Perception of Spectrally Enhanced Speech through Companding in Individual with Auditory Neuropathy

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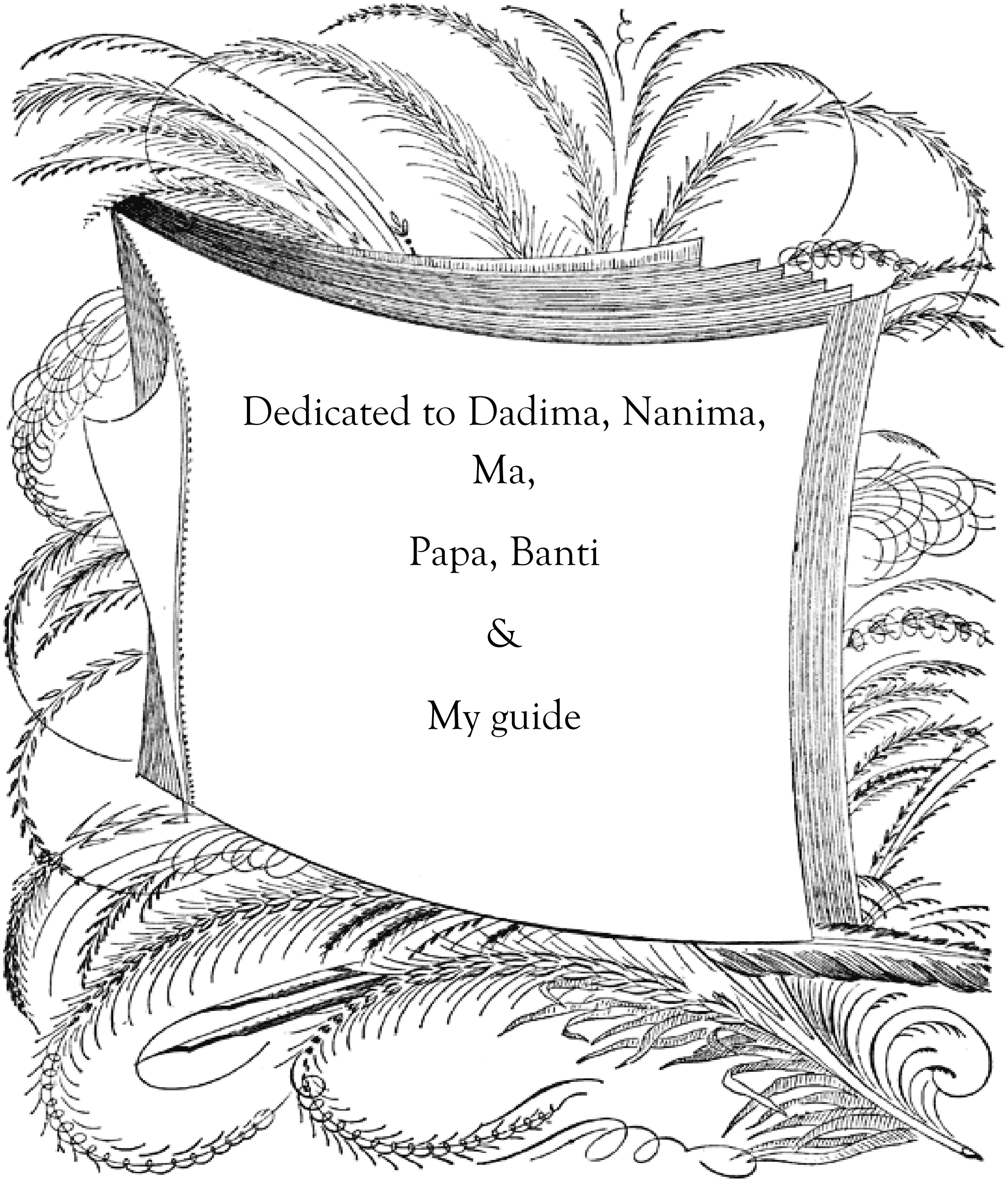

Dedicated to Dadima, Nanima,
Ma,

Papa, Banti

&

My guide

CERTIFICATE

This is to certify that this dissertation entitled **"Perception of Spectrally Enhanced Speech through Companding in Auditory Neuropathy"** is the bonafide work submitted in part fulfillment for the Degree of Master of Science (Audiology) of the student with Registration No.: 10AUD031. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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CERTIFICATE

This is to certify that this dissertation entitled **“Perception of Spectrally Enhanced Speech through Companding in Auditory Neuropathy”** has been prepared under my supervision and guidance. It is also certified that this has not been submitted earlier in other University for the award of any Diploma or Degree.

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DECLARATION

This is to certify that this Master's dissertation entitled **"Perception of Spectrally Enhanced Speech through Companding in Auditory Neuropathy"** is the result of my own study under the guidance of **Dr. Animesh Barman**, Reader in Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier in other University for the award of any Diploma or Degree.

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CHAPTER – 1

Introduction

Auditory dyssynchrony (AD) is a distinct hearing disorder characterized by auditory nerve dysfunction in the presence of normal outer hair cell activity (Starr, Picton, Sininger, Hood & Berlin, 1996). Desynchronized discharges at the level of 8th nerve and brainstem have been proposed as one of the underlying pathophysiologic mechanisms (Zeng, Oba, Garde, Sininger & Starr 1999; Kraus et al., 2000; Kumar & Jayaram, 2005). Psychophysical studies indicated that the consequences of distrupted auditory nerve activity is reflected as a significant impairment in temporal processing and difficulty in understanding speech that is disproptionate to the degree of hearing loss measured by puretone thresholds (Siniger, & Oba, 2001; Zeng et al., 1999).

Difficulty in understanding speech, particularly in noise, is found to be a consistent problem reported by individuals with AD. Studies have investigated speech perception in noise in individuals with AD and illustrate that the noise has more detrimental effect on speech perception than that observed for listeners with normal hearing and those with cochlear hearing loss (Rance et al., 2007; Zeng & Liu, 2006).

The psychoacoustical studies demonstrated impaired frequency discrimination in individuals with AD. It has been reported that frequency discrimination is poorer for low frequency sounds (500 Hz) and the performance improves as the frequency is increased, reaching near normal values at 4000 Hz (Zeng et al. 1999; Rance, Mckay & Grayden 2004). Consistent to these findings, it has been observed that individuals with AD show good identification for phonemes that lie in the high frequency range than those phonemes that lie in the low frequency range (Rance & Barker, 2008; Narne & Vanaja, 2008).

Individuals with AD show severely affected temporal processing abilities that seem to be the basis of their poor speech perception (Zeng et al., 1999). Psychophysical measures showed that the disrupted neural activity significantly impairs timing related perception, such as pitch discrimination at low frequencies, temporal integration, gap detection, temporal modulation detection, forward and backward masking, binaural beats, signal detection in noise, and sound localization using interaural time differences (Zeng, Kong, Michalewski & Starr, 2005). Listeners with AD typically required silent periods of 20 ms or more to detect gap compared to less than 5 ms in normal listeners (Rance et al, 2008).

Speech signals are often degraded by noise, in realistic listening situation. While normal-hearing listeners are capable at extracting the critical information from noisy speech, this ability is affected in individuals with AD.

Different assistive devices, from hearing aids to cochlear implants are available to facilitate hearing, and to improve communication in individuals with hearing impairment. However, all hearing impaired individuals may not benefit from amplification devices. There are evidences to show that individuals with auditory dyssynchrony may not benefit from hearing aids (Starr et al., 1996). Individuals with auditory dyssynchrony often complain that they hear, but do not understand. Furthermore, their problem in understanding speech is aggravated under listening situations where noise and reverberation is present to a greater extent than usual.

Individual with AD seems to do better if the temporal cues are extended. Their performance improves if spoken at a slower rate. Clear speech, in which duration of sentences is extended, showed better performance than natural speech in individuals with AD. This improvement is attributed to enhanced envelope in clear speech (Zeng & Liu, 2006).

Research has also demonstrated that one of the factors linked to increased intelligibility of clear speech in cochlear hearing loss is increased consonant-vowel ratio (Krause & Brida, 2004). Narne and Vanaja (2008) reported improved consonant identification in individuals with AD when the envelope of the speech signal was digitally enhanced. Apoux, Tribut, Debruille and Lorenzi (2004) showed significant improvement in identification scores in presence of background noise, when envelope enhanced stimuli were presented to individuals with normal hearing and cochlear hearing loss.

Several spectral enhancement techniques have focused on compensating the degraded spectral resolution of an impaired ear (Baer, Moore & Gatehouse, 1993; Bunnell, 1990; Clarkson and Bahgat, 1991). By expanding the temporal envelopes in different frequency bands, Clarkson and Bahgat (1991) found a small but significant improvement at 0 dB SNR in normal hearing (NH) listeners.

The performance of cochlear-impaired patients on spectrally enhanced speech tasks has been investigated (Baer et al., 1993., Bunnel, 1990). However there is dearth of literature in usefulness of spectrally enhanced speech tasks in individuals with AD and there is a need to determine these skills in these individuals.

Need for the study

Management of AD continues to be difficult and challenging. Persons with cochlear hearing loss derive significant benefit from hearing aids which employ nonlinear compression circuits. All these hearing aids assume abnormal functioning of outer hair cells (Berlin, Hood, Hurley & Wen 1996). Hence, these aids are of not much use for individuals with auditory dyssynchrony who have normal outer hair cell functioning.

Several other management strategies used by individuals with auditory dyssynchrony include FM systems, cochlear implants, perceptual training, speech reading and cued speech (Kraus, 2001). Conventional hearing aids have achieved limited success (Rance, Cone-Wesson, Wunderlich & Dowell 2002). Many studies emphasized cochlear implants as the treatment of choice for AN (Rance & Barker, 2008). However, the invasive nature of cochlear implants and their doubtful efficacy points to a need for research on alternative strategies to improve speech intelligibility. This is particularly true for individuals with mild AD (Zeng & Liu, 2006).

