p > 0.05$], */i/* [$\chi2$ =0.756, df = 2, $p > 0.05$] and */u/* [$\chi2$ =1.12, df = 2, $p > 0.05$]. Similarly, the word identification scores did not vary significantly across amplification conditions ($\chi2$ = 0.207, df = 2, $p > 0.05$).



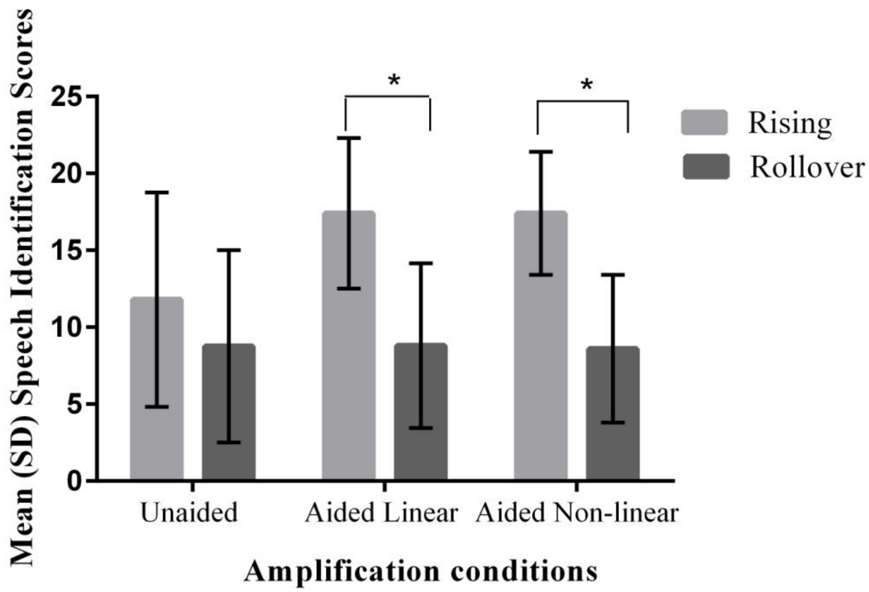
Note. Maximum possible score = 25
Figure 4.12. Mean word identification scores and 1 SD in the rising and rollover groups in different amplification conditions.

4.1.2. Comparison across vowel contexts

In the *rising group*, comparison across vowel context using Friedman test showed no significant difference between vowels in the unaided (χ^2 = 1.44, df = 2, $p > 0.05$), aided linear (χ^2 = 2.80, df = 2, $p > 0.05$) and aided non-linear (χ^2 = 3.44, df = 2, $p > 0.05$) conditions. In contrast, in the *rollover group* there was a significant difference between vowels in the unaided (χ^2 = 10.96, df = 2, $p < 0.05$) and aided linear (χ^2 = 6.08, df = 2, $p < 0.05$) conditions. Such a significant difference between vowels was not observed in the aided non-linear condition (χ^2 = 3.97, df = 2, $p > 0.05$). Comparison of vowel pairs in the unaided condition using Wilcoxon signed rank test revealed a significantly higher perception in the context of /a/ compared to /i/ ($|z|$ = 2.98, $p < 0.0167$). However, there was no significant difference between /a/ and /u/ context ($|z|$ = 1.40, $p > 0.05$) as well as

/i/ and /u/ (|z| = 1.96, $p > 0.167$). In the aided linear condition there was significantly higher perception in the context /u/ than /i/ (|z| = 2.52, $p < 0.0167$). No such significant difference was observed between /a/ and /u/ (|z| = 0.01, $p > 0.05$) as well as /a/ and /i/ (|z| = 2.27, $p > 0.0167$).

4.2. Comparison of amplification conditions between PI-PB function groups. Mann-Whitney test was performed to compare the rising and rollover PI-PB function groups in each amplification condition. For VCV stimuli, it was found that in the *unaided condition* there was no significant difference between the two groups in the vowel context of */a/* (U = 55.5, $p > 0.05$) */i/* (U = 61, $p > 0.05$) and */u/* (U = 57, $p > 0.05$). Similarly, the word identification score also did not vary significantly (U = 47, $p > 0.05$). In the *aided linear condition*, the rising group had significantly higher perception than the rollover group in the context of */a/* (U = 17, $p < 0.05$) and */i/* (U = 20.5, $p < 0.05$). In contrast, no such difference noted in the context of */u/* (U = 29.5, $p > 0.05$). In the *aided non-linear condition*, the rising group got significantly higher perception than the rollover group in all three vowel contexts *[/a/* : (U = 25.5, $p < 0.05$), */i/* : (U = 21.5, $p < 0.05$), & */u/* : (U = 23.5, $p < 0.05$)]. The word identification score was found to be significantly higher in the rising group than what was observed in the rollover group in both *aided linear* (U = 14.5, $p < 0.05$) and *aided non-linear conditions* (U = 14.0, $p < 0.05$), as can be seen in Figure 4.13.



Note. Maximum possible score = 25
Figure 4.13. Mean word identification scores and 1 SD in different amplification conditions in the rising and rollover groups.

The aided benefit (aided SIS minus unaided SIS) between the PI-PB function groups was compared using Mann-Whitney test for VCV syllables as well as words. The results showed significantly higher aided benefit in the rising group compared to the rollover group using VCV syllables in the context of /a/ ($U = 12.0$, $p < 0.05$), /i/ ($U = 26.5$, $p < 0.05$) and /u/ ($U = 26.5$, $p < 0.05$) for linear amplification. The aided benefit obtained in the non-linear condition was significantly higher in the rising group for the VCVs in the context of /a/ ($U = 26.0$, $p < 0.05$) and /i/ ($U = 24.5$, $p < 0.05$). However, in the context of /u/ there was no significant difference between rising and rollover groups ($U = 29.5$, $p > 0.05$). Using PB words, the rising group had significantly higher aided benefit than the rollover group for both linear ($U = 11.0$, $p < 0.05$) and non-linear amplification ($U = 8.0$, $p < 0.05$).

4.3. Comparison of information transfer in two PI-PB function groups for three amplification conditions and vowel contexts.

Sequential information analysis was carried out to determine the amount of information transmitted for the consonantal features. In the *rising PI-PB function group*, compared to the unaided condition, transfer of manner and voicing deteriorated in both the aided conditions in all three vowel contexts (Table 4.17). On the other hand, perception of place improved in both the aided conditions in the context of /a/ and /i/, and did not improve only in the context of /u/. However, these were not statistically significant ($p > 0.05$) as found in Appendix F. In the *rollover PI-PB function group,* perception of manner improved in both the aided conditions in the context of /a/ and /i/ but deteriorated in the context of /u/. However, thought not significant ($p > 0.05$), perception of place and voicing deteriorated in both the aided conditions in all three vowel contexts.

Table. 4.17

Information Transmitted in Bits for the Three Consonantal Features in Three Different Aided Conditions in Rising PI Function Group

Groups	Features / VCV syllables	Amplification conditions								
		Unaided			Aided Linear			Aided Non-linear		
		/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/
Rising	Manner	0.76	0.64	0.7	0.71	0.57	0.78	0.65	0.57	0.76
	Place	0.42	0.38	0.4	0.52	0.53	0.40	0.45	0.39	0.40
	Voicing	0.36	0.37	0.4	0.27	0.19	0.25	0.37	0.31	0.31
Rollover	Manner	0.49	0.43	0.5	0.51	0.45	0.53	0.52	0.46	0.51
	Place	0.28	0.18	0.2	0.19	0.17	0.17	0.25	0.16	0.20
	Voicing	0.21	0.17	0.1	0.18	0.14	0.16	0.20	0.14	0.18

*Note***.** VCV = Vowel-Consonant-Vowel; Consonants used were /p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪/, /l/, /r/.

Friedman test, done to determine if there existed a significant difference in the consonantal feature perception in each of the PI-PB function groups, indicated the presence of a significant difference between three consonantal features transmitted (manner, place, and voicing), in the rollover PI-PB group and for the rising PI-PB groups. The Wilcoxon Signed Rank test (Table 4.18) for the rollover group revealed that perception of manner was significantly better than place and voicing. Similarly, the perception of place was significantly better than voicing. This was found in all three amplification conditions and vowel contexts in the rollover group. In the rising group, manner perception was significantly higher than voicing perception in all three amplification conditions. However, the difference between manner and place as well as place and voicing did not reach significance in all three amplification conditions.

Table 4.18

Significance of Difference for Information Transmitted for the Three Consonantal Features in Three Different Amplification Conditions and Vowel Contexts in two PI-PB Function Groups

PI-PB Group		Vowel context	Manner vs. Place ↓		Manner vs. Voicing ↓		Place vs. Voicing ↓	
			Z value	p value	Z value	p value	Z value	p value
Rising	Unaided	/a/	2.0	.04	2.0	.04	1.6	.10
		/i/	1.8	.06	2.0	.04	1.6	.10
		/u/	2.1	.03	2.0	.04	2.0	.04
	Aided linear	/a/	1.8	.06	2.0	.04	2.0	.04
		/i/	2.0	.03	2.0	.03	1.8	.06
		/u/	2.0	.04	2.0	.04	2.0	.04
	Aided non-linear	/a/	2.0	.04	2.0	.04	2.0	.03
		/i/	2.0	.04	2.0	.04	2.0	.04
		/u/	1.8	.06	2.0	.04	2.0	.04
Rollover	Unaided	/a/	4.1	.000	4.3	.000	4.1	.000
		/i/	4.2	.000	4.4	.000	3.7	.000
		/u/	4.3	.000	4.4	.000	4.1	.000
	Aided linear	/a/	4.2	.000	4.3	.000	4.0	.000
		/i/	4.3	.000	4.4	.000	4.2	.000
		/u/	4.4	.000	4.4	.000	4.1	.000
	Aided non-linear	/a/	4.3	.000	4.3	.000	4.2	.000
		/i/	4.3	.000	4.3	.000	4.5	.000
		/u/	4.3	.000	4.3	.000	4.2	.000

Note. (↓) downward arrow shows significant deterioration of the second feature over the first

5. Relation between PI-PB function / PI-PB rollover index/ TMTF threshold with Scores in Different Amplification Conditions

The correlation of word identification scores obtained in three different amplification conditions (unaided, aided linear, & aided non-linear) with three tests findings [PI-PB function, PI-PB rollover index (PB_{max}-PB_{min}/PB_{max}), & TMTF threshold] was analysed using Spearman's rank correlation. The correlation was checked independently between each amplification condition and test finding (Table 4.19). The relations were checked only with word scores since prior analyses indicate that both words and CVC stimuli yielded similar results. The similarity in performance using either stimuli (VCV syllables or PB words) was noted in the three temporal processing deficit group (mild, moderate, & severe) as well as two PI-PB function groups (rising & rollover), as shown in Tables 4.12 and 4.16.

For all parameters checked, a significant correlation was obtained, however the strength of correlation varied. The word identification scores obtained at each intensity level of the *PI-PB function* were correlated with the scores obtained for each of the three amplification conditions (unaided, aided linear, & aided non-linear). It can be observed from Table 4.19 that speech identification scores obtained in the unaided condition and PI-PB function obtained at 40 dB HL, 50 dB HL and 60 dB showed the highest correlation. However, at lower (30 dB HL) and higher presentation levels (70 dB HL and above) a moderate correlation was found. In both the aided conditions, the word identification score had only a moderate correlation with scores obtained in the lowest presentation levels of the PI-PB function (30 dB HL). In contrast, at higher PI-PB function levels (40 dB HL & above) a stronger correlation was found.

There was a weak correlation between word identification in the unaided condition and *PI-PB rollover index*. However, a moderate negative correlation occurred between PI-PB rollover index and SIS in the two aided conditions. Unlike what was obtained with the PI-PB rollover index, the correlation between *TMTF peak thresholds* and the word identification scores in the three amplification conditions (unaided, aided linear, & aided non-linear) was found to be strong. However, it was stronger in the two aided conditions compared to the unaided condition.

Table 4.19

Relation between SIS Obtained at Each Intensity Level in the PI-PB function, Rollover Index, as well as TMTF Peak Threshold with the SIS Obtained in Three Amplification Conditions

		Amplification conditions		
	Intensity	Unaided	Aided linear	Aided non-linear
		Correlation coefficient 'r'		
Performance intensity function levels	30 dB HL	0.51**	0.46**	0.51**
	40 dB HL	0.90**	0.73**	0.67**
	50 dB HL	0.99**	0.82**	0.79**
	60 dB HL	0.86**	0.89**	0.92**
	70 dB HL	0.70**	0.82**	0.90**
	80 dB HL	0.70**	0.88**	0.87**
	90 dB HL	0.66**	0.86**	0.85**
Rollover index	-	-0.39*	-0.68**	-0.63**
TMTF peak threshold	-	-0.71**	-0.81**	-0.86**

Note. * = $p < 0.05$ ** = $p < 0.01$

6. Comparison of Peak Modulation Detection Thresholds of the Normal Hearing Individuals and those with ANSD, Grouped Based on Their Temporal Processing Ability.

Temporal modulation transfer functions obtained for the normal hearing participants and the individuals with ANSD are compared. Figure 4.14 depicts the mean TMTF threshold along with the standard deviation at different modulation frequencies in two participant groups. All the normal listeners could detect the modulation even at the highest modulation frequency. However, the number of participants with ANSD who could detect modulations decreased as the frequency increased beyond 8 Hz. At 256 Hz, none of those with ANSD could detect even the maximum amount of modulation (100%).

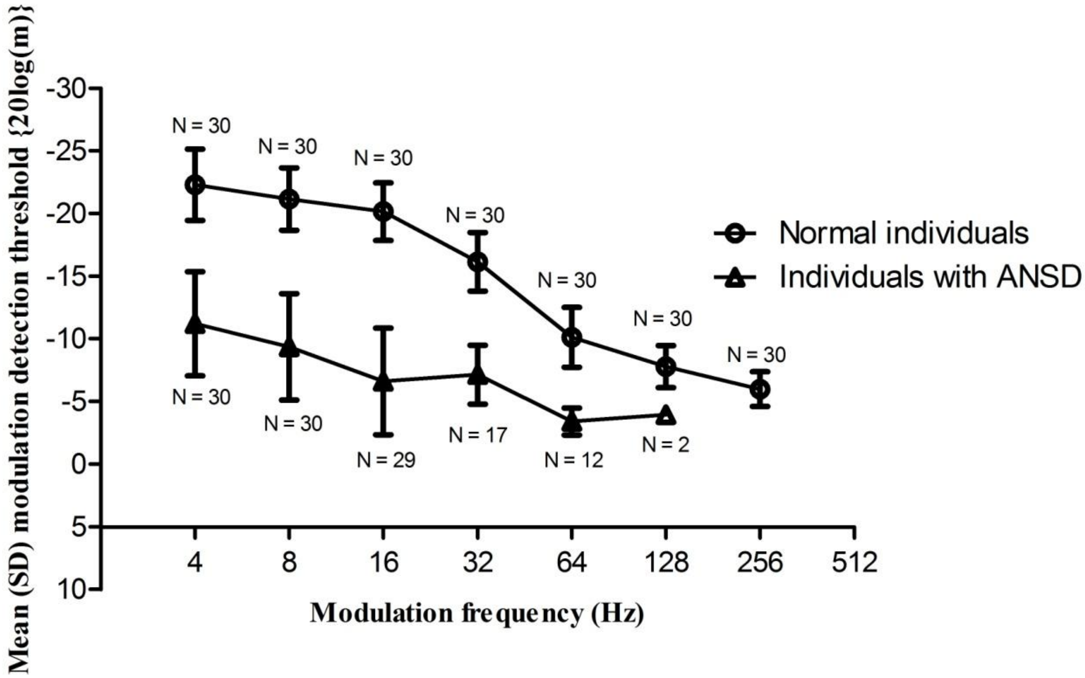


Figure 4.14. Mean and SD of modulation detection threshold in individuals with normal hearing sensitivity and ANSD. (*Note*. N = number of participants)

Further, it is evident from Figure 4.14 that modulation detection threshold of those with ANSD was poorer than that of the normal hearing individuals for all the modulation frequencies. As the modulation frequencies increased, the modulation thresholds became poor in both the groups. Mann-Whitney test showed a significant difference in modulation thresholds between the two participant groups at modulation frequencies 4 to 64 Hz ($p < 0.05$). At 128 Hz, only two participants with ANSD could detect modulation and hence the participant groups were not compared at this frequency.

