Perception of Spectrally Enhanced Speech through Companding in Individuals with Cochlear Hearing Loss

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Abstract

The present study aimed to assess the benefit of spectral contrast enhancement using companding strategy in individuals with cochlear hearing loss. Twenty adult subjects having normal hearing and cochlear hearing loss participated in the study. Consonant recognition scores (quiet, 15 dB SNR, 10 dB SNR and 0 dB SNR) and sentence recognition threshold in noise was obtained in unprocessed (original) and processed (spectrally enhanced using companding strategy) condition. Numbers of correctly recognised consonants were calculated for the consonant recognition task. The SNR level at which 50 % of the correct responses were obtained using sentences (SNR-50), across different SNRs (+20 dB to -10 dB SNR) was found. Results showed that processed condition of consonant recognition scores lead to higher performance than unprocessed in both the groups. Significant improvement was found at 0 dB SNR (12 %) for normal hearing individuals and at 15 dB (4.5 %), 10 dB (5.25 %) and 0 dB SNR (18.75 %) for those with cochlear hearing loss. In sentence recognition threshold in noise (SNR-50) task, both the subjects performed at lower SNR levels in processed than unprocessed condition. Improvement found was about -3.75 dB SNR for normal hearing individuals and -5 dB SNR for those with cochlear hearing loss. Thus, it can be concluded that spectrally enhanced speech through companding strategy improves the speech perception in noise in individuals with cochlear hearing loss to a much greater extent than do for normal hearing individuals.

***Keywords:** Spectral enhancement, Companding, Speech Perception, Cochlear hearing loss*

Introduction

The most common type of hearing loss is sensorineural hearing loss, which is usually associated with a dysfunction of the cochlea. People with cochlear hearing loss can understand speech reasonably well in one-to-one conversation in a quiet room, but they have great difficulty when there is background noise or reverberation, or when more than one person is talking (Plomp, 1978).

Reduced frequency selectivity is a well-documented abnormality that is associated with cochlear hearing loss, which can affect speech perception in noise (Tyler, Wood &Fernandes, 1982; Preminger & Wiley, 1985; Thibodeau& van Tasell, 1987). One mechanism by which impaired frequency selectivity could affect speech understanding in noise involves the perception of spectral shape. The recognition of speech sounds requires a determination of their spectral shapes, especially the locations of spectral prominence. Broader auditory filters associated with cochlear hearing loss, produce a more highly smoothened representation of the spectrum. If spectral features are not sufficiently prominent, they may be smoothed to such an extent that they become imperceptible. Leek, Dorman and Summerfield (1987) reported that the greater spectral contrast was required for vowel identification by hearing impaired than for normal hearing listeners. Adding a noise to speech fills the valleys between the spectral peaks and thereby reduces spectral prominence, resulting in poorer perception of speech in the presence of noise.

Thus, improving the intelligibility of speech in noise for individuals with cochlear hearing loss is one of the most difficult tasks faced by hearing aid manufacturers. There are currently a variety of tools available for this task, which includes the application of digital signal processing to hearing aids. With appropriate prescription and fitting, a hearing aid can significantly improve speech recognition for an individual with hearing impairment in quiet and non-reverberant listening environment. However, this benefit is greatly reduced in the presence of noise (Killion&Niquette, 2000). Hence, one of the challenges in providing amplification for the cochlear hearing loss individuals is to select the technology that will provide the maximum benefit in the presence of noise.

If reduced frequency selectivity impairs speech perception in noise for individuals with cochlear hearing loss, then enhancement of spectral contrasts might improve their performance. A number of spectral enhancement techniques have been tested using normal hearing and hearing-impaired) listeners in order to improve their speech understanding in noise (Bunnell, 1990; Clarkson &Bahgat, 1991) and small to modest benefits have been obtained with the signal enhancement (Baer, Moore & Gatehouse, 1993). Recently, Turicchia and Sarpeshkar (2005) applied a frequency-specific companding strategy for spectral contrast enhancement and showed that it has the potential to improve speech performance in noise in cochlear implant users. Similarly, Bhattacharya and Zeng (2006) studied speech recognition in speech-shaped noise by cochlear implant users using companding strategy. They found significant improvement in the recognition of phonemes, consonants and sentences

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in noise. However, there is a dearth of studies done on investigating the perception of spectrally enhanced speech stimuli using companding strategy in individuals with cochlear hearing loss. Therefore, the current study was conducted.

The aim of the study was to assess the benefit of spectral enhancement using compadingstrategy by comparing thespeech recognition performance in unprocessed (unmodified) and processed (spectrally enhanced) condition among individuals with normal hearingandcochlear hearing loss.