Turicchia and Sarpeshkar (2005) have proposed a novel spectral enhancement scheme, companding, which combines two-tone suppression and dynamic gain control to increase the spectral contrast. Studies have shown that companding is also present along the auditory pathway. Both cochlea and the cochlear nucleus perform logarithmic compression on the input signals, while the brain performs exponential expansion (Zeng & Shannon, 1999). Considering this hypothesis a signal processing strategy has been developed where certain signal will be compressed and certain frequencies will be enhanced which is termed as companding. Implementing the companding strategy, Bhattacharya and Zeng (2007) showed significant improvement in both phoneme and sentence perception in noise, in the cochlear implants users. However usefulness of this option has not been investigated in individuals with AD and there is a need to determine these skills in patients with AD.

It is thus essential to study if listeners with AD can take the benefit from spectral enhancement of speech through companding. A systematic comparison with normal hearing listeners at various SNRs will be more appropriate to determine if the effect is level dependent or not. Keeping all this in mind the present study aimed to investigate the following:

AIM of the study:

The current study aimed to

- Know whether companding of speech stimuli helps to improve speech intelligibility in individuals with normal hearing and with AD.
- Benefit of spectrally enhancing speech through companding at different SNRs in presence of speech shaped noise, in individuals with normal hearing and with AD.
- To determine how normal hearing individual and individual with AD differ in their performance for companded stimuli at quiet and at different SNRs.

CHAPTER – 2

Review of Literature

Auditory dyssynchrony (AD) is described as hearing disorder characterized by abnormal auditory nerve functioning in presence of normal cochlear receptor hair cell activity [Starr et al., 1996]. The term 'Auditory Dyssynchrony' was coined by Starr and colleagues in 1996.

More recently a new term 'Auditory Dyssynchrony Spectrum Disorder' is preferred. ANSD is used to describe the auditory characteristics of patients who exhibit normal Outer hair cell function, as revealed by the presence of Oto-acoustic emissions (OAEs) or Cochlear Microphonics (CM), and aberrant or disordered neural conduction in other sites along the auditory pathway (International Newborn Hearing Screening Conference, 2008).

Berlin (1999) identified several patterns in the time course of auditory dys-synchrony. Some of these are as follows:

a) Some patients show retrograde loss of cochlear microphonics and otoacoustic emissions and become almost indistinguishable from patients with cochlear hearing loss.
b) Some patients retain cochlear microphonics and otoacoustic emissions, but cannot learn speech language by auditory mode alone. They depend on visual information (cued speech, sign language, speech reading).
c) Some patients show worsening of the symptoms and develop other neuropathies.

d) Some patients lose their otoacoustic emissions, but not cochlear microphonics.

e) Some patients go through life without complaining of any problem. They develop speech and language normally and would be identified as cases of auditory dyssynchrony only if an ABR had to be done for some reason (either as a part of a screening procedure or a research project).

f) Some patients with auditory dyssynchrony may show fluctuations in their hearing abilities that are temperature sensitive.

In fact, many patients with auditory dyssynchrony appear to experience moment-to-moment fluctuations in their hearing sensitivity which may be misinterpreted as inconsistent response during testing.

Prevalence

Kumar & Jayaram (2006) estimated the prevalence of auditory dyssynchrony around 1 in 183 (0.54%) in individuals with sensory neural hearing loss. Around 60% of the individuals had no measurable speech identification scores. The female to male ratio of auditory dys-synchrony was 2:1.

Audiological findings

Puretone Threshold

Audiological profile of persons with auditory dyssynchrony is variable. Auditory dys-synchronics present all levels of hearing loss. The degree of hearing loss may range anywhere from normal hearing sensitivity to profound loss. Majority of the patients show bilateral symmetrical hearing loss (Rance et al., 1999; Sininger & Oba, 2001). The reverse slope configuration of audiogram in patients with AD provides evidence that the underlying etiology of the hearing loss in AD is neural rather than cochlear (Sininger & Oba, 2001).

Physiological response

Abnormal middle-ear muscle reflexes are a consistently reported finding for both adults and children with auditory dys-synchrony type hearing loss (Kumar & Jayaram, 2006, Starr et al., 1996, 1998). Otoacoustic emissions are present in most individuals with auditory dyssynchrony (Rance et al, 1999; Sininger & Oba, 2001). Starr et al. (2000) reported that about 80% of the patients with auditory dyssynchrony had clear OAEs.

Electrophysiological Responses

In ears with auditory dyssynchrony, auditory brainstem responses are absent at maximum stimulus presentation levels regardless of behavioral hearing level (Starr et al., 1996; Rance et al., 1999; Sininger & Oba, 2001). In these individuals, disruption of the auditory brainstem response is thought be the result of either a reduction in the number of neural elements available to contribute to the response, or a disruption in the temporal integrity of the neural signal.

The cochlear microphonics prominence in auditory dys-synchrony subjects (Starr et al., 1998, 2001) as well as its persistence for several milliseconds after a click stimulus, has been reported by several authors (Berlin, 1999; Starr et al, 2001), who considered this finding an indication of an abnormal cochlear function (Starr et al., 2001).

Patho-physiology of AD

Based on the electrophysiological and pathological findings, Starr, Picton and Kim (2001) have put forth two mechanisms to account for distorted auditory nerve activity in individuals with auditory dyssynchrony. There is impaired synchrony among auditory nerve fibers and/ or reduced neural input. Dyssynchronized neural discharge can occur due to demylination and ion channel dysfunction in the auditory nerve (Starr et al; 1998) and /or dysfunctional synaptic transmission between the inner hair cells and the auditory nerve (Fuchs, Glowatzki, & Moser, 2003). Loss of neural input to the brain can occur due to inner hair cell loss (Harrison, 1998) and/ or auditory nerve loss (Starr et al; 2003).

Demyeilinating neuropathies affect the Schwan cells which form the myelin sheath around the axons. Demyeilinating neuropathies slowdown or block nerve conduction and produce motor or sensory symptoms distal to the site of demyeilinization. Demyelinated fibers are poor conductors of rapid trains of action potentials. If demyelination affects all the auditory nerve fibers to the same degree, then transmission through all fibers will be slowed down, and amplitude of the compound action potential will be unaffected despite slowing of conduction velocity (Figure 2.1, second column). On the other hand, if the extent of slowing varies from one fiber to the next, then the amplitude of action potential becomes small and smeared (Figure 2.1, third column). This smeared temporal representation of the acoustic stimulus may influence auditory perception that is dependent on temporal cues.

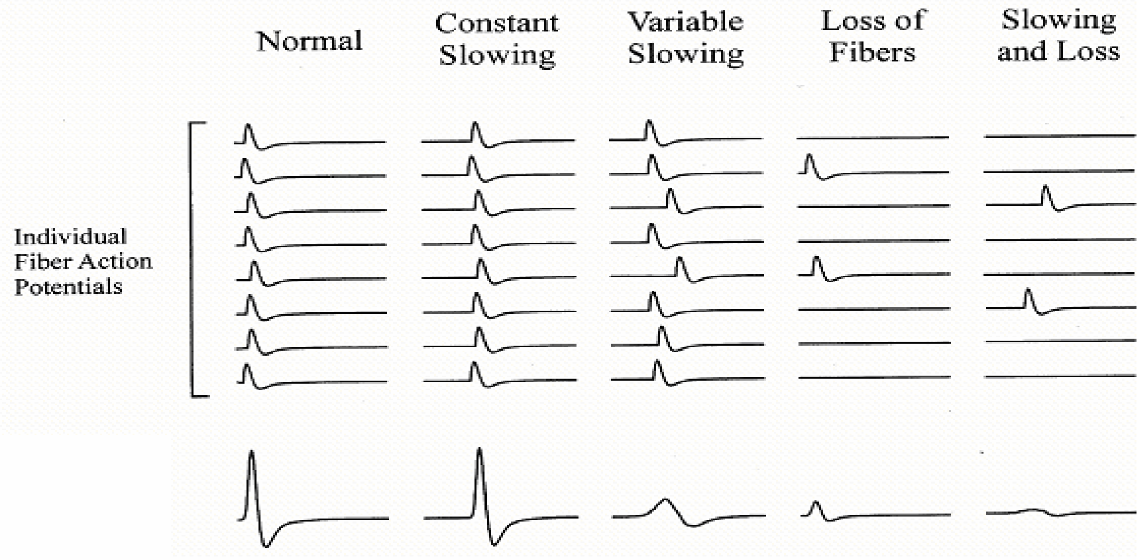

Figure 2.1. Action potential of individual fibers and resultant compound action potential. (From Auditory neuropathy, A new perspective on hearing disorders by Sininger and Starr (2001). Reprinted with permission from Delmar Learning, a division of Thomson Learning).

Axons are affected in axonal neuropathy. The hallmark of many axonal neuropathies is a retrograde degeneration of the distal portion of peripheral nerves. In this condition, though the nerve fibers are reduced in number they function normally in terms of speed of conduction. As the number of the nerve fibers is reduced, a resultant compound action potential is reduced in amplitude.

Psychophysical test results

Frequency Processing

Frequency discrimination ability of patients with auditory dyssynchrony is significantly poorer compared to that of normal hearing subjects, particularly at low frequencies (Rance et al., 2004; Starr et al., 1991; Starr et al., 1996; Zeng et al., 2005). Rance et al. (2004) measured the frequency difference limen and frequency modulation detection limen for 500 Hz and 4 kHz in children with auditory dyssynchrony. Results showed that difference limens obtained using both the methods were better at 4 kHz compared to those at 500 Hz. Furthermore, frequency difference limens were better compared to frequency modulated difference limen scores.

Zeng et al. (2005) also found impaired frequency discrimination ability in 12 subjects with auditory dyssynchrony. The subjects performed extremely poor especially in low to mid frequency range (≤2 KHz) and discrimination in the high-frequency range appeared to be less impaired. This might imply a disruption of the low-frequency temporal discrimination processes in individuals with AD (Zeng et al., 2001; 2005).