Comparison of the normal hearing participants with those with ANSD, grouped in terms of their severity, showed that the former group could detect modulation till 256 Hz. In contrast, the mild temporal processing deficit group could detect the modulations only till 128 Hz and the moderate and severe groups could detect only till 64 and 32 Hz, respectively (Figure 4. 15). Non-parametric Kruskal-Wallis test, used to compare the modulation detection thresholds across the groups at a particular modulation frequency, revealed significant difference at 4 Hz [H (3) = 33.23, $p < 0.05$], 8 Hz [H (3) = 30.88, $p < 0.05$] and 16 Hz [H (3) = 24.66, $p < 0.05$]. Further, Mann-Whitney test showed significant difference between all the pairs of groups at each modulation frequency (normal vs. mild, normal vs. moderate, normal vs. severe, mild vs. moderate, mild vs. severe and moderate vs. severe). Group comparisons were not done at higher modulation frequencies (32, 64, & 128 Hz) as several of the participants with ANSD could not perceive the modulations, thus not permitting the use of statistical tests.

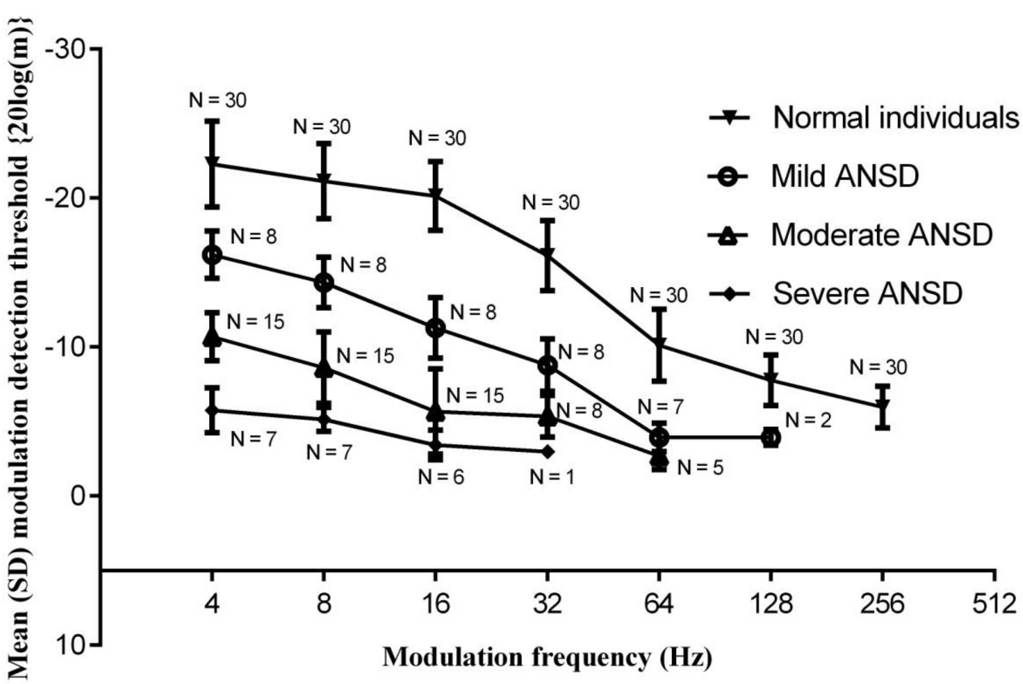


Figure 4.15. Mean and SD of threshold of modulation detection in normal individuals and individuals with ANSD, grouped based on their temporal processing severity. (*Note*. N = number of participants)

The findings of the study are summarised in Tables 4.20, 4.21, 4.22 4.23 4.24, 4.25, 4.26 and 4.27. Table 4.20 depicts the significance of difference in the SIS obtained using VCV syllables in three stimulus modified conditions and vowel contexts in the three temporal processing deficit groups. Similarly, Table 4.21 provides information regarding the significance of difference in the SIS obtained using VCV syllables in three stimulus modified conditions between the three temporal processing deficit groups. Table 4.22 gives information regarding the significance of difference in change in the change in SIS obtained using the two modified stimuli between the three temporal processing deficit groups. Table 4.23 has information about the significance of difference in the SIS obtained using VCV syllables and PB words in three amplification conditions between the three temporal processing deficit groups. Further, the significance of difference in aided benefit obtained using VCV syllables and PB words between temporal processing deficit groups can be observed in Table 4.24. Table 4.25 provides information regarding the significance of difference in the SIS obtained using VCV syllables and PB words in three amplification conditions within each temporal processing deficit groups. Table 4.26 highlights the significance of difference in the SIS obtained using VCV syllables and PB words in the three amplification conditions and vowel contexts in the rising and rollover PI-PB function groups. Finally, Table 4.27 shows the significance of difference in the SIS obtained using VCV syllables and PB words between two PI-PB function groups.

Table 4.20. Significance of difference in SIS obtained using VCV syllables in three stimulus modified conditions (Unprocessed, Spectro-temporally modified, & Stretched) and vowel contexts (/aCa/, /iCi/, /uCu/) in three temporal processing deficit groups

TMTF group	Stimulus conditions									Vowel context pairs								
	Unp vs. Stm			*Unp1 vs. Str*			*Stm vs. Str*			*/a/ vs. /i/*			*/a/ vs. /u/*			*/i/ vs. /u/*		
	/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/	/aCa/	/iCi/	/uCu/	Unp	Stm	Str	Unp	Stm	Str	Unp	Stm	Str
Mild	NS	NS	NS	* ↑	* ↑	* ↑	* ↑	* ↑	* ↑	* ↓	* ↓	* ↓	NS	NS	NS	* ↑	* ↑	* ↑
Moderate	*** ↓	*** ↓	*** ↓	** ↑	** ↑	*** ↑	*** ↑	*** ↑	*** ↑	* ↓	*** ↓	** ↓	NS	NS	NS	* ↑	NS	** ↑
Severe	* ↓	* ↓	* ↓	* ↑	* ↑	NS	* ↑	* ↑	* ↑	NS	NS	NS	NS	NS	NS	NS	NS	NS

Note. Unp = Unprocessed, Stm = Spectro-temporally modified, Str = Stretched; * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, NS = Not Significant; Downward arrow (↓) shows significant deterioration of the second condition over the first, Upward arrow (↑) shows significant improvement of the second condition over the first.

Table 4.21 Summary of the significance of difference in SIS obtained using VCV syllables between three temporal processing deficit groups in three stimulus modified conditions and vowel contexts

Stimulus conditions	Vowel contexts	Temporal processing deficit group		
		Mild vs. Moderate ↓	Mild vs. Severe ↓	Moderate vs. Severe
Unprocessed	/aCa/	NS	**	NS
	/iCi/	*	***	NS
	/uCu/	*	**	NS
Spectro-temporally modified	/aCa/	*	***	* ↓
	/iCi/	**	***	NS
	/uCu/	***	**	NS
Stretched	/aCa/	**	***	NS
	/iCi/	*	***	NS
	/uCu/	*	**	**

Table 4.22 Summary of the significance of difference in change in speech perception score between three temporal processing deficit groups in three vowel contexts

	Vowel contexts	Temporal processing deficit group		
		Mild vs. Moderate	Mild vs. Severe	Moderate vs. Severe
Difference score of stretched and unprocessed	/aCa/	NS	NS	NS
	/iCi/	NS	NS	NS
	/uCu/	NS	NS	NS
Difference score of spectro-temporally modified and unprocessed	/aCa/	* ↓	* ↓	NS
	/iCi/	* ↓	* ↓	NS
	/uCu/	* ↓	* ↓	NS

Note. * = p < 0.05, ** = p < 0.01, *** = p < 0.001, NS = Not Significant; Downward arrow (↓) shows significant deterioration of the second condition over the first

Table 4.23 Summary of the significance of difference in SIS obtained using VCV syllables and PB words between three temporal processing deficit groups in three amplification conditions and vowel contexts

Amplification conditions	Stimuli (PB words/ VCV syllables)	Temporal processing deficit group		
		Mild vs. Moderate ↓	Mild vs. Severe ↓	Moderate vs. Severe ↓
Unaided	/aCa/	NS	**	*
	/iCi/	**	***	*
	/uCu/	NS	**	**
	PB words	NS	**	**
Aided linear	/aCa/	**	***	NS
	/iCi/	***	***	NS
	/uCu/	**	***	NS
	PB words	*	***	***
Aided non-linear	/aCa/	**	***	**
	/iCi/	**	***	NS
	/uCu/	*	***	*
	PB words	*	***	**

Note.* = p < 0.05, ** = p < 0.01, *** = p < 0.001; NS = Not Significant; Downward arrow (↓) shows significant deterioration of the second condition over first

Table 4.24 Summary of the significance of difference in aided benefit between three temporal processing deficit groups in three vowel s

	Stimuli	Temporal processing deficit group		
		Mild vs. Moderate	Mild vs. Severe	Moderate vs. Severe
Difference score of aided linear and unaided	/aCa/	NS	NS	NS
	/iCi/	NS	NS	NS
	/uCu/	NS	NS	NS
	PB words	NS	NS	NS
Difference score of aided non-linear and unaided	/aCa/	NS	NS	NS
	/iCi/	NS	NS	NS
	/uCu/	NS	NS	NS
	PB words	NS	NS	NS

Table 4.25. Significance of difference in the SIS obtained using VCV syllables and PB words in three amplification conditions (Unaided, Aided linear, & Aided non-linear) and vowel contexts (/aCa/, /iCi/, /uCu/) in three temporal processing deficit groups

TMTF group	Amplification conditions												Vowel context pairs								
	Un vs. Al				*Un vs. Anl*				*Al vs. Anl*				*/a/ vs. /i/*			*/a/ vs. /u/*			*/i/ vs. /u/*		
	/aCa/	/iCi/	/uCu/	PB words	/aCa/	/iCi/	/uCu/	PB words	/aCa/	/iCi/	/uCu/	PB words	Un	Al	Anl	Un	Al	Anl	Un	Al	Anl
Mild	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Moderate	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	** ↓	NS	** ↓	NS	NS	NS	** ↑	NS	NS
Severe	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS ↓

Note. Un = Unaided, Al = Aided linear, Anl = Aided non-linear; * = p < 0.05, ** = p < 0.01, *** = p <0.001, NS = Not Significant; Downward arrow (↓) shows significant deterioration of the second condition over the first, Upward arrow (↑) shows significant improvement of the second condition over the first.

Table 4.26. Significance of difference in the SIS obtained using VCV syllables and PB words in three amplification conditions (unaided, aided linear, & aided non-linear) and vowel contexts (/aCa/, /iCi/, /uCu/) in two PI-PB function groups

PI-PB function groups	Amplification conditions												Vowel context pairs								
	Un vs. Al				*Un vs. Anl*				*Al vs. Anl*				*/a/ vs. /i/*			*/a/ vs. /u/*			*/i/ vs. /u/*		
	/aCa/	/iCi/	/uCu/	PB words	/aCa/	/iCi/	/uCu/	PB words	/aCa/	/iCi/	/uCu/	PB words	Un	Al	Anl	Un	Al	Anl	Un	Al	Anl
Rising	* ↑	NS	* ↑	* ↑	* ↑	NS	* ↑	* ↑	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rollover	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	* ↓	NS	NS	NS	NS	NS	NS	** ↑	NS

Note. Un = Unaided, Al = Aided linear, Anl = Aided non-linear; * = p < 0.05, ** = p < 0.01, NS = Not Significant; Downward arrow ( ) shows significant deterioration of the second condition over the first, Upward arrow ( ) shows significant improvement of the second condition over the first.

Table 4.27. Significance of difference in the SIS obtained using VCV syllables and PB words in three amplification conditions (unaided, aided linear,d aided non-linear) and vowel contexts (/aCa/, /iCi/, /uCu/) between two PI-PB function groups

Stimuli	Rising vs. Rollover PI-PB function groups		
	Unaided	*Aided linear*	*Aided non-linear*
/aCa/	NS	* ↓	* ↓
/iCi/	NS	* ↓	* ↓
/uCu/	NS	NS	* ↓
PB words	NS	* ↓	* ↓

Note. * = p < 0.05, NS = Not Significant; Downward arrow (↓) shows significant deterioration of the second condition over the first.

CHAPTER 5 - DISCUSSION

The results obtained from the individuals with ANSD, who were grouped based on their temporal processing abilities and PI-PB function are discussed under the headings given below. From the results of the study, it is evident that stimulus modification had a greater impact than amplification. Hence, the results of the impact of the former are discussed in greater depth compared to the other variables.

1. The effect of temporal processing problem on word identification scores,
2. The effect of PI-PB function response on word identification scores,
3. The effect of stimulus modified conditions (unprocessed, spectro-temporally modified & stretched) on speech identification in participants grouped based on their temporal processing severity
   - 3.1 Effect of stretching the stimuli on speech identification in participants grouped based on their temporal processing deficits,
   - 3.2 Effect of spectro-temporal modification on speech identification in participants grouped based on their temporal processing deficits,
   - 3.3 Comparison between stretching and spectro-temporal modification in participants grouped based on their temporal processing deficits,
   - 3.4 Influence of vowel contexts on speech identification,
   - 3.5 Comparison of stimuli modification conditions across temporal processing severity groups and
   - 3.6 Comparison of information transfer in three temporal processing severity groups for three stimulus modified conditions and vowel contexts.

4. The effect of amplification conditions (unaided, aided linear & aided non-linear) on speech identification in participants grouped based on their temporal processing severity

   4.1 Effect of amplification conditions on speech identification in participants grouped based on their temporal processing deficits

   4.2 Comparison of amplification conditions across temporal processing severity groups

   4.3 Comparison of information transfer in three temporal processing severity groups for three amplification conditions and vowel contexts

5 Effect of amplification conditions on speech identification in PI-PB function groups (rising & rollover)

   5.1 Influence of vowel contexts on speech identification in participants grouped based on PI-PB function

   5.2 Comparison of amplification condition between two PI-PB function groups

6 Relation between PI-PB function / PI-PB rollover ratio / TMTF threshold with amplification conditions and;

7 Comparison of modulation detection thresholds of individuals with ANSD and those with normal hearing.

1. Effect of Temporal Processing Problem on Word Identification Score

In the present study there existed a significant difference in open-set word identification score between the three temporal processing severity groups who were categorised based on their peak modulation detection thresholds (peak sensitivity of mild group was -16.20 dB, moderate group was -10.70, and severe group was -5.77). The mean SIS (61%) in the mild group was significantly higher than that of the moderate

(38%) and severe (8%) groups. Further, the SIS of the moderate group was significantly higher than that of the severe group. Hence, *null hypothesis 1, "There is no significant effect of temporal processing severity on word identification score", is rejected.*

Similarly, Narne (2008) found a significant difference in SIS between groups having different levels of temporal processing severity. They reported of SIS greater than 65% in those with mild temporal processing difficulty, 30% to 60% in those with moderate difficulty and less than 8% in those with severe difficulty. The similar findings in the current study and that of Narne (2008) probably occurred due to the similar way the participants were grouped. The present study grouped the participants using the recommendations of Narne (2008). Hence, it can be construed that comparable word recognition scores will be obtained in individuals with ANSD who have similar temporal processing severity, provided they are grouped using a similar criteria.

Similar to the findings of the current study and that of Narne (2008), many investigators have demonstrated the importance of temporal resolution abilities on speech perception in individuals with ANSD. These studies also noted that higher the peak modulation thresholds, better was the SIS (Kumar & Jayaram, 2005; Narne, 2008; Narne & Vanaja, 2009a; Rance et al., 2004; Zeng et al., 1999). These findings elucidate that good temporal resolution abilities is essential for individuals with ANSD to have good speech perception.

2. Effect of PI-PB function Response on Word Identification Score

The performance-intensity function in individuals with ANSD showed two patterns in the present study, a rising function in which SIS improved with increasing presentation levels and a rollover function where the SIS reduced as the presentation level increased.

It was noted that the rising group had a rollover ratio less than 0.45, whereas the rollover group had the ratio higher than 0.45. In the rising group, increasing the presentation level by 10 dB resulted in significant improvement in SIS up to 20 dB SL. Intensity beyond 20 dB SL did not significantly change the SIS. In the rollover group, with each 10 dB increment a significant deterioration in performance was observed. Based on these findings it can be stated that *null hypothesis 2, "There is no significant effect of PI-PB function on word identification score", is rejected.*

It can be construed from the above findings that individuals with ANSD do not always demonstrate similar loudness growth function. This difference in loudness growth indicates that the patho-physiology varies in individuals with ANSD. Although all the participants in the present study had primary auditory neuropathy (based on neurological examination), they demonstrate functional differences in loudness growth. This difference in loudness growth could be related to variations in neural synchrony seen in the participants.