Method

Participants

The data were collected from a total of 40 participants. All of them were native speakers of Kannada.The participants did not have any psychological and neurological problems. They did not have of middle ear pathology as confirmed by immittance evaluation.The participants were divided into two groups; Group I and Group II. Both the groups consisted of 10 male and 10 females.Group I consisted of 20 individualswith normal hearing in the age range 19 to 48 years. Group II included 20 individuals with cochlear hearing loss of age ranging from 18 to 48 years. They had mild to moderately severe degree of hearing loss.

Instrumentation

A calibrated two-channel diagnostic audiometer (GSI-61) with TDH-39 headphones housed in MX-41/AR ear cushions and a bone vibrator, Radio ear B-71 was used to carry out pure tone audiometry. A calibrated GSI-Tympstar (version 2) immittance meter was used to rule out middle ear pathology,ILO 292 DPEcho port system to assess outer hair cell functioning and Intelligent Hearing Systems (IHS smart EP windows USB version 3.91) to rule out retrocochlear pathology. Toshiba Satellite L645 laptop (Realtek sound card) and AHUJA AUD-101XLR dynamic unidirectional was used to record the speech stimulus.MATLAB-7 (Language of Technical computing, USA) was used to spectrally enhance the speech signal using companding strategy.

Test Material

Consonants: Twenty consonants /p, b, t̪, d̪, k, g, ʈ, ɖ, m, n, tʃ dʒ, s, ʃ, j, v, r, l, ɭ, h/ in the context of the vowel /a/ was used. They were spoken by a native Kannada female speaker (language spoken in southern part of India) and were digitally recorded in an acoustically treated room, on a data acquisition system using 44.1 kHz sampling frequency with a 16-bit analog to digital converter. While recording the microphone was placed at a distance of 15cm from the lips of the speaker. The

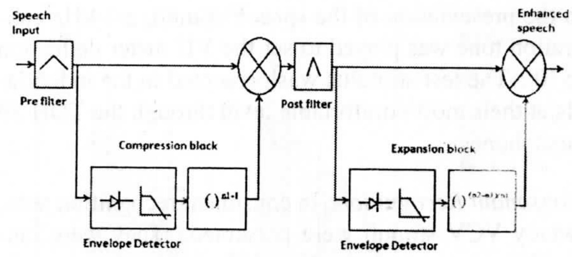

Figure 1: Design of a single channel companding pathway.

recorded stimuli were root mean square normalized to maintain equal loudness.Goodness test for the recorded material was carried out by presenting the stimuli to 10 individuals with normal hearingto assess quality of recording. All the normal hearing participants obtained 100% score indicating that speech material was highly intelligible. In the experiments involving background noise, each consonant was mixed with a speech spectrum shaped noise at SNRs of 0, 10 and 15 dB.

Sentence: The speech stimuli were sentences in Kannada, developed by Avinash, Raksha and Kumar (2008). There were a total of 10 lists, each list consisting of 7 sentences. Each sentence consisted of 5 target words. All the sentence lists were phonetically balanced and were equally difficult. Each list was mixed with speech spectrum shaped noise at different SNR ranging from +20 dB to -10 dB SNR in 5 dB step-size.

Signal processing strategy: The spectral enhancement using companding architecture was implemented in MATLAB. The companding architecture divides the input signal into 40 frequency channels by a bank of relatively broad band-pass filters. Figure 1 shows the design of a single channel companding pathway. Each channel consists of broad pre-filter, a compression block, a relatively narrow-band post-filter and an expansion block. The time constant of the envelope detector governs the dynamics of the compression or expansion. The extent of compression within each channel depended on the output of ED and compression index (n1). Further, the compressed signal was passed through a relatively narrow band-pass filter before being expanded. The gain of the expansion block depended on the corresponding ED output and the ratio n2/n1. The outputs from all the channels were summed to obtain the processed signal.

Here, 40 channels logarithmically spaced between 100 and 10000 Hz with $n1 = 0.3$ and $n2 = 1$ was used. Both consonants and sentences were processed through this companding strategy, to increase the spectral contrast in quiet and different SNR conditions.

Procedure

Speech recognition experiments were done on individuals with normal hearing and cochlear hearing loss. The output from the laptop was routed to the tape input/auxiliary input of the audiometer (GSI-61). Prior to the presentation of the speech stimuli, a 1 kHz calibration tone was played to set the VU meter deflection to '0'. The test stimulus was presented to the individuals at their most comfortable level through the TDH 39 headphones.

Consonant Recognition: In consonant recognition tests, twenty VCV stimuli were presented. They were randomly presented across four different listening conditions (quiet, 15 dB, 10 dB and 0 dB SNR) in unprocessed and processed condition. Subjects were instructed to repeat the consonant that was heard.