These results can be explained on the basis of differential mechanisms of frequency coding at high and low frequencies. Individuals with auditory dyssynchrony may not use the phase locking cues to the same extent as normally hearing subjects do. Hence, high frequency discrimination that does not involve phase locking cues is relatively better compared to discrimination of low frequencies that depends on phase locking cues.

Demyelinated fibers may also display emphatic transmission (cross- talk) between fibers, with one active fiber cutting discharge in adjacent fibers (Starr et al, 2001). These cross talk fibers may lead to broader than normal neural tunning curves and this might lead to poor frequency discrimination in these individuals.

Intensity discrimination

Zeng et al. (2005) reported that AD produces no significant effect on intensity discrimination, and if anything at all, slightly worsens performance at low sensation levels. He also measured loudness growth function in two AD subjects and found no sign of loudness recruitment (Zeng et al., 2001). However, Rance et al. (2004) demonstrated that persons with auditory dyssynchrony show a slightly larger difference limen at low sensation levels than normals, but it approached normal values at high sensation levels similar to that seen in normals.

Temporal processing

Abnormal gap detection (identification of silent period embedded within a noise burst) has been reported in individuals with auditory dyssynchrony (Zeng et al., 1999, 2001). Zeng et al. (2005) reported poor gap detection thresholds in individuals with auditory dyssynchrony. Normal hearing individuals required a silent interval of around 50 ms to detect a gap at 5 dB SL. However, the detection threshold improved to 3 ms at higher sensation levels (30 to 40 dB SL). Individuals with auditory dyssynchrony performed similar to normal hearing subjects at low sensation levels, but unlike normals, required significantly larger gap to detect at higher sensation levels. Another temporal process that has been reported to be abnormal in individuals with auditory dyssynchrony is the temporal modulation transfer function (Rance et al., 2004; Zeng et al., 1999, 2005).

Zeng et al. (1999) reported that individuals with auditory dyssynchrony showed high peak sensitivity (-8.7 dB compared to -19.9 dB in normal controls) and lower cut off frequency (17 Hz compared to 258.1 Hz in normal controls). Rance et al. (2004) reported that individuals with auditory dyssynchrony with speech identification scores less than 30% had poorer modulation detection thresholds compared to subjects who had more than 30% speech identification score.

Masking

Studies have also shown excessive masking of pure tones in auditory dyssynchrony subjects by simultaneous noise, as well as temporal masking (Kraus et al., 2000; Zeng et al. 2005; Zeng et al., 2001). Kraus et al. (2000) reported exaggerated masking effect in one patient with auditory dyssynchrony who had near normal hearing thresholds. Abnormal masking level difference, have been a consistently reported finding in individuals with AD (Starr et al., 1991, 1996). Subjects with auditory dyssynchrony typically show no masking release, whereas subjects with normal hearing usually show a masking level difference of approximately 10 dB (Licklider, 1948).

Temporal masking and simultaneous masking paradigms have shown that individuals with auditory dyssynchrony have difficulty in separating sounds that occur successively as well as in detecting signal in noise (Zeng et al., 2005). Experiments on modulation detection and masking have shown that individuals with auditory dyssynchrony have difficulty in perceiving the temporal envelop of the signal as well as in separating two closely occurring acoustic events. The importance of temporal envelop as well as the effects of smearing of temporal envelop on speech perception has already been demonstrated (Plomp, 1988; Kumar & Jayaram, 2005). Increased degree of temporal masking may result in the masking of critical speech events (transition, burst and VOT) by the steady-state portion of the preceding or succeeding vowel. Effect of masking was more when short duration signals were used than when long duration signals were employed. Hence, increasing the duration of some important short speech events might lead to better speech perception in individuals with auditory dyssynchrony by reducing the masking effects.

Physiologically, these excessive masking effects could be due to inner hair cell loss or loss of synchronous firing due to damaged nerve fibers (Harrison, 1998., Starr et al., 1996). Another possible reason could be demyelinated fibers which may also display emphatic transmission (cross- talk) between fibers. These cross talk fibers may lead to broader than normal neural tuning curves and this might lead to excessive masking in these individuals.

These psychophysical/electrophysiological findings point to the fact that timing and synchronicity in the firing of neurons in the auditory nerve as well as auditory brainstem regions are important for auditory perception. Patients with auditory dyssynchrony have difficulty in perceiving timing and frequency related information but not intensity related information. Thus from these psychophysical experimental findings it is clear that the individuals with AD have a significantly disrupted temporal processing which has adverse effect on speech perception.

Speech perception in individuals with AD

Speech Perception in quiet

Speech perception ability in adults diagnosed with auditory dyssynchrony has shown no correlation with the pure-tone audiogram (Starr et al., 2000; Zeng et al., 2001). In most cases, has been significantly poorer than would have been expected for sensorineural losses of equivalent degree.

However, not the entire reported adult AD cases have shown unusually poor speech understanding at least in quiet listening conditions. 25% of the ears presented by

Starr et al. (1996) and 30% of the Sininger and Oba (2001) subjects showed speech perception scores within the normal range for sensorineural losses of equivalent degree.

Rance and Barker (2008) analyzed the perception of different consonants in AD and reported poor perception of the stop, nasal, semivowel and diphthong categories. AD subjects showed poor ability to use subtle timing cues to discriminate speech sounds involving the stop-consonant pairs /p & b/, /t & d/, and /k & g/. Nasal sounds were difficult to perceive due to the impaired ability to use the low frequency spectral cues. Fricatives (/s/, /sh/) were the easiest to perceive as a result of preserved accurate high frequency pitch discrimination in subjects with AD. This poor result is consistent with psychophysical evidence suggesting that discrimination in the low spectral range (which relies in part on temporally precise neural firing in the auditory pathway to produce stimulus ‘phase-locking’ cues) is severely disordered in patients with AD (Rance et al., 2004; Zeng et al., 2005).

Speech Perception in noise

In realistic listening situations, speech signals are often degraded by noise. While normal-hearing (NH) listeners are remarkably adept at extracting the critical information from noisy speech, this ability markedly affected in individuals having AD. Kraus et al. (2000) measured word identification by manipulating three factors, namely, signal to noise ratio, lexical difficulty, and number of talkers (single vs. multiple talkers) to investigate the effect of multiple sources of variability and signal degradation on speech perception. The subject with auditory dyssynchrony showed marked effect of noise on speech identification compared to normal hearing subjects. Rance et al. (2007) evaluated speech perception in noise for children with AN, children with cochlear hearing loss, and those with normal hearing. Results showed that the performance of children with normal hearing and those with cochlear hearing loss was not altered significantly when the S/N ratio was +5 dB but the performance of the individuals with AN was significantly reduced. Zeng and Liu (2006), studied the perception of 14 AN subjects and found consistent reductions in speech recognition ability, even at signal-to-noise ratios that show little or no effect on subjects with normal hearing (10 to 15 dB).

Strategies to enhance speech perception

To provide noise suppression, Clarkson and Bahgat (1991) expanded the temporal envelopes in different frequency bands. They found a small but significant improvement at 0 dB SNR in normal hearing listeners. Lyzenga *et al.* (2002) employed a similar enhancement technique but followed it by an additional “lift” stage to counteract the effect of upward spread of masking. They applied spectral smearing in the end to simulate loss of frequency selectivity and tested normal hearing listeners. They found that enhancement employed separately did not produce any improvement in SRT but enhancement and lift applied together improved the SRT by approximately 1 dB.

To counterbalance the degraded neural representations of the second ($F2$) and third ($F3$) formant frequencies in the impaired ear Miller *et al.*, (1999a), and Miller *et al.* (1999b) proposed a contrast enhancing frequency shaping algorithm that selectively amplifies $F2$ and $F3$ without modifying the spectral valleys. They found considerable improvements in the neural representation of $F2$ in acoustically traumatized cats.

Bunnell, (1990); Franck *et al.*, (1999) and Lyzenga *et al*, (2002), used a contrast enhancement technique in which the envelope amplitude of each fast Fourier transform bin was enhanced proportionately to the difference in the original envelope amplitude and the average spectrum level. He found a small improvement in the identification of stop consonants in quiet. Baer *et al.* (1993) convolved the spectrum with a difference of Gaussian filter to provide spectral enhancement. They showed that their normal hearing subjects preferred speech in noise with moderate enhancement in terms of quality and intelligibility. This technique, combined with phonemic compression, improved the perception of vowels in hearing-impaired listeners but degraded the understanding of consonants (Franck *et al.*, 1999).

One simple and effective means of improving speech intelligibility is to speak clearly. Theoretically, reduced speaking rate, enhanced temporal modulations, expanded voice pitch range, and vowel space are cardinal features of clear speech (Krause & Braida, 2002).

In a study by Zeng and Liu (2006), the performance of subjects with AD was compared using speech sentences in clear and conversational speech styles. The clear speech used had average sentence duration of 3.3 seconds compared to 1.5 seconds for the conversational speech. Significant advantage to clear speech was observed over conversational speech in the studied subjects when exposed to different listening situations and using different stimulation modes.

Several spectral enhancement techniques have particularly focused on compensating for the degraded spectral resolution of an impaired ear (Baer *et al.*, 1993; Bunnell, 1990; Clarkson & Bahgat, 1991). Moreover, Narne and Vanaja (2008) reported better speech perception in individuals with AD when the envelope of the speech signal was digitally enhanced by 15 dB for different modulation bandwidth. They reported manner cues better perceive than voicing.

Companding Strategy

In a recent paper, Turicchia and Sarpeshkar (2005) proposed a new strategy for time domain spectral enhancement, based on relatively broadband compression followed by more frequency-selective expansion. Studies have shown that, this compressing-and expanding (companding) is also present along the auditory pathway. Both cochlea and the cochlear nucleus perform logarithmic compression on the input signals, while the brain performs exponential expansion (Zeng & Shannon, 1999).