The importance of temporal resolution on speech perception at higher presentation levels has been demonstrated in normal hearing individuals by Miranda and Pichora-Fuller (2002). They were able to simulate rollover in normal hearing individuals using temporally jittered speech signals delivered at high presentation levels (65 & uncomfortable level-5 dB HL) rather than at lower levels (40 & 55 dB HL). However, no rollover was found when unmodified speech stimuli were presented at higher or lower levels. Hence, they concluded that PI-PB rollover occurred due to disruption in temporal synchrony created by the temporally jittered signal presented at a high level. An earlier investigation by Sachs and Young (1979) also substantiated the importance of neural synchrony in speech perception, especially at higher presentation levels. By measuring 'average localised synchronised rate', they showed that auditory nerve fibres with characteristic frequency near the spectral peaks of stimuli had strong synchronisation to the frequency of the spectral peak of the stimuli. Further, they also found that the shape of the 'average localised synchronised rate' resembled the shape of the stimulus spectrum and was stable over a large range of presentation levels.

From the above literature it can be construed that PI-PB rollover, found in the participants of the present study, could have resulted from a temporal dys-synchrony. In contrast, individuals who had no rollover might have had relatively better temporal resolution that preserved speech perception even at higher presentation levels. This is supported by their performance on TMTF. All the participants who had rising PI-PB function had only mild deficits in temporal processing whereas those who had a rollover function showed moderate to severe deficits in temporal resolution.

The presence of a rollover PI-PB function has also been reported in those having 8^{th} nerve tumours (Dirks et al., 1977; Jerger & Jerger, 1971) and also due to aging (Dirks et al., 1977; Gang, 1976; Jerger & Jerger, 1976; Shrinian, 1980). Jerger and Jerger (1971) and Dirks et al. (1977) reported the rollover ratio that was greater than 0.45 in all the clients who had surgically confirmed 8^{th} nerve tumour. However, a control group of individuals with cochlear hearing loss had a rollover ratio of less than 0.45. Although the physiological basis of rollover was not explained in these studies, the presence of a retro-cochlear dysfunction was considered the reason why the rollover occurred.

Additionally, it has been reported in studies that abnormal rollover ratio is present in a few elderly individuals who had no space occupying lesion (Dirks et al., 1977; Gang, 1976; Jerger & Jerger, 1976 Shrinian, 1980). These studies reported of a high correlation between age and rollover ratio. Only those individuals above 80 years had rollover greater than 0.45. They attributed this to age related deterioration leading to retro-cochlear condition. As none of the clients in the present study were above 42 years, the abnormal rollover ratio observed in the present study can be ascribed to the presence of a retro-cochlear pathology that is not subsequent to age related neural dysfunction. Additionally, as none of the participants had any audiological or non-audiological symptoms of 8th nerve tumours, the abnormal rollover can be ascribed to a physiological dysfunction subsequent to ANSD.

3. The effect of Stimulus modified Conditions on Speech Identification in Participants grouped Based on their Temporal Processing Severity

The effect of two stimulus modification conditions (unprocessed, spectro-temporally modified & stretched) on speech identification scores are discussed separately, by comparing them with the unprocessed signal Further, the comparisons between the two modified stimuli are discussed. Additionally, the influence of vowel contexts on speech identification as well as comparison of stimulus modified conditions across temporal processing severity groups are discussed. Finally, the comparison of information transfer in three temporal processing severity groups for three stimulus modified conditions and vowel contexts are given.

3.1. Effect of Stretching the Stimuli on Speech Identification in Participants Grouped based on Their Temporal Processing Difficulty,

In the *mild and moderate temporal processing severity groups*, stretched VCV syllables significantly improved speech perception compared to the unprocessed stimuli, in all the three vowel contexts. Similarly, in the *severe temporal processing severity group*, stretching the entire signal improved speech perception significantly, except in the context of /u/. Hence, *part of null hypothesis 3 "There is no significant effect of speech modification (stretch) on speech identification in participants grouped based on their temporal processing difficulty", is rejected* as stretching had a positive effect and spectro-temporal modification had a negative effect.

The improvement with stretching of the stimuli was attributed by Kumar and Jayaram (2011; 2013) to prolongation of brief and dynamic acoustic elements such as burst, transition duration and voice onset time that were probably difficult to detect in the unprocessed signal. This might have helped the individuals with ANSD who were reported by Krause et al. (2000) to exhibit severe deficit in perceiving short acoustic elements of consonants, especially stops.

The prolongation of the signals in the current study probably enabled the individuals to get a longer time window to process the stops, thereby bringing about an enhancement in perception. It is also possible that stretching the stimuli had an effect similar to what happens when the rate of speech is lowered. Lowering of speech rate has been reported to improve speech perception significantly by Zeng and Liu (2006) and Hassan (2011). They inferred that reduction in rate of speech brought about an improvement in speech perception since it had been noted by Pichney et al. (1986) to be a major property of clear speech. Thus, it can be stated that the time scale modification of stimuli caused acoustical changes similar to that observed in clear speech and results in improved speech perception.

Using different techniques to temporally modify speech, positive outcome have been reported by earlier investigators. The different algorithms used included stretching specific elements of the speech signal (Kumar & Jayaram, 2011, 2013), lowering the rate of the speech signal (Hassan, 2011), use of clear speech (Zeng & Liu, 2006) and stretching the entire signal, similar to that utilised in the current study (Jijo & Yathiraj, 2013a). Kumar and Jayaram showed improvement in speech perception when brief acoustic elements such burst, transition duration and voice onset time were stretched. They hypothesized that stretching the stimulus duration might lower the modulation frequency without altering its modulation depth. This reduction in modulation frequency was considered to be helpful for individuals with ANSD who had better modulation thresholds in the lower frequencies. Unlike Kumar and Jayaram, the investigations by Jijo and Yathiraj showed that stretching the entire VCV syllables by 25% resulted in significant improvement in consonant perception compared to unprocessed stimuli. They attributed this to the prolonged consonantal portion (burst and transition) in the stretched stimuli that might have helped improve perception. Thus, the majority of the studies (Hassan, 2011; Jijo & Yathiraj, 2013a; Zeng & Liu, 2006) demonstrate that temporal enhancement of the entire signal is an effective way to bring about improvement in speech identification, instead of having to stretch only specific segments of speech as done by Kumar and Jayaram. In the latter method, though identification and time scale modification of such acoustic elements can be carried out on small elements of speech, it will be in a tedious for longer speech stimuli. It is recommended that such time scale modification of speech be utilised in training those with ANSD, since implementing in real time is difficult.

In the severe temporal processing severity group of the current study, stretching the entire signal improved speech perception compared to the unprocessed stimuli. However, it was insignificant only in the context of /u/. This highlights that stretching the signal is an effective way to improve speech perception also in those with severe temporal resolution problems, though not to the same extent as those with lesser severity.

The limited benefit of temporal enhancement in those with severe temporal processing difficulties, observed in the current study, is in concurrence with studies reported in literature. Studies that have used either envelope enhancement (Narne & Vanaja, 2008) or time scale modification (Kumar & Jayaram, 2005) have noted limited improvement in speech perception in those with severe temporal resolution problems. Hence, the signal enhancement schemes such as time scale modification or envelope enhancement might not be totally effective for those with severe temporal resolution problems. This highlights that rehabilitative approaches other than above signal enhancement strategies need to be tried for individuals with ANSD having severe temporal processing problems. Auditory training based approaches have been found to be promising in improving speech perception in ANSD. In an auditory training based study, Yathiraj and Avilala (2011) showed improvement in speech perception in individuals with late onset ANSD who had undergone fine grained auditory training. They noted that training using consonant-vowel syllables, modified in terms of voice onset time to form a voiced to unvoiced contrast, resulted in an improvement of in speech perception. The improvement was seen for consonant-vowel syllables as well as open set speech identification scores. Additionally, improvement in perception of voicing and place cues was also reported.

3.2. Effect of Spectro-Temporal Modification on Speech Identification in Participants Grouped based on Their Temporal Processing Difficulty

The *mild, moderate and severe temporal processing severity groups* of the present study demonstrated no positive perceptual effect with the use of spectro-temporal enhancement. In the mild group there was no significant difference found between unprocessed and spectro-temporally modified stimuli in all three vowel contexts. On the other hand, in the moderate and severe groups, spectro-temporal modification resulted in deterioration in performance compared to the unprocessed stimuli. This deterioration was observed in all three vowel contexts. Hence, the *part of null hypothesis 3 "There is no significant effect of speech modification (spectro-temporal) on speech identification in participants grouped based on their temporal processing difficulty", is accepted in those with mild temporal processing severity whereas it is rejected in the other two groups*. This highlights that using natural modulations of 3 to 30 Hz with gain in the frequencies 1 kHz to 4 kHz does more harm than help to individuals with ANSD. This is unlike the findings of the Narne and Vanaja (2008) who found an improvement in perception in individuals with ANSD, using similar spectro-temporal enhancement using Praat software.

To determine the reason for the difference in findings between the present study and that of Narne and Vanaja (2008), the unprocessed stimuli of the current study were spectro-temporally modified using MATLAB as well as Praat (Appendix A). The stimuli enhanced using the two software were analysed using the technique given by Gallun and Souza (2008). The spectro-temporally modified stimuli used in the present study, generated using MATLAB, resulted in no envelope modulation enhancement, while that modified using Praat resulted in enhancement of temporal modulation. The difference in output through the two software is probably due to subtle differences in the algorithms used. The current study used an algorithm identical to that given by Nagarajan et al. (1998), while the Praat software used a variation of the algorithm used by Nagarajan et al. (1998), as given in the description of the latter software. Thus, the spectro-temporal modifications using the two software are not identical. Although the envelope spectrum across the three stimuli (Unprocessed, spectro-temporally modified using Praat, & spectro-temporally modified using MATLAB) were found to be similar at lower frequency bands (500 Hz, 1 kHz & 2 kHz), they were different at the higher frequency band (4 kHz). The envelope at 4 kHz had higher energy when the stimuli were processed using Praat, as done by Narne and Vanaja (2008), compared to the signal enhancement algorithm used in the current study. Thus, it can be construed that spectro-temporal modification that enhances the high frequency region without enhancing the envelope modulation is not beneficial for those with ANSD. However, similar specto-temporal modifications with enhanced modulations will be beneficial.

3.3. Comparison between Stretched and Spectro-temporally Modified Stimuli in Participants Grouped based on Their Temporal Processing Difficulty,

In all three temporal processing severity groups, the stretched stimuli resulted in significantly higher perception than the spectro-temporally modified stimuli. This indicates that individuals with ANSD derived more benefit from the duration enhancement of stimuli than spectro-temporal enhancement. The duration enhanced stimuli probably led to short acoustic cues of speech, that would have been missed earlier, to be more prominent. This would have enabled individuals with ANSD to derive benefit from the stretched stimuli. In contrast, the spectro-temporally modified stumuli led to increased energy in the 1 kHz to 4 kHz region without any change in temporal envelope (Figures 3.3 & 3.4). This increased spectral energy probably was not beneficial to individuals with ANSD who are reported to have more difficulty in temporal perception than intensity perception (Barman, 2008; Zeng et al., 2005). Similar observations were made by Krause et al. (2000) where increase in amplitude of formant transition of a speech signal was not found to beneficial in a single subject with ANSD. Based on this finding they concluded that those with ANSD do not demonstrate increased neural synchrony with enhancement in stimulus intensity. The poor performance of those with ANSD to amplitude enhanced stimuli was attributed to faulty brainstem synchrony that causes imprecise input to the cortex. Hence, it can be concluded that time scale modification of speech is a better approach to improve speech perception in those with ANSD compared to spectro-temporal enhancement.

3.4. Influence of Vowel Contexts on Speech Identification in Three Temporal Processing Severity groups for Three Stimulus Modified Conditions

In the mild and moderate temporal processing severity groups, consonant perception in the context of /a/ and /u/ was significantly better than in the context of /i/ for all three stimulus-modified conditions. A similar trend was observed in the severe temporal processing deficit group, though it was not significant. The change in consonant perception with respect to vowel context could probably be due to difference in spectral characteristics of the vowels used in the current study. This can be observed in the spectrogram of the stimuli provided in Appendix C that indicates that the F2 frequencies were higher for the vowel /i/ compared to that of the vowels /a/ and /u/. Additionally, the F2 transitions were steeper in the context of /i/ than in the context of the other vowels. A spectrographic analysis of stimuli showed the presence of steeply falling F2 transitions especially for bilabial and alveolar stops in the context of vowel /i/. Additionally, the analysis of stimulus-response confusion matrix in all three stimulus modified conditions also showed poorer perception of bilabial and alveolar consonants in the context of /i/ compared to consonants having other place of articulation. Hence, difficulty in perceiving these rapid spectral changes might have led to poor perception of consonants in the context of the vowel /i/. Likewise, Jijo and Yathiraj (2013a) found reduced consonant perception in the context of vowel /i/ compared to /a/ and /u/ in individuals with ANSD. Similar findings were also reported among cochlear implant users by Donaldson and Kreft (2006). The difference in perception across vowel context indicates the importance of studying consonant perception in the context of vowels having varying frequency characteristics, resulting in vowel transitions of varying steepness. This would enable detecting specific perceptual difficulties in individuals with ANSD.

3.5. Comparison of Stimulus Modified Conditions across Temporal Processing Severity Groups

A significant difference between the three temporal processing deficit groups was observed in the present study for all nine stimuli conditions that were evaluated (3 stimulus modified conditions × 3 vowels contexts). In general, those with a mild severity performed better than those with moderate and severe difficulty, irrespective of whether the stimuli were unprocessed or processed. Similarly, the moderate group performed significantly better than the severe group, but only for the processed signals and not for the unprocessed signals. This was observed for both the processed signals (spectro-temporally modified & stretched) in all the vowel context except /i/. The results show that perception of VCV syllables decreases as temporal resolution difficulty increases in individuals with ANSD.

Similarly, Narne (2008) noted that SIS obtained using envelope enhanced stimuli were significantly different across temporal processing severity groups. Kumar and Jayaram (2005) showed a strong negative correlation between SIS obtained using stimuli lengthened for acoustic cues and TMTF peak modulation thresholds. They observed poorer speech perception in participants who had higher modulation detection thresholds compared to those who had lower modulation detection thresholds. Hence, it can be concluded that speech perception in individuals with ANSD depends on their temporal resolution abilities even with the use of signal enhancement.

Further, tt was found in the current study that there was no significant difference in perception of unprocessed VCV syllables between moderate and severe groups. In contrast, open-set word identification scores differed significantly between these two groups. This reflects that testing in a closed-set paradigm may not reflect the perceptual difficulties of those with larger temporal processing severity. The ease of a closed-set task might over estimated the performance of those with higher severity unlike an open-set task that makes use of less predictable stimuli like words. Hence, it is recommended that open-set tests be administered to demarcate those with varying levels of temporal processing difficulties.

The *change in speech perception scores* calculated in the current study by computing the difference in SIS obtained using stretched and unprocessed stimuli showed no significant difference across groups. However, SIS obtained in the stretched condition showed significant difference across some of the groups (Mild vs. Moderate & Mild vs. Severe). Hence, it can be construed that the lack of significant difference for the change in speech perception scores across the three groups showed that improvement due to stretching is proportionately similar across the groups.

In contrast, the change in scores after spectro-temporal modification (difference in scores of spectro-temporally modified and unprocessed stimuli) showed significantly lesser change in scores in those with severe temporal processing problem compared to other two groups. This shows that individuals with severe temporal processing deficits faced highest difficulty in perceiving stimuli modified by giving gain in 1 to 4 kHz region of temporal envelope. This caused a larger reduction in score in the severe group compared to the moderate and mild groups. In those with mild temporal processing deficits, the perception of spectro-temporally modified stimuli was almost similar to that of unprocessed leading to a small change in score.

3.6. Comparison of Information Transfer in Three Temporal Processing Severity groups for Three Stimulus Modified Conditions and Vowel Contexts.

The results of the three *temporal processing severity groups* of the current study indicated that manner information was transmitted significantly higher than place and voicing irrespective of temporal processing deficit groups, stimulus modified conditions and vowel contexts. It is reported that temporal envelope of speech is a cue for manner perception (Drullman, Festen, & Plomp, 1994; Rosen, 1992). In the present study, the consonants stops and liquids that were evaluated had large temporal envelope differences. Stops are known to have faster temporal envelope fluctuations, where as liquids are known to have slow temporal envelope changes. Hence, the difference in temporal envelope might have helped the participants to easily differentiate stops and liquids causing highest transfer of manner information. Similarly, earlier investigations by Narne and Vanaja (2008), Nike and Barman (2011) reported highest transfer of manner in individuals with ANSD compared to other consonantal features.