There are certain similarities between the properties exhibited by the companding algorithm and phenomena such as two-tone suppression that are found at early stages of the auditory periphery (e.g. Sachs and Kiang, 1968; Ruggero *et al.*, 1992). Companding can produce a suppression of the response to one tone by the presence of another, more intense, tone at a nearby frequency, an effect known as two-tone suppression. Two tone suppression is considered to be the primary mechanism underlying spectral enhancement and is thought to improve the SNR of stronger component (Sachs et al 1983).However, there are also differences, such as the differential growth of suppression for low frquency and high frequency side suppressors that is found in the auditory periphery (e.g. Delgutte, 1990), but not in the companding algorithm.

At a more global level, the companding scheme can lead to the enhancement of spectral peaks in a stimulus, relative to nearby spectral valleys. Spectral enhancement techniques have often been used in an attempt to improve speech intelligibility in noise for listeners with hearing loss. Implementing the companding strategy, Bhattacharya and Zeng (2007) showed significant improvement in both phoneme and sentence perception in noise, in the cochlear implants users. Loizou (2005) implemented companding strategy in CI users and found a modest improvement in vowel recognition.

Companding increases the spectral and temporal contrast in speech and listeners are able to take advantage of these enhanced peaks in adverse listening condition (Bhattachrya & Zeng; 2007, Oxenham; Simonson; Turicchia & Sarpeshkar, 2007). However usefulness of this option has not been investigated in individuals with AD and there is a need to determine these skills in patients with AD.

It is thus essential to study if listeners with AD can take the benefit from spectral enhancement of speech through companding. A systematic comparison with normal hearing listeners at various SNRs will be more appropriate to determine if the effect is level dependent or not. Keeping all this in mind the present study is justified.

CHAPTER - 3

Method

The objective of this study was to know whether the spectral enhancement of speech through companding would improve speech perception in individuals with auditory dyssynchrony (AD). To achieve the goal two groups of subjects were taken. They are the clinical group and the control group.

Clinical group

Clinical group consisted of 15 ears from 10 subjects, in the age range of 15 to 42 years (mean age 27 years), fulfilling the criteria of AD in both ears. All participants manifested the following findings, were to be considered in the clinical group.

- Degree of hearing loss ranging between mild to moderately severe sensorineural hearing loss
- Acquired post lingual hearing loss
- Disproportionately poor speech identification scores in relation to their pure tone threshold or poor SIS at 0 dB SNR
- Absent auditory brainstem responses beyond that can be expected with the degree of hearing loss
- Presence of otoacoustic emissions and/or cochlear microphonics indicating normal OHCs function
- 'A' type tympanogram with no ipsi or contralateral reflexes
- No other neurological symptoms reported
- Peripheral neuropathy or space-occupying lesion were ruled out by neurologist

- Any other otological disorder including middle ear infections were ruled out by otologist
- All participants were fluent Kannada speakers and did not have any speech or language problems

The demographic data and audiological test findings of 10 participants are given in table 3.1.

Control group

A total of 15 ears of 15 normal hearing subjects, in the age range of 15 to 42 years (mean age 27 years) were taken. All participants manifested the following findings, to be considered in the control group:

- The age and gender matched subjects (with age & gender of the clinical group)
- All the participants in the control group had normal hearing sensitivity (pure tone thresholds within 15 dB HL in octave frequencies between 250 Hz to 8000 Hz) in both the ears
- Good SPIN scores at 0 dB SNR (60% and above)
- Normal auditory brainstem responses at 80 dBnHL with a repetition rate of 11.1/s
- Presence of otoacoustic emissions
- ‘A’ type tympanogram with present ipsi and contralateral acoustic reflexes
- No other neurological symptoms reported
- All participants were fluent Kannada speakers and did not have any speech or language problems

Table 3.1

The Audiological test findings in individuals with AD

Participants	Age/ Gender	Ear	Severity of Hearing loss	SIS in quiet	SIS at 0 dB SNR	Pure tone configuration	ABR	OAEs/ CM
AD1	42/ F	Right	Mild	34%	0%	Reverse slope	Absent	Present
		Left	Mild	32%	0%	Reverse slope	Absent	Present
AD2	32/M	Right	Moderately severe	88%	0%	Reverse slope	Absent	Present
		Left	Moderately Severe	60%	0%	Reverse slope	Absent	Present
AD3	25/F	Right	Minimal	92%	24%	Flat	Absent	Present
		Left	Minimal	86%	28%	Flat	Absent	Present
AD4	15/F	Right	Mild	84%	36%	Sloping	Absent	Present
		Left	Mild	88%	44%	Flat	Absent	Present
AD5	19/F	Right	Mild	88%	32%	Reverse slope	Absent	Present
		Left	Mild	88%	28%	Flat	Absent	Present
AD6	29/M	Right	Mild	76%	25%	Trough shape	Absent	Present
		Left	Mild	76%	25%	Trough shape	Absent	Present
AD7	26/M	Right	Mild	40%	0%	Reverse slope	Absent	Present
		Left	Minimal	36%	0%	Reverse slope	Absent	Present
AD8	27/ F	Right	Moderate	68%	0%	Reverse slope	Absent	Present
		Left	Mild	92%	0%	Reverse slope	Absent	Present
AD9	38/M	Right	Mild	88%	32%	Flat	Absent	Present
		Left	Mild	100%	36%	Flat	Absent	Present
AD10	19/F	Right	Moderately Severe	40%	0%	Flat	Absent	Present
		Left	Moderately Severe	44%	0%	Flat	Absent	Present

Test environment

All the tests were carried out in a sound treated room. Noise levels within the test room were within permissible limits as per ANSI S3.1-1991.

Test equipment and Procedure

- A calibrated double channel diagnostic audiometer GSI- 61 with TDH- 50 P headphones were used for pure tone audiometry and speech audiometry. Air conduction thresholds were obtained at octave frequencies from 250 Hz to 8000 Hz and bone conduction thresholds from 250 Hz to 4000 Hz. The thresholds were tracked using the modified Hughson and Westlake method (Carhart & Jerger, 1959). Speech Identification Scores (SIS) was obtained at 40 dB SL under the headphones for each ear independently. Speech in noise scores was obtained at 0 dB SNR, both noise and speech stimulus was presented at 40 dB SL.
- A calibrated immittance meter GSI tympstar was used to confirm the normal middle ear function through tympanometry and acoustic reflex measurement. 226 Hz probe tone frequency was used and tympanogram was obtained with the pressure varying from +200 dapa to -400 dapa. Stapedial reflexes were checked for 500 Hz, 1 KHz, 2 KHz, and 4 KHz pure tones.
- Intelligent Hearing system Evoked potential instrument was used to record Cochlear microphonics (CM) and ABR. For both CM and ABR, 100 µsec click stimulus at 90 dBnHL, with a repetition rate of 11.1/sec was used. Filter settings was 30 Hz to 3000Hz. It was recorded at least twice in each participant to ensure wave reproducibility. Rarefaction and condensation polarity stimulus was used as alternate polarity would abolish CM.

- A calibrated ILO V6 instrument was used to measure DPOAEs. Probe tone frequency ratio of 1.2 (F1/ F2) at F2 frequencies of 500 Hz, 1 KHz, 2 KHz, 4 KHz and 8 KHz and intensity of (L1/L2) 65/55 dB SPL was used. Proper sealing of ear canal was maintained while recording.
- A PC with Matlab version (2009) and Adobe Audition version 3 software was used for companding the speech stimuli. Speech stimuli, method used for companding and also procedure used to obtain SIS in different condition is discussed below.

Test stimuli

In the present study two types of stimuli were used. Sentences and VCV nonsense syllables were used.

I) Sentences

Two lists of sentences were taken from quick SIN sentence test in Kannada developed by Methi, Avinash and Kumar (2009). Each list contains 7 sentences and each sentence has 5 key words. The sentences were spoken by a male native speaker of kannada and was digitally recorded in an acoustically treated room using a unidirectional microphone kept at a distance of 10 cm from the speakers mouth. Adobe audition software (version 3) was used to record the stimuli. The recorded sentences were normalized so that all the words in a sentence had equal intensity.

Speech shaped noise was used to generate sentences with different SNRs. Speech shaped noise was used as it was made to have the same long term average spectrum as sentences had. It was generated from the whole set of sentences at a sampling frequency of 44.1-kHz by estimating the long-term power spectrum of recorded test sentences. This was done by randomizing the phase of the Fourier spectrum of concatenated words of original signals using MATLAB (The Math Works, Natick, MA, USA) software (version 2009). It had a spectrum which approximates the long term average spectrum of the target sentences spoken by an adult male with a secondary peak presented around 100 Hz. Different SNRs were generated using MATLAB. In each list, first sentence were recorded without noise, second sentence was recorded at +15 dB SNR, third sentence at+10 dB SNR, fourth sentence at +5 dB SNR, fifth sentence at 0 dB SNR, sixth sentence at -5 dB SNR, and last sentence was recorded at -10 dB SNR. This was done as the sentences were used to obtain minimum SNR at which 50% word correctly identified in a sentence. The rms level of all these noises was adjusted according to the level of the target speech. The noise and speech was added prior to companding process.

II) VCV

Twenty Vowel-Consonant-Vowel syllables (VCV) comprising of the kannada consonants /k, g, ch, t, d, th, dh, n, p, b, m, j, r, v, s, sh, y, h, l, l./ in the context of the vowel /a/ were used. These syllables were spoken by a female native speaker of Kannada and digitally recorded. The data acquisition system had a sampling frequency of 44.1 KHz and 32 bit analogue-to-digital converter.

The 20 VCV syllables were randomized to form 4 lists. Speech shaped noise was used to generate VCV syllables with different SNRs. List 1 was recorded without any noise. List 2 was recorded at +15 dB SNR. List 3 was recorded at +10 dB SNR. List 4 was recorded at 0 dB SNR.

The intelligibility of these recorded stimuli was established by obtaining a speech intelligibility rating on 10 normal hearing young kannada speakers adults. Each VCV syllable and sentence was recorded thrice. The best one out of the three was chosen based on the speech intelligibility rating done by 10 native speakers of Kannada. A three point rating scale was used which included

1) Good intelligibility
2) Fair intelligibility
3) Poor intelligibility

Those VCV syllables or sentences judged as poorly intelligible or fairly intelligible were not considered and were recorded once again. Once the recorded materials were judged as having good intelligibility, then they were considered for the study.

These sentences and VCV syllables were spectrally enhanced using companding both in quiet and at different SNRs conditions. The companding architecture was implemented in MATLAB. These companded test stimuli were named as modified sentences and VCV syllables. The companding was done after the mixing of speech noise and speech stimuli because if this is found to be beneficial for individual with AD then the same can be suggested to incorporate in amplification devices. The devices with this type of strategy incorporated would process noise and speech together as it would receive both simultaneously.

The strategy used a non-coupled filter bank and compression-expansion blocks as shown in Figure. 3.1. Every channel in the companding architecture had a relatively broad prefilter, a compression block, a relatively narrowband postfilter, and an expansion block. The prefilter and postfilter in each channel had the same center frequency. The pre and postfilter banks had logarithmically spaced center frequencies that span the desired spectral range.

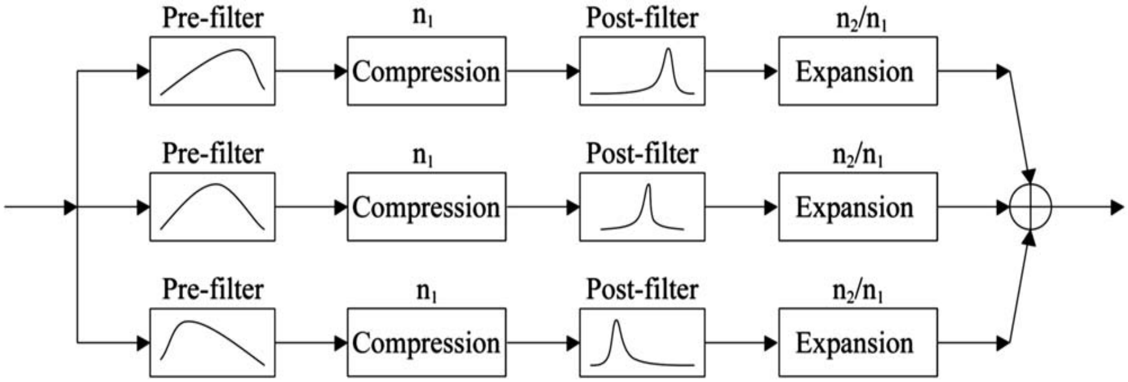

Figure 3.1. Block diagram of the companding architecture, showing the stimulus analyzed in a bank of broad band prefilters. The output of each prefilter was then subjected to compression, and output was filtered again using sharper postfilters, before it was expanded. The outputs from each channel are then summed to produce the processed broadband companded stimulus.

First, the incoming signal was divided into number of frequency channels by a bank of relatively broad bandpass filters *F*. Figure 3.2 shows the detailed architecture of a single channel companding pathway. The signal within each channel was then subjected to amplitude compression. The extent of compression was dependent on the output of the envelope detector, (ED), and the compression index, (*n*1). The compression index *n*1 had a value of 0.3. The compressed signal was then passed through a relatively narrow bandpass filter *G* before being expanded. The gain of the expansion block depends on the corresponding ED output and the ratio of *n*2 /*n*1. The *n*2 parameter of the algorithm is expansion index and had a value of 1. The outputs from all the channels were summed to obtain the processed signal.

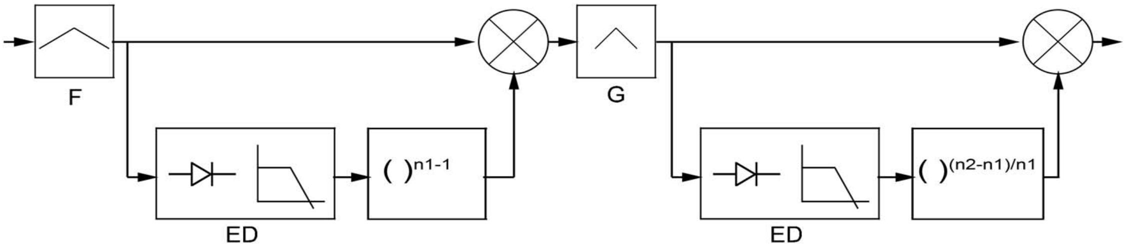

Figure.3.2. Detailed architecture of a single channel ED-envelope detector.

The broadband filter determines the frequency range that can affect the gain of the compressor in a given channel. The narrowband filter determines a narrower subset of these frequencies that can affect the gain of the expander. The compressor and expander were complementary, such that a tone at the center frequency of the filters undergoes sequential compression and expansion and emerge unchanged in level. However, sufficiently intense frequencies outside the narrowband filter passband but within the broadband filter passband can determine the gain of the compressor only to be filtered out by the narrowband filter. This resulted in the suppression of weak frequency components at or near the filters' center frequency by stronger more remote frequency components.

The Adobe audition software (Version 3) was used to normalize the test stimuli to a level of -15dB. After implementing companding process there were all together 8 VCV syllables list (4 with & 4 without companding VCV syllables list) and 4 sentence test material (2 with & 2 without companding sentence test material).

These sentences lists and the VCV syllables lists were transferred digitally to a recordable compact disc. A calibration tone of 1 kHz with a level matched to the normalized level of the stimuli, was recorded prior to each list, using the 1-kHz calibration tone, VU meter on the audiometer was adjusted to read '0'.

Procedures

Speech recognition experiments were conducted in normal hearing listeners and individuals with Auditory Dyssynchrony. The test stimuli were played manually by a PC and were routed to a calibrated diagnostic audiometer (GSI-61) which was presented to the subjects monaurally at their most comfortable level through the TDH 50 headphones.

In the sentence recognition tests and the VCV syllable recognition tests, the subjects were presented with a target sentence and the VCV syllables respectively. They were told that, they would hear the stimulus without any background noise and then in a noisy background. They were instructed to repeat or write the stimuli, after the stimuli were heard.

All the subjects with normal hearing had to take a pretest consisting of syllables and sentences (with and without companding) at 0dB SNR and subjects who scored 60% and above for sentences and 40 % or above for the VCV syllables were allowed to participate in the study.

All VCV syllables lists (companded and without companding) at different SNRs were presented and numbers of syllable correctly identified were obtained for both the Clinical as well as the Control group in the following steps:

- Without any modification VCV syllables were presented in quiet and number of syllables correctly identified was obtained in both the groups (clinical and control group)
- Modified (spectrally enhanced through companding) VCV syllables were presented in quiet and number of syllable correctly identified was obtained in both the groups

- Without any modification VCV syllables were presented at different SNRs (+15, +10, +0 dB) and number of syllable correctly identified was obtained in both the groups.
- Modified (spectrally enhanced through companding) VCV syllables were presented at different SNRs (+15, +10, +0 dB), and number of syllable correctly identified was obtained in both the groups.

For the VCV syllables list, the number of syllable correctly identified at each SNR was obtained, whereas for the sentence identification, it is the minimum SNR that resulted in more than 50% SIS was obtained. Each sentence list contains 7 sentences at different SNR. The minimum SNR that resulted in more than 50% word correctly identified was considered.

- Out of the 2 companded sentence list, one of the sentence test material is taken and companded sentences were presented at quiet initially and number of word correctly identified was noted. If they have correctly identified at least 50% word then SNR was reduced to + 15 dB and different set of sentences were presented once again. The same procedure was followed till they achieve minimum SNR at which they could correctly identified 50% word in a sentence and that SNR value was noted.
- Similar procedure was used to obtain minimum SNR require to correctly identify 50% word in a sentence for without companded sentence material.

Sentences list was chosen randomly to minimize the list bias. The noise conditions in all the steps were presented in the order of increasing level of difficulty.

Scoring:

- Number of syllables correctly identified for VCV syllables, for both the conditions (with and without companding) in quiet and at different SNR provided the raw data for each subject for the clinical and the control group.
- Minimum SNR at which 50% of the word correctly identified in a sentence, for both the conditions (with and without companding) provided the raw data for each subject for the clinical and the control group.
- Data obtained in two stimulus conditions (with and without companding) in control group was compared to know in which condition the control group performed better.
- Data obtained in two stimulus conditions (with and without companding) in clinical group was compared to know in which condition the clinical group performed better.
- Data obtained between the clinical and the control group for without companding condition was compared to know the relative performance of the group.
- Data obtained between the clinical and the control group for with companding condition was compared to know the relative performance of the group.

CHAPTER – 4

RESULTS

To know the usefulness of speech enhancement technique (companding), two groups of subjects were taken namely the control group (consisting of normal hearing individuals) and the clinical group (consisting of individuals with AD). To achieve the objectives syllable identification task at different SNRs and minimum SNR was obtained across two stimulus conditions (companded and without companded stimulus). Data obtained in different condition from both the groups were analyzed using SPSS version 16.0.

The following analyses were done between and within the groups:

1. Descriptive statistics for all the parameters tested.
2. Two way repeated measure ANOVA was done to see the overall main effects of different SNR and stimulus conditions (with and without companding) on syllable identification scores for the control group.
3. Bonferroni's adjusted multiple comparisons was done to see syllable identification scores between which two SNR conditions differ significantly within the control group.
4. Paired sample t- test was done for pairwise comparison between stimulus conditions (with and without companding) at each SNR for syllable identification score within the control group.
5. Paired sample t- test was done for pairwise comparison of the minimum SNR that

resulted in at least 50% of the word correctly identified in a sentence, between the stimulus conditions (with and without companding) for sentence test material within the control group.

6. Wilcoxon Signed Ranks test was carried out to see whether there was any significant difference in performance for syllable identification scores at two different SNR, across the stimulus conditions (with and without companding) within the clinical group.
7. Wilcoxon Signed Ranks test was carried out to see whether there was any significant difference in the minimum SNR that resulted in at least 50% of the words correctly identified in a sentence, between the stimulus conditions (with and without companding) for sentence test material within the clinical group.
8. Mann Whitney U test was administered to compare the syllable identification ability between the clinical and control group at different SNRs and also at each stimulus condition (with and without companding).
9. Mann Whitney test was administered to compare the minimum SNR that resulted in at least 50% of the word correctly identified in a sentence between the clinical and control group, at two stimulus condition (with and without companding) for the sentence test material.