It was also found in the present study that information transmitted for voicing was poorer than place of articulation. It is established that the place information is primarily conveyed through spectral cues (Xu, Thompson, & Pfingst, 2005) whereas voicing information is transmitted by temporal cues (Lisker, 1986). Hence, individuals with ANSD having relatively better processing of frequency compared to temporal information might have perceived place cues better than voicing. The findings of the current study regarding perception of voicing and place cues are in consonance with studies reported in literature (Kumar & Jayaram, 2011, 2013; Narne & Vanaja, 2008; Nike & Barman, 2011).

The results of information transfer analysis in the study at hand revealed that stretching the stimuli led to slight improvement in perception of consonantal features (manner, place and voicing) in all three temporal processing severity groups. However, this was insignificant. The slight improvement in place and voicing after stretching the stimuli could be due to prolongation of brief acoustic elements of stop consonants (transition & closure duration). It has been well established that transitions, especially the second format transition, are important cues used in the perception of place of articulation (Delattre, Liberman, & Cooper, 1955; Dorman Studdert-Kennedy, & Raphael, 1977; Kewley-Port, 1982; Lahiri, Gewirth, & Blunstein, 1984). Likewise, several studies have confirmed the importance of closure duration in the perception of voiced-unvoiced contrasts in medial position (Lisker, 1986; Savithri, Swapna, & Rajeev, 1996).

The spectro-temporal modification of the stimuli resulted in slightly worse perception of place and voicing in all three temporal processing deficit groups. In contrast, the perception of manner improved marginally in the mild group whereas in the other two groups there was a deterioration in manner perception. However, these were not significant. As mentioned earlier, the spectro-temporal modification did not increase the modulation depth of stimuli in any of the frequency bands, but only increased the gain in the frequencies 1 kHz to 4 kHz. It is reported that individuals with ANSD need higher depth of modulation to process the fast elements of stops that help in the perception of its place and voicing (Narne & Vanaja, 2008). As the stimuli used in the present study did not enhance the modulation depth, it probably did not improve place of articulation.

The lack of improvement seen in the perception of voicing after spectro-temporal modification could have been due to reduced energy in the low frequency region in the modified signal. This reduction of low frequency was an offshoot of the signal enhancement strategy used in the current study, as can be seen in Figure 3.3 provided in the method chapter. It is reported that voicing cues during closure is a strong cue for voicing perception of medial stop consonants (Lisker, 1986). Similarly, Narne and Vanaja (2008) reported no improvement in perception of voicing even after envelope enhancement. They too ascribed the poor perception of voicing to the lack of enhancement of the voicing bars after envelope enhancement. It is also known that voicing perception of inter-vocalic stop consonants are cued by closure duration (Lisker, 1957; Savithri et al., 1996). Individuals with ANSD, having severe temporal processing deficits, could have had difficulty differentiating this short temporal cue leading to poor voicing perception.

In contrast to place and voicing perception, the observed improvement in manner perception after spectro-temporal enhancement in the mild group can be attributed to the relatively better temporal processing in the mild group. This might have helped those with mild impairment to differentiate the consonants (liquids & stops) based on their duration. It is noted that liquids have longer duration of compared to stops. In contrast, individuals with moderate and severe temporal processing deficits did not show improvement in manner probably because they were unable to make used the durational difference between two consonants.

The results of the *effect of vowel context* in the study at hand revealed that perception of manner, place and voicing were higher in the context of /a/ and /u/ compared to /i/. This was found in all three temporal processing deficit groups (mild, moderate, & severe) and stimuli conditions (unprocessed, spectro-temporally modified, & stretched). However, this was not statistically significant.

The slight difficulty in *place* perception in the context of /i/ could have been due to the steepness of the F2 transition. The spectral analysis of the VCV syllables in various vowel contexts showed the presence of higher F2 frequencies for the vowel /i/ which resulted in steep F2 transitions. In contrast, the lower F2 for the vowels /a/ and /u/ led to relatively slow change in transition (Appendix C). Hence, it can be inferred that the rapid change in formant transition in the context of vowel /i/ resulted in poor place perception. This finding substantiates the difficulty individuals with ANSD have in the perception of rapid temporal changes.

Poor voicing perception in the context of /i/ can be attributed to a contrast effect seen in co-articulated speech. Voicing bars in the low frequency region, important for voicing perception of medial consonants (Lisker, 1986), could have shifted lower in percept due to contrasting frequency cues when voiced consonants are present in the context of /i/. This would have made the low frequency voicing bars in the presence of /i/ sound lower than in the presence of the other two vowel contexts that do not result in such large frequency differences. Similar auditory contrast effect has been reported by Nittrouer and Studdert-Kennedy (1987) for other speech contrasts. Hence, individuals with ANSD, having difficulty in processing low frequency signals, would face more difficulty perceive voicing in the context of /i/ than in the context of /a/ and /u/. These findings are in agreement with earlier published information. Deterioration in perception of place and voicing cues in the context of /i/ compared that of /a/ and /u/ was also reported by Jijo and Yathiraj (2013a). Similar findings were reported among cochlear implant users by Donaldson and Kreft (2006).

4. The effect of amplification conditions on speech identification in participants grouped based on their temporal processing severity

The effect of three amplification conditions (unaided, aided linear & aided non-linear) on speech identification scores are discussed in participants grouped based on their temporal processing severity. Additionally, comparison of amplification conditions across temporal processing severity groups are discussed. Finally, the comparison of information transfer in three temporal processing severity groups for three amplification conditions and vowel contexts are given.

4.1. Effect of Amplification Conditions (linear & non-linear) on Speech Identification in Participants Grouped based on their Temporal Processing Difficulty

The results of the present study revealed that in all three temporal processing deficit groups (mild, moderate, & severe) there was no significant difference between the unaided and both the aided conditions (linear & non-linear amplification) in any of the vowel contexts. Similarly, no significant difference was found in the word identification score between the three amplification conditions in any of the temporal processing deficit groups. Hence, *null hypothesis 4,"There is no significant effect of amplification (linear & non-linear) on speech identification in individuals with ANSD grouped based on their temporal processing difficulty", is accepted*.

Thus, it is clear that the use of amplification is not beneficial for individuals with ANSD, irrespective of their temporal processing abilities. This is in accordance with the earlier reports that have established that there exists no improvement with hearing aids in individuals with late onset ANSD (Berlin et al., 1993; Berlin et al., 1999; Berlin et al., 2002; Lee et al., 2001; Miyamoto et al., 1999; Shallop etal., 2001; Sininger et al., 1995; Starr et al., 1996; Trautwein et al., 2000; Widen et al., 1995). Berlin (1999) opined that hearing aids might not be useful because they are designed to compensate for the loss of outer hair cells rather than temporal dys-synchrony resulting from neural dysfunction.

Lack of improvement with a hearing aid in the present study is in contrast with the series of reports by Rance and colleagues. They showed significant aided improvement in 50% of children with ANSD (Rance et al., 1999; Rance & Barker, 2007; Rance & Barker, 2009; Rance et al., 2007a; Rance et al., 2007b; Rance et al., 2002). They accredited the aided improvement to early diagnosis and management of the children during the sensitive period of speech and language development. Rance (2005) opined that the qualitative difference in perceptual abilities of adults, compared to that of children with ANSD might cause poor aided performance in them. They observed that children with ANSD grow-up with the impaired but consistent neural input, whereas those with late onset ANSD might have different and deteriorating neural input. Hence, they concluded that improvement in auditory awareness using hearing aid might result in better language development by a more versatile brain in the pre-lingual group.

In the present study, it was observed that there was no significant difference in perception using either linear or non-linear amplification. It was hypothesized that linear amplification might lead to improvement in speech perception compared to non-linear amplification, based on the observation by Van Tassel (1993). The latter study reported that linear amplification preserved temporal envelope of speech, whereas non-linear amplification distorted the temporal envelope. However, in the current study, an analysis of the temporal envelope of the stimuli recorded after linear and non-linear amplification showed no much difference in temporal envelope between the two stimuli (Appendix D). The minimal impact of non-linear amplification on temporal envelope might be related to the presentation level of the stimuli. The presentation level (50 dB HL) that was used while investigating the aided performance was only slightly higher than the compression threshold (60 dB SPL) of the hearing aid used. Hence, some portions of the stimuli might have fallen below the compression threshold of the hearing aid, leading to minimal changes in temporal envelope.

In line with the observation regarding presentation level and compression ratio, Jenstad and Souza (2005) reported of minimal changes in the temporal envelope when the stimuli were presented at 50 dB SPL with a hearing aid having a compression threshold of 45 dB SPL. However, they observed larger envelope changes at higher presentation levels. Additionally, Hickson, Dodd, and Byrne (1994), who compared speech perception using linear and non-linear amplification in individuals with sensorineural hearing loss, showed no significant difference. They too attributed the lack of difference between linear and compression amplification in quiet to the small compression ratio that they used that led to minimal changes in consonant-vowel ratio. Likewise, in the present study, the use of a wide dynamic range compression hearing aid with a small compression ratio would have resulted in minimal changes in the consonant-vowel ratio. Hence, individuals with ANSD, who require larger temporal envelope modulation, did not benefit using the current amplification strategy that used a small compression ratio and an input presentation level just above the compression threshold of the hearing aid. These setting caused little change in temporal envelope of speech leading to similar speech perception using either amplification strategies (linear or non-linear amplification).

Effect of vowel context on amplification conditions indicated that in the mild and severe temporal processing deficit groups the performance of the three vowel contexts was not significantly different in any of the three amplification conditions. However, it was found that perception in the context of /i/ was poorer compared to that of /a/ and /u/. On the other hand, in the moderate temporal processing deficit group, perception of stimuli in the context of /a/ and /u/ were significantly higher than that of /i/ in the unaided and aided non-linear conditions. No significant effect of vowel was found in the aided linear condition.

Overall, the effect of the vowel context was similar to what was noticed with the three stimulus modified conditions (unprocessed, spectro-temporally modified, & stretched). Similar to what was observed in these conditions, consonant perception with amplification was reduced the context of vowel /i/. The spectral characteristics of stimuli in various vowel contexts could have contributed to this performance difference.

4.2. Comparison of Amplification Conditions Across Temporal Processing Severity Groups.

Aided performance in all the nine stimuli (3 amplification conditions × 3 vowels) differed significantly between the temporal processing deficit groups. Although the unaided performance between the *mild and moderate groups* was not significantly different for the SIS obtained using VCV syllable and PB words, in both the aided conditions there was a significant difference. The lack of difference between the mild and moderate groups in the unaided condition probably occurred since the testing was done at a low presentation level (50 dB HL), resulting in both groups obtaining equally poor scores. In contrast, the unaided SIS obtained at a supra-threshold level (40 dB HL above SRT) and the aided SIS showed significant difference between the two groups. The significantly higher performance in the mild group at higher presentation levels can be attributed to relatively better temporal processing in them. This can be elucidated using the physiological explanations of the rollover phenomenon given by Miranda and Pichora-Fuller (2002). They demonstrated that rollover occurred in normal hearing individuals while listening to temporally jittered speech signals presented at higher presentation levels. However, no rollover was found when unmodified speech stimuli were presented at higher presentation levels. Thus, they highlighted the importance of temporal synchrony for speech perception at higher presentation levels. Similarly, in the present study, when the speech was presented at a higher presentation level there might have been more demand for temporal synchrony, whereas at a lower presentation level lesser temporal synchrony was required. Further, as the moderate group would have had greater temporal dys-synchrony, they might have performed poorer at a higher level of presentation.

There was a significant difference found between the performance of the *mild and severe groups* in the unaided as well as both the aided conditions in all three vowel contexts. A trend, similar to that obtained with VCV syllables was observed with the word identification scores. The difference in performance between the two severity groups could have been due to large differences in their temporal processing abilities. Additionally, six out of the seven individuals in the severe group had hearing thresholds below the unaided testing level. These might have caused extremely poor scores in the severe group in the unaided condition. Though the problem with audibility was resolved in the aided conditions, amplified speech did not compensate the deficits in temporal envelope processing in the severe group. This would have resulted in poor performance in the severe group, even with the use of hearing aids, irrespective of whether it had linear or non-linear amplification.

The *moderate group* performed significantly better than the *severe* groups, in all three vowel contexts in the unaided condition. In the aided linear condition, though the performance of the moderate group was higher than the severe group in all three vowel contexts, it was not significant. In the aided non-linear condition, there was a significant difference between the two groups in the contexts of vowel /a/ and /u/ but not in the context of /i/. The poor aided performance observed in the severe group compared to the moderate group can be ascribed to poor temporal resolution in the latter group.

The *aided benefit* calculated by computing the difference in SIS obtained using aided and unaided stimuli showed no significant difference across groups. This is probably due to the limited aided improvement seen in all three temporal processing deficit groups.

4.3. Comparison of Information Transfer within three Temporal Processing Severity Groups for three Amplification Conditions and Vowel Contexts

As was seen in the stimulus modification condition, comparison of information transmitted for the consonantal features in the amplification conditions showed significantly higher perception of manner compared to place and voicing. Further, perception of place was significantly higher than voicing. As mentioned earlier, the better perception of manner can be attributed to the distinctly different temporal envelope of liquids and stops. Additionally, as discussed earlier, the better processing of frequency information compared to temporal cues might have helped the participants to perceive place cues better than voicing.

The information analysis showed that except for the mild group, transfer of manner, place and voicing deteriorated in both the aided conditions (linear & non-linear) in all three vowel contexts. In the mild temporal processing deficit group, compared to the unaided condition, both aided conditions resulted in slight improvement in transfer of manner, place and voicing information in all three vowel contexts. However, these were insignificant for all three severity groups. This indicates that use of amplification does not have a major impact in improving perception of manner, place and voicing in any of the temporal processing severity groups. However, the slight improvement with amplification seen in the mild group could have been on account of relatively better neural synchrony compared to the moderate and severe groups. In contrast, the moderate and severe groups who probably had poorer synchrony, showed deterioration in perception at higher levels. In addition, the possible reason for the lack of improvement in place of articulation in the current study was due to the absence of enhancement in modulation depth after amplification. In contrast, Narne and Vanaja (2008), who used an envelope enhancement scheme, showed an improvement in place of articulation. They credited this improvement to increased modulation depth used by them that helps in the perception of faster temporal envelope of stop consonants.

5. Effect of Amplification Conditions (Unaided, Linear & Non-linear) on Speech Identification in Participants Grouped Based on the PI-PB Function Responses

The comparison across stimuli conditions, within a PI-PB function group indicated that in the *rising group*, SIS obtained in both the aided conditions (linear & non-linear) were significantly higher than the unaided score in the context of vowel /a/ and /u/. A similar trend was noted in the context of /i/, though it was not significant. However, no significant difference was found between the two aided conditions in any of the vowel contexts. The performance for word identification was similar with both aided scores being significantly higher than the unaided, but not differing from each other. In the *rollover group,* there was no significant difference in the perception of VCV syllables across amplification conditions in any of the vowel context. Similar results were found for the word identification scores. Thus, the *null hypothesis 5, "There is no significant effect of intensity levels on speech identification scores", is rejected in the rising group whereas it is accepted in the rollover group*.

The improvement in speech perception observed in the rising group can be accredited to relatively good speech perception observed in them even at higher presentation levels, when the PI-PB function was estimated. The importance of obtaining a PI-PB function in individuals with ANSD was reported by Cone-Wesson et al. (2001). They opined that a PI-PB function might give more information regarding supra-threshold processing and aided improvement in speech perception. They reported that a rising PI-PB function would show a probable positive benefit a person may obtain when using a hearing aid, whereas a flat or rollover PI-PB function might show a lack of benefit. In accordance with the findings of Cone-Wesson et al. (2001), the results of the present study show that hearing aids significantly improved speech perception in those with a rising PI-PB function. In contrast, none of the individuals with a rollover PI-PB function showed any significant improvement in speech perception.

The aided speech perception improvement observed in the rising PI-PB function group of the current study is in concurrence with earlier studies. In a retrospective study, Jijo and Yathiraj (2013b) observed a significant positive correlation between SIS obtained at a higher presentation level of 40 dB SL (ref to SRT) and aided improvement. They observed that those who had SIS higher than 40% had aided improvement ranging from 24% to 52%, whereas limited or no aided improvement was noted in those having SIS between 10 to 40%. Thus, the authors recommended the use of a PI-PB function in individuals with ANSD, in order to obtain a clear indication of aided performance. Similarly, Deltenre et al. (1999) reported that the aided word and phoneme identification obtained in their participants with ANSD was similar to the unaided scores obtained at a higher presentation level. They made this observation based on identification scores obtained in three different conditions (unaided at 55 dB, aided at 55 dB, & unaided at 70 dB). They noted that word identification scores improved from 0% in the unaided low level presentation to 80% in both aided and unaided at 70 dB conditions respectively. Similar trend was observed using phoneme identification scores in the unaided (0%) as well as aided (96%) and unaided at 70 dB (88%) conditions. Thus, it can be inferred that identification scores obtained at a supra-threshold level gives a clear indication of aided performance in individuals with ANSD.