The results obtained are discussed under the following headings:

1. Control group having normal hearing sensitivity

a. Mean and Standard deviation for the number of syllables correctly identified (Syllable identification scores) at different SNR and at two stimulus condition (with and without companding)

b. Effect of companding and SNR on syllable identification

c. Mean and Standard deviation of the minimum SNR that resulted in 50% of the words correctly identified in sentence test materials, in two stimulus conditions (with and without companding)

d. Effect of companding on the minimum SNR that is required to correctly identify 50% of the words in a sentence.

2. Clinical group having Auditory Dyssynchrony

a. Mean and Standard deviation for the number of syllable correctly identified (syllable identification scores) at different SNR and at two stimulus conditions (with and without companding)

b. Effect of companding and different SNRs on syllable identification scores

c. Mean and Standard deviation of the minimum SNR that resulted in 50% of the words correctly identified in sentence test materials, in two stimulus conditions (with and without companding)

d. Effect of companding on the minimum SNR that is required to correctly identify 50% of the words in a sentence.

3. Between group comparisons

a. Comparison of number of syllable correctly identified between the clinical and control group at different SNRs in two stimulus conditions (with and without companding)

b. Comparison of effect of companding on the minimum SNR that is required to correctly identify 50% of the words in a sentence between the clinical and control groups

1. Control group having normal hearing sensitivity

a. Mean and Standard deviation for the syllable identification

A total of 15 ears of 15 individuals with normal hearing sensitivity were included. The mean and standard deviation for the number of VCV syllables correctly identified across two stimulus conditions (with and without companding) at four different SNRs (quiet, +15 dB SNR, +10 dB SNR, +0 dB SNR) were calculated and details are given in the table 4.1.

Table 4.1.

Mean and standard deviation (SD) for number of VCV syllables correctly identified (syllable identification scores) at 4 different SNRs (quiet, +15, +10, 0 dB) in, two stimulus conditions (with and without companding) in control groups

	Mean	SD	N
VCV at quiet without companding (vcq)	20.00 (min=20, max=20)	0.00	15
VCV at quiet with companding (vcqc)	20.00 (min=20, max=20)	0.00	15
VCV at +15 dB SNR without companding (vc15)	19.53 (min=18, max=20)	0.74	15
VCV at +15 dB SNR with companding (vc15c)	19.13 (min=17, max=20)	1.30	15
VCV at +10 dB SNR without companding (vc10)	18.20 (min=16, max=20)	1.37	15
VCV at +10 dB SNR with companding (vc10c)	18.00 (min=16, max=20)	1.51	15
VCV at 0 dB SNR without companding (vc0)	10.47 (min=8, max=14)	2.13	15
VCV at 0 dB SNR with companding (vc0c)	13.00 (min=9, max=16)	2.33	15

It is evident from the table that the number of syllable identified at 0 dB SNR without companding signal was least and maximum number of syllable correctly identified was at quiet condition. Syllable identification improved as the SNR improved for both with and without companding stimuli. The control group performance reached maximum possible scores at quiet for both with and without companding condition. At +15 dB SNR and +10 dB SNR without companding condition showed better scores than stimulus with companding. However at 0 dB SNR with companding condition showed slightly better scores than without companding.

b. Effect of different SNRs and companding on syllable identification

To know whether there was any significant difference in performance of the control group at different SNR and two stimulus condition (with and without companding) for VCVs identification, Two way repeated measure ANOVA was done. A significant main effect on syllable identification was seen at different SNRs [F (3, 42) = 143.72, $p < 0.05$]. A significant main effect was observed with and without companding conditions [F (1, 14) = 8.83, $p < 0.05$]. The results also showed a significant interaction between SNRs and conditions [F (3, 42) = 24.11, $p < 0.05$].

As Two way repeated measure ANOVA showed significant difference across SNRs, Bonferroni's adjusted multiple comparison test was done to see between which two SNRs syllable identification scores are significantly different from each other. Details of the Bonferroni adjusted multiple comparison test is shown in table 4.2.

Table 4.2.

Bonferroni adjusted multiple comparision test results for syllable identification scores obtained between any two SNRs (quiet, +15, +10, 0 dB) in the control groups

quiet	(J) SNR	Mean Difference (I-J)	Significant level
	+15dB SNR	.667	.138
	+10dB SNR	1.900	.000
	+0dB SNR	8.267	.000
+15dB SNR	+10dB SNR	1.233	.006
	+0dB SNR	7.600	.000
+10dB SNR	+0dB SNR	6.367	.000

The Bonferroni adjusted multiple comparision test revealed significant difference in syllable identification between any two SNRs condtion except between quiet and +15 dB SNR condition.

As significant interaction was observed between SNR and stimulus condition (with and without companding) in two way repeated measure ANOVA, for the pairwise comparison at each SNRs between two stimulus condition (with and without companding), initially one way repeated measure ANOVA was carried out to see significant difference. One way repeated measure ANOVA test failed to show any results, as at quiet with and without companding condition, all the subjects in the control group had same scores making the mean equal to 20 and Standard deviation equal to 0. Hence, Paired sample t-test was administered to see significant difference in syllable identification between the conditions at also between two SNRs. Details of the paired sample t- test are shown in table 4.3.

Table 4.3.

t-value, degree of freedom and level of significance for pairwise comparison of syllable identification scores between stimulus condition (with and without companding) and different SNRs in the control group

		t-value	df	Sig. (2-tailed)
Pair 1	vcq - vc15	2.432	14	.029
Pair 2	vcq - vc10	5.077	14	.000
Pair 3	vcq - vc0	17.305	14	.000
Pair 4	vc15 - vc10	4.394	14	.001
Pair 5	vc15 - vc0	15.178	14	.000
Pair 6	vc10 - vc0	12.306	14	.000
Pair 7	vcqc - vc15c	2.578	14	.022
Pair 8	vcqc - vc10c	5.123	14	.000
Pair 9	vcqc - vc0c	11.636	14	.000
Pair 10	vc15c - vc10c	3.012	14	.009
Pair 11	vc15c - vc0c	8.991	14	.000
Pair 12	vc10c - vc0c	8.787	14	.000
Pair 14	vc15 - vc15c	2.449	14	.028
Pair 15	vc10 - vc10c	.642	14	.531
Pair 16	vc0 - vc0c	5.429	14	.000

Note: vcqc: VCV in quiet with companding, vcq: VCV in quiet without companding, vc15c: VCV at 15 dB SNR with companding, vc15: VCV at 15 dB SNR without companding, vc10c: VCV at 10 dB SNR with companding, vc10: VCV at 10 dB SNR without companding, vc0c: VCV at 0 dB SNR with companding, vc0: VCV at 0 dB SNR without companding. Abbreviations are same for the next tables also

Paired sample t-test results showed significant difference in all the conditions expect VCV at +10 dB SNR that is the control group performed equally well in VCV identification at +10 dB SNR between the stimulus conditions (with and without companding). The control group performs significantly better for without companding than with companding at +15 dB SNR. However at +0 dB SNR the control group showed significantly better performance with companding than without companding.

c. Mean and Standard deviation of the minimum SNR that resulted in minimum 50% of the words correctly identified in sentence test materials, in two stimulus condition (with and without companding)

Mean and standard deviation for the minimum SNR that resulted in minimum of 50% of the words correctly identified for the sentence test materials, in two stimulus condition (with and without companding) obtained in the control group was calculated. The details are shown in table 4.4

Table 4.4.

Mean and standard deviation (SD) of minimum SNR at which in minimum 50% of the words correctly identified in sentence test materials, in two stimulus conditions (with and without companding) in the control group

	Mean	N	SD
Minimum SNR without companding	-2.67	15	2.582
Minimum. SNR with companding	-5.00	15	.000

It is evident from the table that for the sentence test materials the minimum SNR that resulted in at least 50% of the words correctly identified in sentence was low (better) for companding condition compared to without companding condition. That is the control group subjects performed better at lower SNR for with companded stimuli compared to without companded sentence test materials.

d. Effect of companding on the minimum SNR that required to correctly identify 50% of the words in a sentence

To know whether there was a significant difference for the minimum SNR that resulted in at least 50% of the words correctly identified in a sentence between two conditions (with and without companding) paired sample t- test was done. A significant difference in the minimum SNR between with and without companded sentence test materials was seen [t (14) =3.50, $p < 0.05$]. That is the control group subjects performed significantly better at lower SNR for the sentence test materials with companding compared to without companding.

2. Clinical group having Auditory Dyssynchrony

a. Mean and Standard deviation for the syllable identification

A total of 15 ears (10 individuals) having auditory dyssynchrony comprised the clinical group. The clinical group subjects couldn’t identify any syllable at +10 dB SNR and 0 dB SNR. The mean and standard deviation for the syllable identification scores across two stimulus conditions (with and without companding) in quiet and +15 dB SNR is given in table 4.5.

Table 4.5.

Mean and standard deviation (SD) of number of syllable correctly identified (syllable identification scores) in two conditions (with and without companding) obtained in quiet and +15 dB SNR in the clinical groups

	VCV in quiet without companding	VCV in quiet with companding	VCV at 15 dB SNR without companding	VCV at 15 dB SNR with companding
Mean	10.67	12.47	3.33	4.33
Std. Deviation	6.275	6.413	4.451	5.912

It is evident from the table that the number of syllable identified was more for companded stimuli than without companded stimuli, both in quiet as well as at +15 dB SNR. As the standard deviation was found to be very high in clinical group, parametric test couldn’t be done and non parametric test were used for the clinical group to see the significant difference.

b. Effect of companding on syllable identification at different SNR

To know whether the performance of the subjects in the clinical group differs significantly across the two stimulus condition and also at two different SNRs, Wilcoxon Signed Rank Test was carried out. Details of the Wilcoxon Signed Rank test results are in table 4.6.

Table 4.6.

Z-value and level of significance for pairwise comparison of syllable identification between two stimulus conditions (with and without companding) and 2 different SNRs (quiet, +15 dB) obtained in the clinical groups.

	vcqc - vcq	vc15c - vc15	vc15 - vcq	vc15c - vcqc
Z-value	-3.088	-1.897	-3.187	-3.184
Significance level	.002	.058	.001	.001

As evident from the table Wilcoxon Signed Rank Test showed significant difference in syllable identification for three pair ie: VCV at quiet without companding and VCV at quiet with companding, VCV at +15 dB SNR without companding and VCV at quiet without companding, and also VCV at +15 dB SNR with companding and VCV at quiet with companding. However no significant difference in syllable identification score were obtained for VCV at +15 dB SNR between with and without companding conditions in the clinical group.

c. *Mean and Standard deviation of the minimum SNR that resulted in minimum 50% of the words correctly identified in sentence test materials, in two conditions (with and without companding).*

For sentence test material only 13 ears were tested as data from two ears couldn't be obtained for the task. The mean and the standard deviation obtained in above mentioned conditioned for the clinical group is shown in table 4.7.

Table 4.7.

Mean and standard deviation (SD) of minimum SNR at which 50% of the word correctly identified in sentence test materials, in two conditions (with and without companding) in the clinical group

	Mean	SD
Minimum SNR without companding	4.62 (N=13)	2.47
Minimum SNR with companding	0.77 (N=13)	3.44

It is evident from the table that for the sentence test materials the minimum SNR that resulted in correct identification of 50% word in a sentence is low (better) for companded stimulus compared to without companding condition.

d. *Effect of companding on the minimum SNR that resulted in minimum 50% of the word correctly identified in sentence test materials*

To know whether there was a significant difference for the minimum SNR that resulted in minimum 50% of the word correctly identified in a sentence between two conditions (with and without companding) Wilcoxon Signed rank test was carried out. A significant difference in the minimum SNR between with and without companded sentence test materials was seen [$Z = -2.89$, $p < 0.05$]. Clinical group subjects performed significantly better at lower SNR for the sentence test materials with companding compared to without companding.

II. **Between group comparisons**:

a. *Comparison of number of syllable correctly identified across the clinical and control group at different SNRs in two conditions (with and without companding)*

To compare the performance across the clinical and control group for the syllable identification task for VCVs at different SNRs in two conditions (with and without companding) Mann-Whitney Test was administered. The details of the Mann-Whitney results are shown in table 4.8.

Table 4.8.

Z- value and level of significance for comparison of VCV syllable identification scores between the clinical and control groups obtained at 2 different SNRs (quiet, +15 dB) and also in two conditions (with and without companding)

	vcq	vcqc	vc15	vc15c
Z- value	-4.992	-4.991	-4.825	-4.826
Significance level	.000	.000	.000	.000

The results of Mann-Whitney Test showed significant difference in performance between control and clinical group for syllable identification at both the SNRs and also in two conditions (with and without companding). The control group performed significantly better than clinical group for VCV identification task at all the SNRs in both with and without companding conditions.

b. *Comparison of effect of companding on the minimum SNR that resulted in minimum 50% of the word correctly identified in sentence test materials between the clinical and the control group*

To compare the performance between the clinical and the control group for the minimum SNR that resulted in 50% of the words correctly identified in sentence test material (with and without companding), Mann-Whitney Test was administered. The details of the Mann-Whitney Test results are shown in table 4.9

Table 4.9

Z- value and level of significance for comparison of minimum SNR that resulted in 50% of the words correctly identified in sentence test materials, in two conditions (with and without companding) between the clinical and the control groups

	Minimum SNR without companding	Minimum SNR with companding
Z- value	-4.397	-4.729
Significance level	.000	.000

The Mann-Whitney Test results showed significant difference in performance between the control and the clinical group for the minimum SNR, both in with and without companded sentence test materials. The control group performed at a significantly lower (better) SNR than the clinical group for both with and without companded sentence test materials.

The results obtained in the current study thus can be summarized as follows:

Control group having normal hearing sensitivity:

- Higher the SNR, more the number of syllables correctly identified
- A significantly better performance is seen for without companding compared to with companded syllables at +15 dB SNR, no significant difference at quiet and +10 dB SNR was observed
- At 0 dB SNR performance was significantly better for with companded syllables

compared to without companding

- For companded sentences SNR required to correctly identify 50% of the word in a sentence was lower (better) than without companded sentences

Clinical group having Auditory Dyssynchrony

- At quiet performance was significantly better for companded syllables compare to without companding
- At +15 dB SNR no significant difference between with and without companded syllables observed
- For companded sentences SNR required to correctly identify 50% of the words in a sentence was lower (better) than without companded sentences

Between group comparisons

- A significantly better performance of control group compared to clinical group for syllable identification at all the SNRs in two stimulus conditions (with and without companding) was observed
- The SNR required to correctly identify 50% of words in a sentence was significantly lower (better) for control group compare to the clinical group in both the sentence test materials (with and without companding)

CHAPTER – 5

Discussion

Perception of companded VCV syllables at different SNR and word perception in sentences was investigated in normal hearing individuals and individuals with Auditory Dyssynchrony (AD). For the VCV syllables, the subjects were asked to identify the syllables at each SNR, whereas for the sentences the subjects were asked to repeat as many words as possible from the sentence and the minimum SNR which resulted in 50% identification was considered. The results obtained are discussed below:

Control group having normal hearing sensitivity:

Effect of companding on syllable identification at different SNR

In the present study number of syllable correctly identified significantly reduced as the SNR reduced. The number of syllable identified at 0 dB SNR without companding signal was least and maximum number of syllable correctly identified was at quiet condition.

The results obtained in present study are similar to those obtained by earlier investigators (Dorman, Loizou & Tu, 1998). Houtgast and Steeneken (1985) also reported that speech intelligibility reduces in the presence of background noise. This is partly because the noise reduces the modulations of speech envelope. In addition, the decline in intelligibility may also results from distortion of temporal fine structure and introduction of spurious envelope modulation as these modulations obscure or masks the modulation pattern of speech, and obliterates some of the cues for identification (Drullman 1995).

The individual in the control group demonstrate a significant benefit from companded VCV syllables at 0 dB SNR. This shows that companding enhances the spectral peaks and listeners could take advantage of these enhanced peaks in adverse listening condition.

The result of the present study is in agreement with the results of previous investigators where they showed significant improvement in identification scores in presence of background noise, when envelope enhanced stimuli were presented to individuals with normal hearing and cochlear hearing loss (Apoux, Tribut, Debruille & Lorenzi, 2004; Baer *et al.*, 1993; Bunnell, 1990; Clarkson & Bahgat, 1991; Franck *et al.*, 1999; Lyzenga *et al.*, 2002). Turicchia and Sarpeshkar (2005) also showed that spectral contrast is an emergent property of the companding strategy and had speculated that this strategy has the potential to improve speech performance in noise.

Studies have found small improvement in the identification of stop consonants in quiet, using a contrast enhancement technique in which the envelope amplitude of each fast Fourier transform bin is enhanced proportionately to the difference in the original envelope amplitude and the average spectrum level (Bunnell, 1990, Franck *et al.*, 1999; Lyzenga *et al.*, 2002). Baer *et al.* (1993) convolved the spectrum with a difference of Gaussian filter to provide spectral enhancement. They showed that their normal hearing subjects preferred speech in noise with moderate enhancement in terms of quality and intelligibility.

In quiet condition the performance of normal hearing individual was maximum and due to ceiling effect benefit of companding couldn’t be seen. As normal hearing individual don’t have any kind of spectral and temporal deficit and the modification in the stimulus might not be useful for them at higher SNR, when the individual are able to extract envelope cues from speech signal. But companding will be effective in adverse listening condition, which is shown by better performance at 0 dB SNR.

Effect of companding on the minimum SNR that is required to correctly identify 50% of the words in the sentence test materials

The results of the normal hearing individuals averaged across 15 listeners showed that for companded sentences the minimum SNR that is required to correctly identify 50% of the words is achieved at significantly lower SNR (better) than without companded sentences. This shows better performance at lower SNR for with companded stimuli compared to without companding sentence test material.

These results are consistent to earlier investigator’s results who reported average improvement in sentence and word recognition in noise, in normal hearing subjects using companding strategy (Bhattachrya & Zeng; 2007, Oxenham, Simonson, Turicchia & Sarpeshkar, 2007). Normal hearing individuals, in the adverse listening conditions utilized the enhanced spectral and temporal contrast of the companded speech stimuli. The improvement observed in the present study for the companded stimuli can be attributed to the increased spectral and temporal contrast provided by companding strategy.

Clinical group having Auditory Dyssynchrony

Effect of companding on syllable identification at different SNR

Individuals with AD also showed the similar trend that is number of syllable correctly identified reduced as the SNR reduced. Subjects in the clinical group could only perform at two SNR that is in quiet and at +15 dB SNR.

As the SNR decreased they failed to perceive even single VCV syllables. This suggests that AD have difficulty in utilizing available information if the condition is even slightly worse. Studies have investigated speech perception in noise in individuals with AD and illustrated that the noise has detrimental effect on speech perception (Rance et al., 2007; Zeng & Liu, 2006). The results in the present study are in accordance with the previous studies (Rance et al., 2007; Zeng & Liu, 2006). Adding noise to the speech signal leads to problem in perceiving the envelope of speech, because of reduction in modulation depth and addition of spurious modulation (Drullman, 1995). This explanation would explicate severe degradation in speech intelligibility in the presence of background noise for individual with AD.

The exact mechanism causing extreme difficulty in understanding speech in the presence of noise in individuals with AD is unclear. Zeng et al. (2005) have reported excessive masking effects for detection of tones in the presence of noise. This excessive masking may be one of the factors in these individuals contributing to the extreme difficulty in understanding speech in the presence of noise.