Vanaja and Manjula (2004) reported aided improvement in three out of five individuals with late onset ANSD. Although none of their clients obtained adequate benefit with hearing aids, one client had 40% improvement and two had 20% using a linear amplification. It was noted in their data that individuals who had highest aided improvement (40%) had higher supra-threshold SIS (25%) compared to those who had poor SIS (0%) and relatively poorer aided improvement (20%). The observed aided improvement was attributed to preserved neural synchrony that was confirmed by the presence of late latency response. Hence, the participants of the present study who demonstrate good speech perception at high presentation level, might have preserved neural synchrony, as reported by Miranda and Pichora-Fuller (2002). This might have helped them to have significant aided improvement.

In the present study, the performance with aided linear and aided non-linear amplification was not significantly different in the rising and rollover groups. This lack of difference between the two forms of amplification may be due to the low compression ratio (less than 2:1) and a low presentation level that were utilised. The presentation level used (50 dB HL) was only slightly above the compression threshold of the hearing aid (60 dB SPL). This would have resulted in the compression in the hearing aid being minimal. Earlier studies hypothesized that compression hearing aids could deteriorate speech perception in individuals with ANSD as they may alter the temporal envelope of speech signals (Hood, 1998; Zeng & Liu, 2006). However, in present study, the small compression ratio of the wide dynamic range hearing aid as well as the low presentation level used would not have resulted in change in the temporal envelope, similar to linear amplification. Hence, further investigation needs to be carried out using similar hearing aids but stimuli presented at a higher presentation level that to trigger the compression circuit. Stimuli presented at a higher level to a wide dynamic range compression hearing aid is known to alter the temporal envelope of speech signals more than that of a linear hearing aid (Jestand & Sauza, 2005). This might help establish the utility of linear amplification over non-linear one in individuals with ANSD.

5.1. Influence of Vowel Contexts on Speech Identification in Participants Grouped Based on PI-PB function

In the *rising PI-PB function group*, in all three amplification conditions (unaided, aided linear & aided non-linear), there was no significant difference in consonant perception in the context of different vowels. In the *rollover group,* while there was a significantly poorer consonant perception in the context of vowels /i/ than /a/, there was no difference between /a/ and /u/ as well as /i/ and /u/. With linear amplification there was significantly lower consonant perception in the vowel contexts /i/ than /u/. However, there was no significant difference between the contexts of /a/ and /u/ as well as /a/ and /i/. In the aided non-linear condition, there was no significant difference between any of the vowel contexts. Overall, the mean scores in both the PI-PB function groups showed poorer consonant perception in the vowel context /i/ compared to /a/ and /u/. This again can be ascribed to the spectral characteristics of vowel /i/, as described earlier, that caused poorer consonant perception compared to other two vowels.

5.2. Comparison of Amplification Conditions between PI-PB Function Groups

Comparison between the rising and rollover groups in the *unaided condition* showed no significant difference in any of the vowel contexts. Similar results were also found for the unaided word identification scores. The unaided evaluations were carried out at relatively low presentation levels (50 dB HL). Similarly, at lower presentation levels of the PI-PB function (0 dB SL to 10 dB SL) both rising and rollover groups showed no significant difference. Thus, it can be inferred that at low presentation levels, individuals with rising or rollover PI-PB function will perform similarly on speech perception tests.

In the *aided linear condition*, the rising PI-PB function group performed significantly better than the rollover PI-PB function group in the context of /a/ and /i/. A similar trend was noted in the context of /u/, though it was not significant. In the *aided non-linear condition* there was a significant difference between two groups in all three vowel context, with the rising group performing better than the rollover group. Similarly, the word identification scores in both the aided conditions in the rising group were significantly higher than the rollover group. Thus, it can be stated that *null hypothesis 6, "There is no significant effect of amplification (aided linear & aided non-linear) on speech identification in participants grouped based on their PI-PB function", is rejected*.

The comparison of supra-threshold SIS (SRT +40 dB HL) between the rising and rollover groups in current study revealed that the former group had significantly better SIS than the latter group at higher presentation levels (20 dB SL to 50 dB SL). Similarly, the aided stimuli presented at a higher level (50 dB HL + gain of the hearing aid) resulted in significantly higher speech perception in the rising group compared to the rollover group. The results are in agreement with the postulation of Cone-Wesson et al. (2001) who reported of improvement in speech perception with hearing aids in those having a rising PI-PB function, but not in those having a flat or falling function. Likewise, Rance et al. (2002) reported of improvement in speech perception with hearing aids in a few children with ANSD. They opined that higher presentation levels might improve neural synchrony in a few children with ANSD. Thus, the improvement is speech perception seen in the rising group of the current study could be due to preserved neural synchrony in them. In contrast, those who had a rollover PI-PB function could have had poor neural synchrony resulting in deterioration in speech perception at higher presentation levels.

The *aided benefit* in the rising group was significantly higher than the rollover group for both aided linear and non-linear conditions. This was significant for both PB words and three vowel contexts except in the context of /u/ for aided non-linear condition. The higher performance in the rising group can be attributed to better neural synchrony compared to the rollover group who probably had poorer neural synchrony.

6. Relation between PI-PB function / PI-PB rollover ratio / TMTF threshold with Amplification conditions

In the current study, there existed no correlation between SIS in various PI-PB function levels and the unaided SIS except at 40 to 60 dB HL. On the other hand, there was a moderate, significant correlation between SIS obtained at 30 dB HL and the two aided scores. The SIS at other intensity levels (40, 50, 60, 70, 80, & 90 dB HL) had a strong significant correlation with the SIS in the two aided conditions. Hence, the *null hypothesis 7, "No significant relation between speech identification score across different intensity levels and unaided, aided-linear and aided non-linear stimuli", is rejected*.

The strong correlation noted between three of the presentation levels in the PI-PB function (40, 50 & 60 dB HL) and unaided SIS is due to the similarity in presentation level adopted in the two measures. Although the unaided testing was done at 50 dB HL, it can be noted that a there continues to be a strong correlation with the presentation levels that vary by ± 10 dB HL.

The strong correlation between SIS at higher intensity levels and aided SIS indicate that PI-PB function is a good indicator of aided speech perception in ANSD. Cone-Wesson et al. (2001) suggested that performance-intensity function in individuals with ANSD might be a good indicator of aided speech perception improvement. They reported that those with a rising PI-PB function might show benefit using hearing aids whereas those with a flat or rollover PI-PB function might show lack of benefit. Accordingly, the results of the present study also indicate that the participants who had SIS that increased with presentation levels had improvement in speech perception using hearing aids. In contrast, those having reducing SIS with increase in presentation levels had poor aided speech perception.

It was found in the present study that TMTF peak threshold had a strong negative correlation with the unaided as well as the two aided SIS. It is well documented that temporal resolution is a deciding factor of speech perception in individuals with ANSD (Kumar & Jayaram, 2005; Narne, 2008; Rance et al., 2004). Thus, obtaining the temporal resolution abilities using TMTF might be an indicator of aided performance in individuals with ANSD. Further, in the present study there was a moderate negative correlation between rollover ratio and the two aided scores, whereas a weak negative correlation was found between the rollover ratio and unaided scores. Thus, higher the rollover ratio, larger was the speech perception deficit at higher presentation levels leading to severe impairment in aided speech perception. Hence, obtaining a PI-PB function in individuals with ANSD might help distinguish those who might improve using hearing aid from those who might not.

7. Comparison of Peak Modulation Detection Thresholds of the Normal Hearing Individuals and those with ANSD, Grouped Based on Their Temporal Processing Ability.

The temporal resolution ability that was investigated using TMTF in the current study showed higher modulation detection thresholds in individuals with ANSD compared to normal listeners. Further, in both groups (normal hearing & ANSD) the modulation detection threshold increased as the modulation frequencies increased. Thus,*null hypothesis 8, "There is no significant difference in the peak modulation detection thresholds of the normal hearing individuals and those with ANSD, grouped based on their temporal processing abilities", is rejected.*

The higher modulation detection thresholds in individuals with ANSD compared to normal hearing individuals is consistent with the earlier reports in literature (Kumar & Jayaram, 2005; Narne, 2008; Zeng et al., 2005). Zeng et al. (2005) observed that dys-synchronies or reduced spike rate in those with ANSD led to smeared internal representation of average neural response to physical stimuli. This smeared neural representation was considered to cause difficulty in discriminating two stimuli that differed minimally in terms of their amplitude modulation. Further, many investigators have reported that individuals with ANSD exhibit higher modulation detection thresholds at higher frequencies (Kumar & Jayaram, 2005; Narne, 2008; Zeng et al., 2005). Kumar and Jayaram (2005) attributed the higher modulation detection thresholds at higher modulation frequencies to different levels of the auditory system being responsible for processing of modulated signals. They proposed this explanation based on the observations made by Giraud et al. (2000) who found higher modulation frequencies to be processed at the level of the auditory nerve and brainstem, while the thalamus and auditory cortex to be responsible for lower modulation frequencies. Further, as noted by Frisina (2001), synchronous response was considered essential for temporal coding at the level of the auditory nerve and brainstem while higher centres needed less synchronous firing. Hence, it was concluded by Kumar and Jayaram that dys-synchronous firing at the brainstem level in those with ANSD could lead to poor processing of higher modulation frequencies.

Thus, from the findings of the current study it can be inferred that individuals with ANSD exhibit severe deficit in temporal resolution that impairs their perception of speech. Time scale modification of the entire speech signal was found to improve their speech perception significantly. On the other hand, spectro-temporal modification was found to deteriorate perception of speech. There was a significant difference in speech identification scores between the temporal processing deficit groups for both unprocessed and two modified stimuli. However, the change in speech perception due to stretching did not vary between the temporal processing deficit groups. In contrast, the change in speech perception due to spectro-temporal modification did vary significantly between the temporal processing deficit groups. The three amplification conditions vary significantly between the temporal processing deficit groups. However, there was no significant difference in aided benefit between the temporal processing severity groups. A large number of individuals showed evidence of rollover at higher intensity levels. Those who showed lesser rollover had significant improvement in speech perception using hearing aids. Use of linear and non-linear amplification strategies did not alter speech perception significantly. Thus, the study does shed light on a promising means of habilitation for those with late onset ANSD, which could be tried also on children with the condition.

CHAPTER- 6- SUMMARY AND CONCLUSIONS

Individuals with Auditory Neuropathy Spectrum Disorder (ANSD) have been noted to have more problems processing temporal information compared to frequency or intensity information (Barman, 2008; Starr et al., 1991; Zeng et al., 2005). Severe deficits in temporal resolution has been found to adversely affect their speech perception abilities. Hence, rehabilitative techniques for ANSD to compensate for impaired temporal resolution to improve speech perception are required.

Several rehabilitation techniques have been recommended for those with ANSD. Modification of speech signal using different signal enhancement algorithms is found to be an effective approach to improve speech perception. Time scale modification of short and dynamic acoustic cues have been shown to improve perception of stops (Hassan, 2011; Kumar & Jayaram, 2011; 2013). However, difficulty in identifying these dynamic cues in long segments of speech necessitates the use of alternative techniques to alleviate temporal processing difficulties of individuals with ANSD. Similarly, the enhancement of temporal envelope of speech was reported to improve speech perception in ANSD (Narne & Vanaja, 2008). However, this did not improve the perception liquid speech sounds. Hence, further research on signal modification in ANSD is warranted.

Amplification of speech using hearing aids is yet another available rehabilitative option for individuals with late onset ANSD. Studies on the usefulness of amplification in those with late onset ANSD often showed limited or unsuccessful outcome (Miyamoto et al., 1999; Shallop et al., 2001; Sininger et al., 1995; Widen et al., 1995). It was hypothesized by Hood (1998) that a compression circuit in a hearing aid might distort the temporal envelope of speech causing deterioration in speech perception. Thus, there is a possibility that hearing aids with linear amplification, that preserves temporal envelope of speech, could be used instead of compression hearing aids in individuals with ANSD. However, there are a few studies that show improvement in speech perception with the use of hearing aids in some individuals with late onset ANSD (Jijo & Yathiraj, 2013b; Narne et al., 2014b; Vanaja & Manjula, 2004). Research is required to determine the factor that enables some individuals with ANSD to benefit from hearing aids and others not to.

The aim of the study was to investigate the effect of two signal enhancement strategies as well as PI-PB function and aided performance in 30 individuals with late onset ANSD. The study was executed in four phases. In the first phase the effect of two signal enhancement strategies on perception were evaluated. The second phase of the study, investigated the effect of intensity on speech perception in individuals with ANSD. This was carried out by obtaining a performance-intensity for phonemically balanced (PI-PB) function as well as aided performance using linear and non-linear hearing aid amplification. In the third phase, temporal processing ability was evaluated using TMTF in both normal hearing individuals and individuals with ANSD. In the final phase participants with ANSD were grouped based on their temporal resolution abilities and PI-PB function.

Two groups of participants were included in the study, those having ANSD and those having normal hearing. The former group had 30 individuals, aged 14 to 42 years

(12 males & 18 females), and the latter had 40 individuals, aged 18 to 35 years. Among the 40 normal hearing individuals, 10 were recruited for the development of the stimuli and the remaining 30 were evaluated in the third phase of the study, to obtain a baseline for temporal resolution using TMTF, in a sound-field set-up. The 30 participants with ANSD were evaluated in the first three phases of the study and based on their performance in Phases II and III, they were grouped in two different ways in Phase IV. The first grouping was done based on the temporal resolution abilities of the participants and the second was based on their PI-PB function. Based on their temporal processing difficulties, the participants were grouped as having mild, moderate and severe difficulty. Further, based on their PI-PB function they were grouped as having a rising or rollover functions.

The participants were evaluated using phonemically balanced word test developed by Yathiraj and Vijayalakshmi (2005) and amplitude modulated white noise developed by Narne (2008). Additionally, they were evaluated using 30 natural vowel-consonant-vowel (VCV) syllables comprising of 10 stop and liquid consonants (/p/, /t/, /k/, /b/, /d/, /g/, / t̪ /, /d̪ /, /l/, /r/) in the context of three vowels (/a/, /i/ and /u/). These natural syllables were modified temporally and spectro-temporally to develop enhanced stimuli. The data obtained were analysed within and across participant groups. The major findings and conclusions of the study are as follows:

Effect of Temporal processing and Performance-Intensity Function on Word Identification Scores in Individuals with ANSD

- There was a significant difference in word identification scores between the temporal processing deficit groups. The word identification scores deteriorated as their temporal processing deficit increased.
- In the rising PI-PB function group, increasing the presentation level by 10 dB resulted in significant improvement in SIS up to 20 dB SL, beyond which the SIS was stable.
- In the rollover PI-PB function group, each 10 dB increment resulted in significant deterioration in performance.

Effect of Speech Modification Strategies (stretch & spectro-temporal modification) on Speech Identification in Participants Grouped Based on Their Temporal Processing Difficulty

- Compared to speech identification using unprocessed stimuli, stretching the entire stimuli by a 25% resulted in significant improvement in perception in all three temporal processing severity groups (mild, moderate & severe).
- In contrast, the spectro-temporal modification of stimuli caused deterioration in speech perception in the moderate and severe temporal processing deficit group whereas the mild group showed no significant difference in speech perception.
- Comparison between spectro-temporally modified and stretched stimuli showed significantly higher speech perception in the latter condition in all three temporal processing deficit groups.
- Overall, the mild group performed significantly better than the moderate and severe groups in all three stimulus modified conditions. The moderate group performed better than the severe group in all three stimulus modified conditions. However, their SIS scores were significantly

different only for the spectro-temporally modified VCV syllable in the context of /a/ and stretched syllables in the context of/u/.

- The change in speech perception due to stretching did not vary between the temporal processing deficit groups. In contrast, the change in speech perception due to spectro-temporal modification did vary significantly between temporal processing deficit groups.

Effect of Vowel Context on Speech identification in Participants Grouped Based on Their Temporal Processing Severity

- In the context of the vowel /i/, consonant perception deteriorated more compared to consonant perception in the context of /a/ and /u/. This was observed in all three stimulus modified conditions and temporal processing deficit groups, except in the severe group. In the severe group, it was not significant.
- In the context of vowel /a/ and /u/ there was no significant difference in consonant perception observed.
- The results of information transfer analyses showed highest perception of consonantal features (manner, place, & voicing) in the context of /a/ followed by /u/, and it was the least in the context of /i/.
- Perception of consonantal features improved using stretched stimuli, whereas spectro-temporal modification resulted in deterioration in perception of all three consonant features.

Effect of Amplification Conditions on Speech Identification in Participants Grouped Based on Their Temporal Processing Deficits

- There was no significant difference in speech perception between the unaided and two aided conditions (linear & non-linear) in all three temporal processing severity groups, either using VCV syllables or words.

- Similarly, there was no significant difference in speech perception between the two aided conditions.
- Comparison between the temporal processing deficit groups showed that the mild group outperformed the moderate and severe groups in all three amplification conditions (unaided, aided linear & aided non-linear). Although the moderate group performed higher than the severe group in all three amplification conditions, it was insignificant in the aided linear condition.
- There was no significant difference in aided benefit between the temporal processing severity groups.

Effect of Amplification Conditions on Speech Identification in PI-PB function Groups

- In general, the rising PI-PB function group showed significant improvement in speech identification using both linear and non-linear amplification.
- In contrast, in the rollover PI-PB function group, there was no significant difference between unaided and two aided conditions.
- There was no significant difference between linear and non-linear amplification in both the PI-PB function groups.
- Comparison between rising and rollover groups showed no significant difference between them in the unaided condition. However, both the aided conditions resulted in significantly higher perception in the rising group compared to the rollover (except VCVs in the context of /u/).
- The aided benefit in the rising group was significantly higher than the rollover group for both aided linear and non-linear conditions.

Relation between PI-PB function / PI-PB rollover index / TMTF threshold with Scores in Different Amplification Conditions

- There was a strong positive correlation found between word recognition scores obtained in the PI-PB function and two aided word recognition scores. However, only a moderate correlation was noted in the unaided condition (except at 40, 50, & 60 dB HL).
- There was a strong negative correlation found between TMTF peak threshold and three amplification conditions (unaided, aided linear & aided non-linear). A moderate correlation was found between PI-PB rollover ratio and the two aided conditions.
- However, only a weak correlation was observed between word identification in the unaided condition and PI-PB rollover index.

Thus, from the findings of the current study it can be inferred that individuals with ANSD exhibit severe deficit in temporal resolution that impairs their perception of speech. Time scale modification of the entire speech signal was found to improve their speech perception significantly. In contrast, spectro-temporal modification was found to deteriorate speech perception. A large number of individuals showed evidence of rollover at higher intensity levels, when a PI-PI function was tested. Those who showed lesser rollover had significant improvement in speech perception using hearing aids. Use of linear and non-linear amplification strategies did not alter speech perception significantly.

Implication of the study

- Stretching the entire duration of the signal by 25% is a viable option to improve speech perception in individuals with ANSD. Such stretched speech stimuli could be used for rehabilitation of individuals with ANSD, irrespective of their temporal processing severity.

- As consonant perception in the context of context /i/ and /a/ provided a wide range of perceptual difficulties in individuals with ANSD, speech identification should be done using these vowel environments.
- PI-PB function in individuals with ANSD gives a clear indication of those who are likely to benefit or not benefit from hearing aids.
- A wide dynamic range compression hearing aid with small compression ratio results in similar speech perception performance as a linear hearing aid.

REFERENCES

American National Standard Institute (1999). *Maximum Permissible Ambient Noise for Audiometric Rooms.* ANSI S3.1-1999. New-York: American National Standard Institute.

American National Standard Institute (2004). *American National Standard for Audiometers*. ANSI S3.6-2004. New-York: American National Standard Institute.

American National Standard Institute (R1996). *American National Standard Specifications for Instruments to Measure Aural Acoustic Impedance and Admittance (Aural Acoustic Immittance).* ANSI S3-39-1987 (R 1996). New-York: American National Standard Institute.

Apoux, F., Tribut, N., Debruille, X., & Lorenzi, C. (2004). Identification of envelope-expanded sentences in normal hearing and hearing impaired listeners. *Hearing Research, 189*, 134-24.

Barman, A. (2008). *Psycho-acoustical profile in normals and individuals with auditory dys-synchrony*. Unpublished doctoral thesis submitted to University of Mysore. Mysore, India.

Bench, J., & Bamford, J. (1979). *Speech-hearing tests and the spoken language of hearing-impaired children*. London: Academic Press.

Berlin, C. I. (1999). Auditory neuropathy: Using OAEs and ABRs from screening to management. *Seminars in Hearing, 21*, 307-315.

Berlin, C. I., Hood, L. J., & Rose, K. (2001). On renaming auditory neuropathy as auditory dys-synchrony. *Audiology Today*, *13*, 15-17.

Berlin, C. I., Hood, L. J., Cecola, R. P., Jackson, D. F. & Szabo, P. (1993). Does Type I afferent neuron dysfunction reveal itself through lack of efferent suppression, *Hearing Research, 65,* 40-50.

Berlin, C. I., Hood, L. J., Goforth-Barter, L., & Bordelon, J. (1999). Auditory neuropathy: three time courses after early identification. *ARO Abstracts*, *22*, 169.

Berlin, C. I., Hood, L. J., Morlet, T., Rose, K., & Brashears, S. (2002). Auditory Neuropathy/Dys-Synchrony: After the Diagnosis, then What? *Seminars in Hearing, 23,* 209-214.

Berlin, C. I., Hood, L. J., Morlet, T., Wilensky, D., Li, L., Mattingly, R. K., Frisch, A. S. (2010). Multi-site diagnosis and management of 260 patients with auditory neuropathy/dys-synchrony (auditory neuropathy spectrum disorder). *International Journal of Audiology, 49*: 30–43.

Berlin, C. I., Hood, L. J., Morlet, T., Wilensky, D., St John, P., Montogomery, E., & Thibodaux, M. (2005). Absent or elevated middle ear muscle reflexes in the presence of normal otoacoustic emissions: a universal finding in 136 cases of auditory neuropathy/ dys-synchrony. *Journal of American Academy of Audiology, 16,* 546-553.

Bhat, J. S., Kumar, K., & Sinha, S. K. (2007). Auditory neuropathy/dys-synchrony in school aged hearing impaired children: A south Indian perspective. *Asia Pacific Journal of Speech Language and Hearing, 10*, 157-164.

Bhattacharya, A., & Zeng, F. (2007). Companding to improve cochlear-implant speech recognition in speech-shaped noise. *Journal of the Acoustical Society of America, 122,* 1079– 1089.

Breneman, I. A., Gifford, H. R., & Dejong, D. M. (2012). Cochlear implantation in children with auditory neuropathy spectrum disorder: long term outcomes. *Journal of American Academy of Audiology, 23,* 5-17.

Butinar, D., Zidar, J., Leonardis, L., Popovic, M., Kalaydjieva, L., Angelicheva, D.,........Starr, A. (1999). Hereditary auditory, vestibular and motor neuropathy in Slovenian Roma (Gypsy) kindred. *Annals of Neurology, 46,* 36-44.

Carhart, R., & Jerger, J. (1959). Preferred method for clinical determination of pure-tone thresholds. *Journal of Speech and Hearing Disorders, 24,* 330-345.

Cone Wesson, B., Rance, G. & Sininger, Y.S. (2001). Amplification and rehabilitation strategy for patients with auditory neuropathy. In Sininger YS & Starr A (eds.) *Auditory Neuropathy: A New Perspective on Hearing Disorders*. Sandiago: Singular-Thomson Learning, pp. 233-250.

Delattre, P. C., Liberman, A. M., & Cooper, F. S. (1955). Acoustic loci and transitional cues for consonants. *Journal of the Acoustical Society of America,* 27, 769-773.

Delmaghani, S., del Castillo, F. J., Michel, V., Leibovici, M., Aghaie, A., Ron, U.,.....Petit, C. (2006). Mutation in the gene encoding pejvakin, a newly identified protein of the afferent auditory pathway, cause DFNB59 auditory neuropathy. *Nature Genetics, 38*, 770-778.

Deltenre, P., Mansbach, A. L., Bozet, C., Christiaens, F., Barthelemy, P.,Paulissen, D., & Renglet, T. (1999). Auditory neuropathy with preserved cochlear microphonics and secondary loss of otoacoustic emissions. *Audiology, 38*, 187-195.

Dirks, D. D., Kamm, C., Bower, D., & Betsworth, A. (1977) Use of Performance-Intensity Functions for Diagnosis. *Journal of Speech and Hearing Disorders, 42,* 408-415.

Donaldson, G. S., Kreft, H. A. (2006). Effect of vowel context on the recognition of initial and medial consonants by cochlear implant users. *Ear and Hearing, 27,* 358 – 677.

Dorman M., Studdert-Kennedy M & Raphael, L . (1977). Stop consonant recognition release burst and formant transition as functionally equivalent context dependent cues. *Perception and Psychophysics*, 22, 109-122.

Drullman, R., Festen, J. M., & Plomp, R. (1994). Effect of temporal envelope smearing on speech perception. *Journal of the Acoustical Society of America, 95,* 1053-1064.

Fortune, T. W., Woodruff, B. D., & Preves, D. A. (1994). A new technique for quantifying temporal envelope contrasts. *Ear and Hearing, 15,* 93–99.

Frisina, R. D. (2001). Subcortical neural coding mechanisms for auditory temporal processing. *Hearing Research*, *158,* 49-54.

Gallun, F., & Souza, P. (2008). Exploring the role of the modulation spectrum in phoneme recognition. *Ear and Hearing, 29,* 800 – 813.

Gang, R.P. (1976). The effect of age on the diagnostic utility of the rollover phenomenon. *Journal of Speech and Hearing Disorders, 41,* 63-69.

Giraud, A., Lorenzi, C., Ashburner, J., Wable, J., Johnsrude, I., Frackowiak, R., Kleinschmidt, A. (2000). Representation of the temporal envelope of the sounds in the human brain. *Journal of Neurophysiology*, 84, 1588-1598.

Hassan, D. M. (2011). Perception of temporally modified speech in auditory neuropathy. *International Journal of Audiology, 50,* (1) 41 – 49.

Hickson, L., Dodd, B., & Byrne, D. (1994) Consonant perception with linear and compression amplification*. Scandinavian Audiology, 24,* 175-184.

Hood, L. J. (1998). Auditory neuropathy: what is it and what can we do about it? *Hearing Journal, 51,* 10-18.

Jerger, J., & Jerger, S. (1971). Diagnostic significance of PB word functions. *Achieves in Otolaryngology*, *93,* 573-580.

Jerger, J., & Jerger, S. (1976). Comments on Effect of age on the diagnostic utility of the rollover phenomenon. *Journal of Speech and Hearing Disorders. 41*, 556-557.

Jestand, M. L., Souza, P. E. (2005). Quantifying the effect of compression hearing aid release time on speech acoustics and intelligibility. *Journal of Speech Language and Hearing Research, 48,* 651-657.

Jijo, P. M., & Yathiraj, A. (2012). Audiological characteristics and duration of the disorder in individuals with auditory neuropathy spectrum disorder (ANSD) – a retrospective study. *Journal of Indian Speech Language and Hearing Association, 26*, 17–26.

Jijo, P. M., & Yathiraj, A. (2013a). Effect of temporal modification and vowel context on speech perception in individuals with auditory neuropathy spectrum disorder (ANSD). *Hearing Balance and Communication*, *11,* 198-207.

Jijo, P. M., & Yathiraj, A. (2013b). Audiological findings and aided performance in auditory neuropathy spectrum disorder: A retrospective study. *Journal of Hearing Science, 3*, 18-26.

Kalaydjieva, L., Gresham, D., Gooding, R., Heather, L., Bass, F., de Jonge, R.,.....Thomas, P.K. (2000). N-myc downstream-regulated gene 1 is muted in hereditary motor and sensory neuropathy- Lom. *American Journal of Human Genetics*, *67*, 47-58.

Katona, G., Buki, B., Farkas, Z., Pytel, J., Simon-Nagy, E., & Hirschberg, J. (1993). Transitory evoked otoacoustic emission (TEOAE) in a child with profound hearing loss. *International Journal of Paediatric Otorhinolaryngology*, *26*(3), 263-267.

Kewley-Port. (1982). Measurement of formant transition in a naturally produced stop consonant vowel syllable. *Journal of the Acoustical Society of America*, *72*, *379-389.*

Kovach, M. J., Lin J., Boyadjiev, S., Campbell, K., Mazzeo, L., Herman, K.,......Kimonis, V.E. (1999). A unique point mutation in the PMP22 gene is associated with Charcot-Marie-Tooth disease and deafness. *American Journal of Human Genetics*, *64*, 1580-1593.

Kraus, N., Bradlow, A. R., Cheatham, M. A., Cunningham, J., King, C. D., Koch, D. B., Wright, B. A. (2000). Consequences of neural synchrony: A case of auditory neuropathy. *Journal of the Association for Research in Otolaryngology 1*(1), 33-45.

Krause, J. C., & Brida, L. D. (2004). Acoustic properties of naturally produced clear speech at normal speaking rates. *Journal of the Acoustical Society of America, 115*, 362–378.

Kumar U. A., & Jayaram, M. (2005). Auditory processing in individuals with auditory neuropathy. *Behavioural and Brain Functions*, 1:21. doi:10.1186/1744-9081-1-21.

Kumar, A. U., & Jayaram, M. (2006). Prevalence and audiological characteristics in individuals with auditory neuropathy/auditory dys-synchrony. *International Journal of Audiology, 45*, 360-366.

Kumar, A. U., & Jayaram, M. K. (2011). Speech perception in individuals with auditory dys-synchrony. *Journal of Laryngology and Otology, 125,* 236 – 245.

Kumar, A. U., & Jayaram, M. K. (2013). Speech perception in individuals with auditory dys-synchrony: effect of lengthening of voice onset time and burst duration of speech segments. *Journal of Laryngology and Otology*, *127*, 656 – 665.

Kumar, A.U. (2006). *Perception of some temporal parameter in speech in individuals with auditory dys-synchrony*. Unpublished doctoral thesis. University of Mysore, Mysore, India.

Lahiri, A., Gewirth, L., & Blumstein, S. E. (1984). A reconsideration of acoustic invariance for place of articulation in diffuse stop consonants: Evidence from a cross language study, *Journal of the Acoustical Society of America*, *76*, 391–404.

Lee, J. S. M., McPherson, B., Yuen, K. C. P., & Wong, L. L. N. (2001). Screening for auditory neuropathy in a school for hearing impaired children. *International Journal of Pediatric Otorhinolaryngology, 61, 39-46.*

Leonardis, L., Zidar, J., Popovic, M., Timmerman, V., Lofgren, A., Broeckhoven, C., Butinar, D. (2000). Hereditary motor and sensory neuropathy associated with auditory neuropathy in a Gypsy family. *European Journal Physiology, 439,* 208-210.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49,* 467-477.

Lisker, L. (1957). Closure duration and the intervocalic voiced-voiceless distinction in English. *Language*, 33, 42–9.

Lisker, L. (1986). ‘Voicing’ in English: A Catalogue of Acoustic Features Signaling /b/ Versus /p/ in Trochees. *Language and Speech. 29*(1), 3–11.

Lorenzi, C., Wable, J., Moroni, C., Derobert, C., Frachet & Berlin, C. (2000). Auditory temporal envelope processing in a patient with left hemisphere damage. *Neurocase, 6*, 231-244.

Lynne, A., Werner & Gray, L. (1998). Behavioural studies of hearing development. In E, Rubel., A. Popper & R.R, Fay (Edn).*Development of Auditory System*. Pp, 15-47, NY, Springer.

Madden, C., Rutter, M., Hilbert, L., Greinwald, J., & Choo, D. (2002). Clinical and audiological features in auditory neuropathy. *Archives of Otolaryngology Head and Neck Surgery*, *128*, 1026-1030.

Malah, D. (1979). Time domain algorithms for harmonic bandwidth reduction and time scaling of speech signals. *IEEE Transactions on Acoustics, Speech and Signal Processing, 27*, 121-133.

Mason, J. C., De Michele, A., Stevens, C., Ruth, R. A., & Hashisaki, G. T. (2003). Cochlear implantation in patients with auditory neuropathy of varied etiologies. *Laryngoscope, 113*, 45-49.

Merlini, L., Villanoa, M., & Sabtalli, P. (1998). Hereditary motor and sensory neuropathy Lom type in an Italian Gypsy family. *Neuromuscular Disorders, 8*, 182-185.

Merzenich, M., Jenkins, W. Johnston P, Schreiner C., Miller S., & Tallal P. (1996). Temporal processing deficits of language-learning impaired children ameliorated by training. *Science*, 271, 77–81.