Results of the present study unequivocally demonstrated benefit from companding. Companded VCV syllables significantly improved syllable identification in quiet. Companding increases the spectral and temporal contrast in speech (Bhattachrya &

Zeng; 2007, Oxenham, Simonson, Turicchia & Sarpeshkar, 2007). Loizou (2005) implemented companding strategy in CI users and found a modest improvement in vowel recognition. Narne and Vanaja (2008) have shown that enhancing the envelope improved consonant identification at quiet in individuals with AD. In addition, Zeng and Liu (2006) have said that the subjects with AD showed improved performance, in quiet when clear speech is presented and this improvement is attributed to enhanced envelopes in the clear speech. Thus, it can be said in the present study that, the enhanced spectral and temporal contrast for the companded stimuli might be the reason for the improved speech perception in individuals with AD.

There was a difference in performance between with companding (mean=4.33) and without companding (mean=3.33) VCV syllables at + 15 dB SNR, but it was not statistically significant. Lack of significant difference at + 15 dB SNR suggests that, individuals with AD cannot utilize enhanced information in the presence of noise which indicates that they have more of neural problem, which predominantly exhibit temporal deficit.

The results of the individuals with AD averaged across 15 ears showed that for companded sentences the minimum SNR that is required to correctly identify 50% of the words is achieved at significantly lower SNR (better) than without companded sentences.

Hassan (2011) reported temporal modification of speech to be beneficial for subjects with AD. These results are consistent to earlier investigator who reported average improvement in sentence and word recognition in noise, with individuals with AD using enhanced envelope cues (Zeng & Liu, 2006). Companding enhances the spectral peaks and listeners are able to take advantage of these enhanced peaks in adverse listening condition (Bhattachrya & Zeng; 2007, Oxenham; Simonson; Turicchia & Sarpeshkar, 2007). Bhattachrya and Zeng (2007) reported that companding apart from improving spectral contrast also enhances the temporal contrast. As the individual with AD exhibit temporal deficits enhancing the spectral and temporal contrast might have lead to significant improvement.

Between group comparisons

Syllable identification scores in the presence of noise was significantly more severely affected in individuals with AD (clinical group) when compared to listeners with normal hearing (control group).

Studies have reported that normal hearing listeners use fine structure in understanding speech in adverse listening conditions (Dorman, et al., 1998; Zeng & Liu, 2006). However, individuals with AD are impaired in extracting both envelope and fine structure cues from speech signal even in quiet, adding noise to the speech signal may exaggerate their problem in perceiving the envelope of speech, because of reduction in modulation depth and addition of spurious modulation (Drullman, 1995). In the present study, probably the impaired ability to extract the envelope and fine structure cue could be the reason for their poorer performance compared to normal hearing individuals.

Another possible reason for the poorer performance in presence of noise in individuals with AD compare to normal hearing individuals might be due to the excessive masking effect in individuals with AD (Zeng et al., 2005). They could not utilize any information in presence of noise which indicates they have more of neural problem, which predominately exhibits temporal difficulty.

There was improvement in both the group for companded VCV syllables perception, but the performance of the normal group was significantly better compared to clinical group for syllable identification at all the SNRs.

The results suggest that Individuals with auditory dyssynchrony were unable to fully utilize the temporal and spectral cues. Potential reasons behind this can be attributed to the poor temporal and spectral processing abilities (Rance et al., 2004; Zeng et. al., 2005).

Secondly, spectral enhancement provided by the companding was across frequencies, including low frequencies. The low frequencies instead of enhancing speech perception might have caused upward spread of masking, thus the benefit which individuals with AD got from high frequency enhancement also reduced causing minimal improvement in their SIS compared to normal hearing individuals.

I*mprovement in both the group, for the minimum SNR that is required to correctly identify 50% of the words in a sentence for the companded sentence test stimuli compared to without companded stimuli was observed, but the performance of the normal group was significantly better compared to clinical group.*

Apoux et al. (2004) have clearly shown that envelope enhancement enhances the consonant portion and compresses the vowel portion of the signal and improves perception of speech in noise better than other signal processing strategies in individuals with normal hearing. In addition, Picheny, Durlach and Braida (1985, 1986) have said that advantage of clear speech over conversational speech in noise for cochlear hearing loss listeners may be due to the increased consonant to vowel ratio and enhanced envelopes. Thus, it can be said that improvement observed in the present study may probably be due to enhanced spectral and temporal contrast.

Possible reason for poorer performance of AD compared to normal hearing individual is their inability to fully utilize the temporal and spectral cues. In Individual with AD the neural temporal processing disrupts, affect the listener's ability to cope with dynamic nature of speech signal. Severe disruption of timing cues could impair not only the ability to use amplitude envelope cues in speech but also to perceive rapidly changing spectral shapes in the flow of speech stimuli (Rance et al. 2004).

To conclude, speech identification abilities is significantly impaired in individuals with AD. This is probably the reflection of excessive masking and diminished temporal processing abilities in individuals with auditory dyssynchrony. Enhancing the spectral and temporal contrast through companding improved speech perception in these individuals. The present study suggests that utilizing the companding strategy in hearing instrument will probably provide significant benefit to many individuals with auditory dyssynchrony.

CHAPTER – 6

Summary and Conclusions

Auditory dyssynchrony (AD) is a distinct hearing disorder characterized by auditory nerve dysfunction in the presence of normal outer hair cell activity (Starr, Picton, Sininger, Hood & Berlin, 1996). Psychophysical studies indicated that the consequences of distrupted auditory nerve activity significantly impair temporal processing and difficulty in understanding speech that is disproptionate to the degree of hearing loss measured by puretone thresholds (Siniger & Oba, 2001; Zeng et al., 1999).

Management of AD continues to be difficult and challenging. Conventional hearing aids have achieved limited success (Rance et al., 2002). New signal processing strategies need to developed to help them understand speech in quiet as well as in the presence of noise. Research indicated that companding the signal improve speech identification in cochlear implant users. However usefulness of this option has not been investigated in individuals with AD and there is a need to determine these skills in patients with AD.

Thus, this study was taken with the purpose (a) to know whether companding of speech stimuli helps to improve speech intelligibility in individuals with normal hearing and with auditory dyssynchrony (b) benefit of spectrally enhancing speech through companding at different SNRs in presence of speech shaped noise, and also (c) to determine how normal hearing individual and individual with auditory dyssynchrony differ in their performance for companded stimuli at quiet and at different SNRs.

To achieve the objective 15 ears of ten individuals with auditory dyssynchrony (mean age 27 years) and 15 ears of fifteen normal hearing individuals (mean age 27 years) were taken. Speech identification abilities of these individuals were assessed in quiet and at three different SNRs (+15 dB, +10 dB, +0 dB) for VCV syllables with and without companding. The minimum SNR at which these individuals correctly identified 50% of the words in a sentence was also assessed using with and without companded Quick SIN sentences test in Kannada developed by Methi, Avinash and Kumar (2009). Speech Shaped noise was used to generate different SNRs. Companding was carried out using program developed in MATLAB, where speech signal are processed by compression and expansion scheme.

The data collected in the study were statistically analyzed. Analysis of the data warranted the following results:

- As the SNR increased, number of syllable correctly identified increased for both with and without companded VCV syllables, in both the group
- Normal hearing individuals reached ceiling effect for syllable identification in quiet, for both with and without companded VCV syllables
- Normal hearing individuals showed significantly better performance for with companded stimuli compared to without companded VCV syllables at + 0 dB SNR
- Normal hearing individuals required significantly lower SNR (better) for companded sentences than without companded sentences, to correctly identify 50% words in a sentence
- Individuals with auditory dyssynchrony showed significantly better syllable

identification score with companding compared to without companding condition at quiet

- At +15 dB SNR no significant difference in syllable identification between with and without companded syllables observed
- For companded sentences SNR required to correctly identify 50% of the words in a sentence was lower (better) than without companded sentences, in individuals with auditory dyssynchrony.
- The normal hearing individuals performed well at a significantly lower (better) SNR than the individuals with auditory dyssynchrony for both with and without companded sentence test materials

Reduction in speech identification abilities as the SNR reduces, for both the groups (normal hearing and individuals with auditory dyssynchrony), is explained with the fact that noise reduces the modulations of speech envelope and distorts temporal fine structure (Drullman, 1995). For individuals with AD the more reduction in performance suggests that individuals with AD show excessive masking effect (Zeng et al 2005). They cannot utilize any information in presence of noise which indicates they have more of neural problem, which predominately exhibits temporal difficulty.

The improvement in speech identification abilities for the companded speech stimuli at quiet and at noise, for both the groups, is explained as companding increased the spectral and temporal contrast. Listeners could take advantage of these enhanced spectral and temporal contrast in adverse listening conditions (Bhattachrya & Zeng; 2007; Oxenham, Simonson, Turicchia, & Sarpeshkar, 2007).

Compared to normal hearing individuals, poorer performance of individuals having auditory dyssynchrony for with companded stimuli is explained as these individuals are unable to fully utilize the temporal and spectral cues. Potential reasons behind this can be attributed to the poor temporal and spectral processing abilities in these individuals (Rance et al., 2004; Zeng et al., 2005). Also the spectral enhancement was across frequencies, including low frequencies due to companding. The low frequencies instead of enhancing speech perception might have caused upward spread of masking and so the benefit which they got from spectral enhancement at high frequencies would have reduced. Thus, resulted in minimal improvement in speech perception.

Conclusion

Though, at present, cochlear implantation is the preferred treatment option for auditory dys-synchrony, our behavioral data suggests that companding the speech signal, enhances the spectral and temporal contrast and lead to better speech perception in individual with auditory dyssynchrony. The significance of this study should be seen in the following context:

There are as many studies which say that hearing aids have failed to show beneficial effects in subjects with auditory dyssynchrony. The present study provides indirect evidence that hearing aids having companding strategy, which process speech to enhance spectral and temporal contrast may be beneficial to persons with auditory dyssynchrony. Thus it can be suggested that companding of signal can be used as one of the signal processing strategies improve speech perception in auditory dyssynchrony.

Implication

- This can be used to study speech perception deficit in individual with auditory dyssynchrony
- This can be used to explain physiological basis for speech perception abilities in individuals with auditory dyssynchrony
- Design signal processing strategy which can be used for better speech perception

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