Miranda, T. T., & Pichora-Fuller, M. T. (2002). Temporally Jittered Speech Produces Performance Intensity, Phonetically Balanced Rollover in Young Normal-Hearing Listeners. *Journal of American Academy of Audiology, 13,* 50-58.

Miyamoto, R. T., Kirk, K. I., Renshaw, J., & Hussain, D. (1999). Cochlear implantation in auditory neuropathy. *Laryngoscope, 109*, 181-185.

Moulines, E., & Laroche, J. (1995). Non-parametric techniques for pitch scale and time-scale modification of speech. *Speech Communication*, *16*, 175-205.

Nagarajan, S. S., Wang, X., Merzenich, M. M., Schreiner, C. E., Johnston, P., Jenkins, W. M., Miller, S., & Tallal, P. (1998). Speech modification algorithms used for training language learning-impaired children. *IEEE Transactions on Rehabilitation Engineering, 6*, 257-268.

Narne, V. K., & Vanaja, C. S. (2008). Effect of envelope enhancement on speech perception in individuals with auditory neuropathy. *Ear and Hearing*, *29*, 45-53.

Narne, V. K., & Vanaja, C. S. (2009b). Perception of envelope enhanced speech in the presence of noise in individuals with auditory neuropathy. *Ear and Hearing*, *30*, 136–142.

Narne, V. K., Barman, A., Deepthi, M & Scachi (2014b). Effect of companding on speech recognition in quiet and noise for listeners with ANSD. *International Journal of Audiology, 53(*2), 94-100.

Narne, V. K., Prabhu, P., Chandan, H. S., & Deepthi, M. (2014a). Audiological profiling of 198 individuals with auditory neuropathy spectrum disorder. *Hearing, Balance and Communication, 12,* 112-120.

Narne, V.K & Vanaja, C.S (2012). Speech Identification with Temporal and Spectral Modification in Subjects with Auditory Neuropathy. *ISRN Otolaryngology*. doi:10.5402/2012/671247.

Narne, V.K. (2008). *Perception of spectral and temporal modification of speech in individuals with auditory dys-synchrony*. Unpublished doctoral thesis submitted to the University of Mysore.

Narne, V.K. (2013). Temporal processing and Speech Perception in Noise by Listeners with Auditory Neuropathy. *Plos one, 8*, 1-11.

Narne, V.K.,& Vanaja, C.S. (2009a). Perception of speech with envelope enhancement in individuals with auditory neuropathy and simulated loss of temporal modulation processing. *International Journal of Audiology*, 48, 700-707.

Nike, G. G., & Barman, A. (2011). *Relation between consonant perception and psychoacoustic measures in individuals with auditory dys-synchrony*. Unpublished masters dissertation. University of Mysore, Mysore, India.

Nittrouer, S., & Studdert-Kennedy, M. (1987). The role of coarticulatory effects in the perception of fricatives by children and adults. *Journal of Speech and Hearing Research*, 30, 319–329.

Picheny, M. A., Durlach, N. I., & Braida, L. D. (1986). Speaking clearly for the hard of hearing. II. Acoustic characteristics of clear and conversational speech. *Journal of Speech Language and Hearing Research, 29*, 434–446.

Pickett, J. M., Bunnel, H, T., & Revoile, S. G. (1995). Phonetics of intervocalic consonant perception: retrospect and prospect. *Phoneticia, 52*, 1 – 40.

Pinsky, E (2011) Amplification and Team Management of a Pediatric Patient with Suspected ANSD. *Hearing Review. 18*(11) 24-26.

Plomp, R. (1988). The negative effect of amplitude compression in multichannel hearing aids in the light of the modulation transfer function. *Journal of the Acoustical Society of America, 83,* 2322-2327.

Prabhu, P., Avilala, Y. K. V & Barman (2011). Speech perception abilities for spectrally modifi ed signals in individuals with auditory dys-synchrony. *International Journal of Audiology*. *50* (5), 349-352.

Prabhu, P., Avilala, Y. K. V., & Manjula, P. (2012). Predisposing factors in individuals with late-onset auditory dys-synchrony. *Asia Pacific Journal of Speech, Language, and Hearing*, *15*(1), 41-50.

Ramirez, J., & Mann, V. (2005). Using auditory visual speech to probe the basis of noise impaired consonant vowel perception in dyslexia and auditory neuropathy. *Journal of the Acoustical Society of America*, *118*, 1122-1133.

Rance, G. (2005). Auditory neuropathy/dys-synchrony and its perceptual consequences. *Trends in Amplification, 9* (1), 1-43.

Rance, G., & Barker, E. (2007). Speech perception in children with auditory neuropathy/dys-synchrony managed with either hearing aids or cochlear implants. *Otology Neurotology, 29*, 179-182.

Rance, G., & Barker, E. J. (2009). Speech and language outcome in children with auditory neuropathy/dys-synchrony managed with either cochlear implants or hearing aids. *International Journal of Audiology*, *48,* 313–20.

Rance, G., Barker, E. J., Sarant, J. Z., & Ching, T. (2007a). Spoken language abilities in children with auditory neuropathy/dys-synchrony type hearing loss. *Ear and Hearing*, *28*(5), 694-702.

Rance, G., Barker, E., Mok, M., Dowell, R., Rincon, A., & Garratt, R. (2007b). Speech perception in noise for children with auditory neuropathy/dys-synchrony type hearing loss. *Ear and Hearing*, *28* (3), 351- 360.

Rance, G., Beer, D. E., Cone-Wesson, B., Shepherd R. K., Dowell, R. C., King, A. K., Rickards, F. W., & Clark, G. M. (1999). Clinical findings for a group of infants and young children with auditory neuropathy. *Ear and Hearing, 20*, 238-252.

Rance, G., Cone-Wesson, B., Wunderlich, J., & Dowell, R. C. (2002). Speech perception and cortical event related potentials in children with auditory neuropathy. *Ear and Hearing, 23*, 239-253.

Rance, G., Corben, L., Barker, E., Carew, P., Chisari, D., Rogers, M., Dowell, R., Jamaluddin S., Bryson, R., & Delatycki, M. B. (2010). Auditory perception in individuals with Friedreich's ataxia. *Audiology Neurotology, 15*, 229-240.

Rance, G., Fava, R., Baldock, H., Chong, A., Barker, E., Corben, L., & Delatycki, M. (2008). Speech perception ability in individuals with Friedeich ataxia. *Brain, 131*, 2002-2012.

Rance, G., McKay, C., & Grayden, D. (2004). Perceptual characterization of children with auditory neuropathy. *Ear and Hearing, 25*, 34-46.

Raveh, E, Buller, N, Ola Badrana, Attias, J. (2007). Auditory neuropathy: clinical characteristics and therapeutic approach. *American Journal of Otolaryngology*. *28*, 302-308.

Rodriguez- Ballesteros, M., del Castillo, F. J., Martin, Y., Moreno-Pelayo, M. A., Morera, C.,.......del Castillo, I. (2003). Auditory neuropathy in patients carrying mutations in the otoferlin gene (OTOF). *Human Mutations, 22*, 451-456.

Rodriguez Ballesteros, M., Reynoso, R., Olarte, M., Villamar, M., Morera, C., Prieto, F.,....... del Castillo, I. (2009). A multicenter study on the prevalence and spectrum of mutations in the otoferlin gene (OTOF) in subjects with non syndromic hearing impairment and auditory neuropathy. *Journal of Human Genetics*, *54*, 382-385.

Rosen, S. (1992). Temporal information in speech: acoustic, auditory and linguistic aspects: Philosophical transactions. *Biological Sciences*, *336*, 367–373.

Rothman, K. J. (1990). No adjustments are needed for multiple comparisons. *Epidemiology, 1,* 43-46.

Roush, P., Frymark, T., Venediktov, R., & Wang, B. (2011). Audiologic Management of Auditory Neuropathy Spectrum Disorder in Children: A Systematic Review of the Literature. *American Journal of Audiology, 20,* 159-170.

Sachs, M. B., & Young, E. D. (1979). Representation of steady-state vowels in the temporal aspects of the discharge patterns of populations of auditory nerve fibres. *Journal of Acoustic Society of America*, *66,* 1381-1403.

Savithri, S.R., Swapna, N., Rajeev (1996). *Speech perception in children. Temporal aspects*. Project report submitted to the department of science and technology, India.

Shallop, J. K. (2002). Auditory neuropathy/ Dys-Synchrony in adults and children. *Seminars in Hearing*, 23(3), 215-222.

Shallop, J. K., Peterson, A., Facer, G. W., Fabry, L. B., & Driscoll, C. L. (2001). Cochlear implants in five cases of auditory neuropathy: Postoperative findings and progress. *Laryngoscope, 111,* 555-562.

Shivashankar, N., Satishchandra, P., Shashikala, H. R., & Gore, M. (2003). Primary auditory neuropathy- an enigma. *Acta Neurologica Scandinavica*, *108,* 130-135.

Shrinian, M. J., & Arnst, D. (1980). PI-PB rollover in a group of aged listeners. *Ear and Hearing, 1*, 50-53.

Sininger, Y. S., Hood, L. J., Starr, A., Berlin, C. I., & Picton, T. W. (1995). Hearing loss due to auditory neuropathy. *Audiology Today, 1*, 10-13.

Sininger, Y.S., & Hayes, D. (2008). At the consensus conference on auditory neuropathy/ Dys-dynchrony, NHS, Como, Italy, June 19-21.

Sininger, Y.S., & Oba, S. (2001). Patients with auditory neuropathy: Who are they and what can they hear? In Sininger YS, Starr A (eds): *Auditory Neuropathy A New Perspective on Hearing Disorders* San Diego: Singular Publishing, 15-36.

Spirakis, E. S. (2011). Auditory neuropathy spectrum disorder and hearing aids: rethinking fitting strategies: *Hearing Review*.18(11), 28-33.

Starr, A., McPherson, D., Patterson, J., Don, M., Luxford, W., Shannon, R., Sininger, Y. S., Tonakawa, L., & Waring, L. (1991). Absence of both auditory evoked potentials and auditory percepts dependent on timing cues. *Brain, 111*, 1157-1180.

Starr, A., Picton, T. W., Sininger, Y. S., Hood, L. J., & Berlin, C. I. (1996). Auditory Neuropathy. *Brain*, *119*, 741–753.

Starr, A., Sininger, Y. S. & Pratt, H. (2000). The varieties of auditory neuropathy. *Journal of Basic Clinical Physiology and Pharmacology, 11*, 215– 230.

Tallal, P., Miller, S. L., Bedi, G., Byma,G., Wang, X., Nagarajan,S. S., Schreiner, C., Jenkins, W. M., & Merzenich, M. M. (1996). Language comprehension in language learning impaired children improved with acoustically modified speech. *Science 271*, 81-84.

Tang, T. P. Y., McPherson, B., Yuen, K. C. P., Wong, L. L., & Lee, J.S. (2004). Auditory neuropathy/auditory dys-synchrony in school children with hearing loss: Frequency of occurrence. *International Journal of Paediatric Otorhinolaryngology, 61, 75*-183.

Trautwein, P., Sininger, Y. S., & Nelson, R. (2000). Cochlear implantation of auditory neuropathy. *Journal of American Academy of Audiology, 11*, 309-315.

Uchanski, R. M., Geers, A. E., & Protopapas, A. (2002). Intelligibility of Modified Speech for Young Listeners With Normal and Impaired Hearing. *Journal of Speech, Language, and Hearing Research, 45*, 1027–1038.

Van Tasell, D. J. (1993). Hearing loss, speech, and hearing aids. *Journal of Speech and Hearing Research, 36*, 228–244.

Vanaja, C. S., & Manjula, P. (2004). *LLR as a measure of benefit derived from hearing devices with auditory dys-synchrony*. In first conference on auditory neuropathy. Edited by Sivashanker N, Shashikala H.R. Bangalore: Department of Speech pathology and Audiology. National Institute of Mental Health and Neuro sciences. 136-146.

Varga, R., Avenarius, M. R., Kelley, P. M., Keats, B. J., Berlin, C. I., Hood, L. J...... Kimberling, W.J. (2006). OTOF mutations revealed by genetic analysis of hearing loss families including a potential temperature sensitive auditory neuropathy allele. *Journal of Medical Genetics. 43*, 576-581.

Varga, R., Kelley, P. M., Keats, B. J., Starr, A., Leal, S. M., Cohn, E., Kimberling, W.J. (2003). Non- syndromic recessive auditory neuropathy is the result of mutations in the otoferlin (OTOF) gene. *Journal of Medical Genetics, 40,* 45-50.

Viemeister, N.F. (1979). Temporal modulation transfer function based upon modulation thresholds. *Journal of Acoustic Society of America. 66,* 1364-1380.

Wang, D. Y., Wang, Y. C., Weil, D., Zhao, Y. L., Rao, S. Q., Zong, L.,.......Wang, Q.J. (2010). Screening mutations in Chinese patients with auditory neuropathy, including a familial case of temperature- sensitive auditory neuropathy. *BMC Medical Genetics, 11,* 79.doi:10.1186/1471-2350-11-79

Wang, Q., Gu, R., Han, D., & Yang, W. (2003). Familial auditory neuropathy. *Laryngoscope, 113,* 1623-1629.

Widen, J. E., Ferraro, J. A., & Trouba, S. E. (1995). Progressive neural impairment: Case report. *Journal of American Academy of Audiology, 1*, 217-224.

Xu, L., Thompson, C. S., & Pfingst, B. E. (2005). Relative contributions of spectral and temporal cues for phoneme recognition. *Journal of the Acoustical Society of America*, *117*, 3255–3267.

Yathiraj A. & Avilala, V. K. Y (2011). *Efficacy of fine-grained auditory training in individuals with auditory Dys-synchrony*. Unpublished Project. All India Institute of Speech and Hearing, Mysore, India.

Yathiraj, A., & Vijayalakshmi, C. S. (2005). *Phonemically balanced word list in Kannada*. A test developed at the department of Audiology, AIISH, Mysore.

Zeng, F. G., & Liu, S. (2006). Speech perception in individuals with auditory neuropathy. *Journal of Speech Language and Hearing Research. 49,* 367-80.

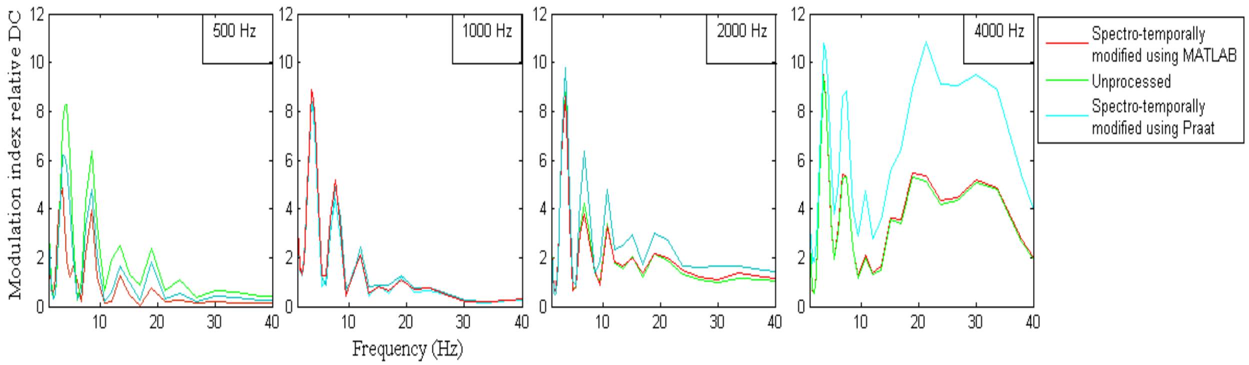
Zeng, F. G., Kong, Y. Y., Michalewski, H. J., &Starr, A. (2005). Perceptual consequences of disrupted auditory nerve activity. *Journal of Neurophysiology, 93*, 3050–3063.

Zeng, F. G., Oba, S., Grade, S., & Starr, A. (1999). Temporal and speech processing deficits in auditory neuropathy. *Neuro Report*, *10*, 3429-3435.

Zeng, F.G., Oba, S., Grade, S., Sininger, Y., & Starr, A. (2001). Psychoacoustics and speech perception in auditory neuropathy. In Y. Sininger & A. Starr (eds.). *Auditory Neuropathy: A New Perspective on Hearing Disorders.* Sandiago: Singular-Thomson Learning, pp. 15-35.

APPENDIX A

Unprocessed and spectro-temporally modified envelope modulation spectra oF the VCV syllable /apa/ using MATLAB as well as Praat, analysed for four octave bands (500 Hz, 1 kHz, 2 kHz, & 4 kHz), presented in relation to energy at 0 Hz or DC.



APPENDIX B

Significance of difference of information transmitted for the three consonantal features in three different stimulus modified conditions and vowel contexts in three temporal processing deficit groups

Group		Vowel context	Unpr vs. str		Unpr vs. spec temp mod		Spec temp mod vs. str	
			z value	p value	z value	p value	z value	p value
Mild	Manner	/a/	1.8	0.85	1.8	0.06	1.3	0.18
		/i/	2.0	0.03*	1.9	0.04*	0.55	0.56
		/u/	0.44	0.65	0.00	1.00	0.44	0.65
	Place	/a/	1.7	0.08	.95	0.34	1.5	0.11
		/i/	1.7	0.08	1.9	0.04*	0.54	0.58
		/u/	4.2	0.67	4.0	0.68	0.85	0.93
	Voicing	/a/	1.1	0.27	.52	0.60	1.9	0.04*
		/i/	0.74	0.45	1.5	0.11	0.96	0.33
		/u/	0.67	0.50	1.0	0.30	1.3	0.59
Moderate	Manner	/a/	1.7	0.86	2.3	0.4*	2.4	0.1*
		/i/	0.08	0.93	2.8	0.01*	2.9	0.00*
		/u/	2.1	0.03*	0.8	0.93	2.2	0.02*
	Place	/a/	0.36	0.71	.83	0.40	1.3	0.16
		/i/	0.71	0.47	1.3	0.19	1.8	0.06
		/u/	0.74	0.45	1.9	0.04*	1.8	0.7
	Voicing	/a/	0.81	0.41	1.0	0.27	0.61	0.51
		/i/	1.9	0.05	.53	0.59	2.3	0.02*
		/u/	0.44	0.65	.32	0.74	0.66	0.50
Severe	Manner	/a/	1.3	0.19	1.1	0.24	0.54	0.58
		/i/	1.3	1.8	1.3	1.6	1.7	0.07
		/u/	1.5	1.1	.41	0.68	1.4	0.14
	Place	/a/	0.96	0.33	.97	0.33	0.00	1.0
		/i/	0.0	1.00	1.4	1.6	1.5	1.3
		/u/	1.0	0.28	0.7	0.48	1.7	0.08
	Voicing	/a/	1.4	0.15	1.5	0.12	1.9	0.05
		/i/	0.0	1.0	1.1	0.25	1.0	0.31
		/u/	0.33	0.73	1.2	0.20	1.6	0.10

Note. Unpr = unprocessed, str = stretched; spec-temp mod = spectro-temporally modified

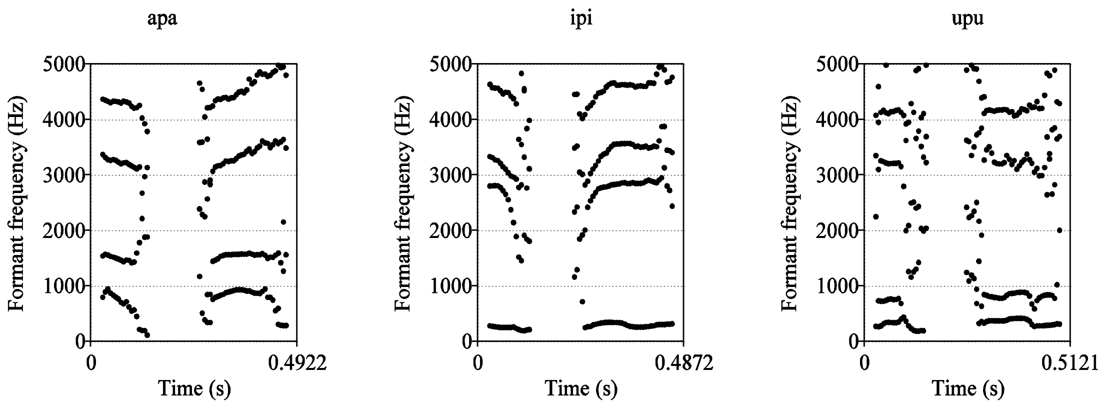
APPENDIX B

Significance of difference of information transmitted for the three consonantal features in three different vowel contexts in three stimulus modified conditions in three temporal processing deficit groups

Group	Stim- mod condition	Vowel	/a/ vs. /i/		/a/ vs. /u/		/i/ vs. /u/	
			z value	p value	z value	p value	z value	p value
Mild	Unprocessed	Manner	1.4	0.14	0.18	0.85	2.0	0.03*
		Place	2.5	0.01*	0.84	0.40	2.3	0.01*
		Voicing	1.5	0.12	0.73	0.46	1.97	0.04
	Spectro-temporally modified	Manner	0.53	0.59	0.53	0.59	0.0	1.00
		Place	0.51	0.61	0.14	0.88	0.68	0.49
		Voicing	0.68	0.49	1.2	0.20	1.5	0.11
	Stretched	Manner	1.0	0.31	1.73	0.08	1.0	0.31
		Place	1.74	0.08	1.6	0.10	0.53	0.59
		Voicing	1.6	0.09	0.41	0.68	1.3	0.16
Moderate	Unprocessed	Manner	2.1	0.03*	0.21	0.83	2.3	0.01*
		Place	2.5	0.01*	2.3	0.01*	0.25	0.79
		Voicing	1.8	0.07	1.4	0.14	0.04	0.96
	Spectro-temporally modified	Manner	2.4	0.01*	1.9	0.05*	0.62	0.53
		Place	2.5	.009*	1.0	0.30	1.2	0.20
		Voicing	2.5	0.01*	1.2	0.21	1.1	0.26
	Stretched	Manner	2.1	0.03*	2.0	0.04*	0.25	0.79
		Place	2.2	0.02*	1.1	0.23	1.1	0.27
		Voicing	0.23	0.81	0.25	0.80	0.18	0.85
Severe	Unprocessed	Manner	1.0	0.31	0.84	0.39	1.1	0.24
		Place	0.0	1.0	0.27	0.78	0.14	0.88
		Voicing	1.4	0.15	0.37	0.70	0.70	0.48
	Spectro-temporally modified	Manner	2.3	0.01*	1.6	0.09	0.81	0.41
		Place	0.0	1.00	1.4	1.6	1.5	1.30
		Voicing	2.0	0.04*	1.4	0.15	1.4	0.15
	Stretched	Manner	0.0	1.0	0.17	0.86	0.27	0.78
		Place	0.81	0.41	0.44	0.65	0.81	0.41
		Voicing	0.0	1.0	0.44	0.65	0.44	0.65

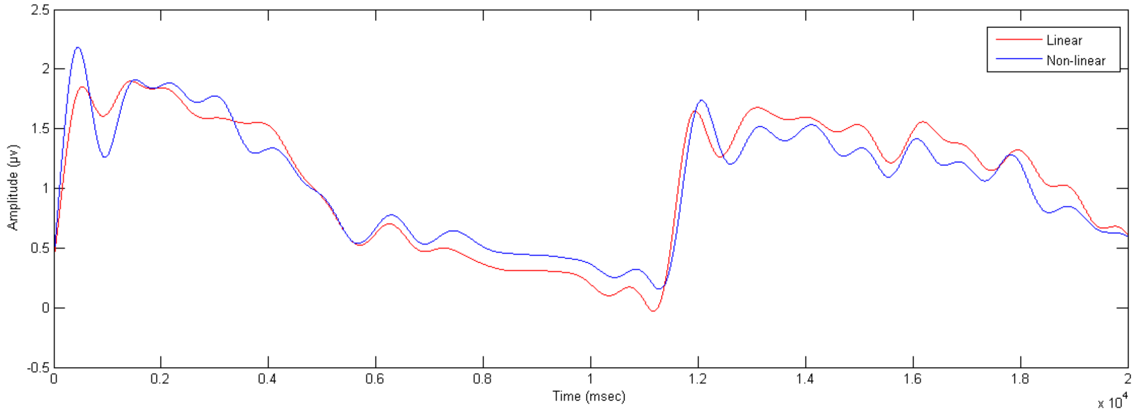
APPENDIX C

The spectrogram of VCV syllable /p/ in the context of /a/, /i/ and /u/. The figure also depicts the steeply falling F2 transition (frequency change more than 200 Hz in 25-30 ms) for the /ipi/ and slowly changing F2 transition (frequency change less than 40 Hz in 25-30 ms) for /apa/ and /upu/.



APPENDIX D

Temporal envelope of the VCV syllable /apa/, recorded from the hearing aid used in the study, that was programmed using linear and non-linear prescriptive formule.



APPENDIX E

Significance of difference of information transmitted for the three consonantal features in three different amplification conditions and vowel contexts in three temporal processing deficit groups

Group		Vowel context	Unaided vs. Aid lin		Unaid vs. Aid non-lin		Aid-lin vs. Aid non-lin	
			z value	p value	z value	p value	z value	p value
Mild	Manner	/a/	0.54	0.58	0.0	1.0	0.42	0.67
		/i/	0.54	0.58	1.4	0.14	1.6	0.10
		/u/	0.0	1.0	0.68	0.49	1.1	0.25
	Place	/a/	0.87	0.38	0.43	0.66	1.9	0.04*
		/i/	0.37	0.70	0.33	0.73	0.27	0.78
		/u/	0.13	0.89	0.10	0.91	0.21	0.83
	Voicing	/a/	0.08	0.93	0.34	0.73	0.55	0.58
		/i/	0.41	0.68	0.21	0.83	0.96	0.33
		/u/	0.99	0.32	0.40	0.68	1.3	0.18
Moderate	Manner	/a/	0.35	0.72	0.47	0.63	0.07	0.94
		/i/	0.95	0.33	2.9	0.004*	2.5	0.01*
		/u/	1.4	0.15	0.16	0.86	1.3	0.16
	Place	/a/	0.73	0.46	0.63	0.52	0.21	0.83
		/i/	1.6	0.09	3.1	0.002*	1.9	.05*
		/u/	0.40	0.68	0.09	0.92	0.96	0.33
	Voicing	/a/	0.79	0.42	1.2	0.22	0.83	0.43
		/i/	0.11	0.91	2.2	0.02*	1.6	0.09
		/u/	0.99	0.31	0.09	0.92	1.5	0.13
Severe	Manner	/a/	0.37	0.70	0.92	0.35	0.97	0.33
		/i/	1.1	0.25	.081	0.41	1.5	0.13
		/u/	0.95	0.33	0.55	0.58	0.41	0.68
	Place	/a/	0.85	0.39	0.84	0.39	0.27	0.78
		/i/	1.3	0.18	2.12	0.03*	1.0	0.31
		/u/	1.0	0.28	0.55	0.57	1.7	0.08
	Voicing	/a/	0.0	1.0	0.96	0.33	0.96	0.33
		/i/	0.57	0.56	1.6	0.10	1.1	0.25
		/u/	0.33	0.73	1.2	0.20	1.6	0.10

Note. Aid-lin = aided linear, aid non-lin = aided non-linear

APPENDIX E

Significance of difference of information transmitted for the three consonantal features in three different vowel contexts in three amplification conditions in three temporal processing deficit groups

Group	Amplification condition	Vowel	/a/ vs. /i/		/a/ vs. /u/		/i/ vs. /u/	
			z value	p value	z value	p value	z value	p value
Mild	Unaided	Manner	0.31	0.75	0.0	1.0	0.70	0.48
		Place	0.68	0.49	0.54	0.58	0.85	0.39
		Voicing	0.52	0.58	0.68	0.49	0.34	0.73
	Aided linear	Manner	0.42	0.67	0.27	0.78	0.36	0.71
		Place	1.3	0.16	0.95	0.34	0.35	0.71
		Voicing	0.92	0.35	0.68	0.49	0.40	0.68
	Aided non-linear	Manner	1.5	0.13	0.14	0.88	1.0	0.22
		Place	0.0	1.0	1.1	0.27	1.4	0.15
		Voicing	1.6	0.09	0.41	0.68	1.3	0.16
Moderate	Unaided	Manner	2.2	0.02*	0.25	0.79	2.1	0.03*
		Place	2.6	0.00*	0.39	0.69	2.4	0.01*
		Voicing	1.9	0.04*	0.74	0.45	1.2	0.22
	Aided linear	Manner	1.6	0.09	1.4	0.13	0.24	0.80
		Place	0.84	0.40	0.09	0.93	0.83	0.40
		Voicing	1.5	0.13	1.1	0.25	0.21	0.82
	Aided non-linear	Manner	1.5	0.11	0.40	0.67	1.95	0.05*
		Place	0.75	0.44*	0.73	0.46	0.09	0.92
		Voicing	1.42	0.15	0.55	0.58	0.69	0.49
Severe	Unaided	Manner	1.7	0.08	0.27	0.78	0.96	0.33
		Place	1.5	0.12	0.13	0.89	1.5	0.12
		Voicing	0.37	0.70	0.37	0.70	0.37	0.70
	Aided linear	Manner	1.9	0.05*	1.1	0.23	1.3	0.18
		Place	1.5	0.13	2.0	0.04*	1.3	0.18
		Voicing	0.0	1.0	0.0	1.0	0.0	1.0
	Aided non-linear	Manner	0.73	0.46	1.08	0.27	0.37	0.70
		Place	0.57	0.56	0.44	0.65	0.0	1.0
		Voicing	0.0	1.0	0.44	0.65	0.57	0.56

APPENDIX F

Significance of difference of information transmitted for the three consonantal features in three different amplification condition two PI-PB function groups

Group		Vowel context	Unaid vs. Aid linr		Unaid vs. Aid non-linr		Aid lin vs. Aid non-lin	
			z value	p value	z value	p value	z value	p value
Rising	Manner	/a/	0.53	0.59	0.37	0.70	0.55	0.58
		/i/	0.0	1.0	0.36	.71	0.81	0.41
		/u/	0.44	0.65	0.00	1.0	0.81	0.41
	Place	/a/	0.73	0.46	1.1	0.25	2.1	0.03*
		/i/	0.44	0.65	0.0	1.0	0.57	0.56
		/u/	0.37	0.70	0.37	0.70	0.55	0.58
	Voicing	/a/	1.5	0.13	1.84	0.06	0.81	0.41
		/i/	0.74	0.45	1.5	0.11	0.96	0.33
		/u/	1.5	0.13	0.37	0.70	1.8	0.05*
Rollover	Manner	/a/	1.7	0.86	1.8	0.7	1.4	0.20
		/i/	0.08	0.93	0.68	0.11	1.9	0.40
		/u/	1.1	0.30	0.8	0.93	1.2	0.12
	Place	/a/	0.36	0.71	0.83	0.40	1.3	0.16
		/i/	0.71	0.47	1.3	0.19	1.8	0.06
		/u/	0.74	0.45	1.1	0.30	1.8	0.7
	Voicing	/a/	0.81	0.41	1.0	0.27	0.61	0.51
		/i/	1.9	0.05	0.53	0.59	1.3	0.16
		/u/	0.43	0.65	0.36	0.71	0.60	0.50

Note. Aid lin = aided linear, aid non-lin = aided non-linear

APPENDIX F

Significance of difference of information transmitted for the three consonantal features in three different vowel context in two PI-PB function groups

PI-PB group	Amplification condition		/a/ vs. /i/		/a/ vs. /u/		/i/ vs. /u/	
			z value	p value	z value	p value	z value	p value
Rising	Unaided	Manner	0.55	0.58	0.0	1.0	0.37	0.70
		Place	1.3	0.89	0.54	0.59	0.00	1.0
		Voicing	0.13	0.17	0.18	0.09	0.36	0.71

	Aided linear	Manner	0.73	0.46	0.81	0.41	0.27	0.78
		Place	1.1	0.25	1.6	0.10	0.70	0.48
		Voicing	1.8	0.06	1.6	0.10	0.37	0.70
	Aided non-linear	Manner	0.44	0.65	0.55	0.58	0.37	0.70
		Place	1.4	0.15	1.1	0.25	0.57	0.56
		Voicing	0.55	0.58	0.0	1.0	1.0	0.27
Rollover	Unaided	Manner	0.20	0.06	0.10	0.13	1.8	0.73
		Place	3.3	0.00*	0.39	0.69	2.8	0.01*
		Voicing	2.1	0.03*	0.74	0.45	1.2	0.22
	Aided linear	Manner	1.8	0.09	1.4	0.13	0.33	0.80
		Place	1.6	0.40	1.2	0.93	0.83	0.40
		Voicing	1.5	0.10	1.1	0.21	0.27	0.78
	Aided non-linear	Manner	1.5	0.13	0.13	0.17	0.95	0.09
		Place	0.24	0.80	0.78	0.43	0.42	0.67
		Voicing	1.1	0.26	0.11	0.90	0.79	0.43