Speech Recognition Threshold in Noise: The participants were instructed to listen to the sentence and repeat aloud as many of the words as possible. The experimenter noted the number of words that were correctly repeated by the participant. Stimuli were presented at comfortable level. The starting SNR was +20 dB which was lowered by 5 dB till the level at which two of the four or three of the five words of the sentence are repeated correctly. The SNR at which two of four or three of five words were repeated correctly, was considered as SNR-50.

Results

The data obtained was tabulated and analyzed using Statistical Package for Social Sciences (version 16.0).This was examined for consonant identification and sentence recognition threshold in noise (SNR-50).

Consonant Recognition in Unprocessed Condition

Consonant recognition scores were obtained in unprocessed condition among individuals with normal hearing and cochlear hearing loss. Individuals with normal hearing achieved 95 - 100 % consonant recognition scores in the quiet condition than in the presence of noise. Across different SNRs, maximum scores were obtained at 15 dB SNR, followed by 10 dB and 0 dB SNR. Performance reduced with the decrease in the SNR. Individuals with cochlear hearing loss obtained relatively poorer scores than those with normal hearing as shown in Figure 2. In quiet condition, identification scores obtained were 78 % whereas at 0 dB SNR, scores dropped to 20 %.

Repeated measure ANOVA was performed to assess the difference in unprocessed consonant recognition scores across the four listening conditions (quiet, 15 dB, 10 dB and 0 dB SNR) within individuals with normal hearing and cochlear hearing loss separately. Analysis revealed a significant difference in individuals with normal hearing [$F_{(3,57)} = 300.03$, $P<0.001$] and also cochlear hearing loss [$F_{(3,57)} = 122.17$, $P<0.001$]. For both the groups, there was significant difference between consonant recognition scores in the four listening conditions.

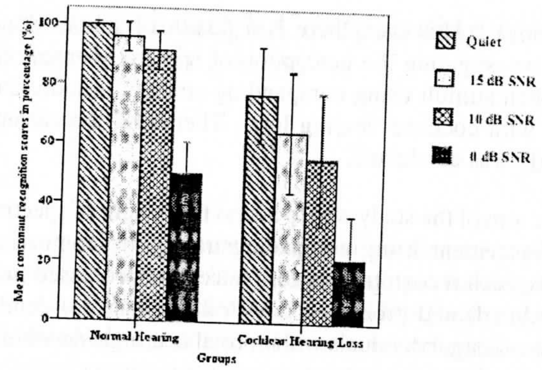

Figure 2: Mean and standard deviation (SD) of unprocessed Consonant recognition scores in normal hearing and cochlear hearing loss group. Error bars indicate SD.

The pairwise comparison was performed using Bonferroni test in both the groups. Results showed that there was significant difference across the different listening conditions for both the groups ($p< 0.05$).

Further, MANOVA was done to compare the unprocessed consonant recognition scores between individuals with normal hearing and cochlear hearing loss across all the four listening conditions. Results showed a significant difference in consonant recognition scores between the groups in quiet [$F_{(1,38)} = 43.56$, $p< 0.05$], 15 dB SNR [$F_{(1,38)} = 45.55$, $p< 0.05$], 10 dB SNR [$F_{(1,38)} = 48.43$, $p< 0.05$] and 0 dB SNR [$F_{(1,38)} = 47.54$, $p< 0.05$].

From the results of present study, it can be noted the normal hearing individuals obtained 100 % consonant recognition scores in quiet condition. However as the SNR decreased, there was a minimal reduction in scores at 15 dB and 10 dB SNR, whereas at 0 dB SNR scores reduced drastically. However, in individuals with cochlear hearing loss, poorer scores were obtained in quiet condition compared to normal hearing individuals. Also as the SNR reduced, there was a drastic decrease in the scores for those with cochlear hearing loss. This reduction in scores was much greater than the normal hearing individuals.

Consonant recognition in unprocessed versus processed condition

Consonant recognition scores were obtained for normal hearing and cochlear hearing loss in both unprocessed and processed condition. Individuals with normal hearing obtained almost similar scores in quiet, 15 dB and 10 dB SNR in both unprocessed and processed condition, whereas scores improved by 12 % at 0 dB SNR in processed condition. Among cochlear hearing loss individuals, improvement in processed condition was about 4.5 % at 15 dB, 5.25 % at 10 dB SNR and 18.75 % at 0 dB SNR. Both the groups obtained higher scores in processed than unprocessed condition as shown in Figure 3 and 4. In addition, individuals with cochlear hearing

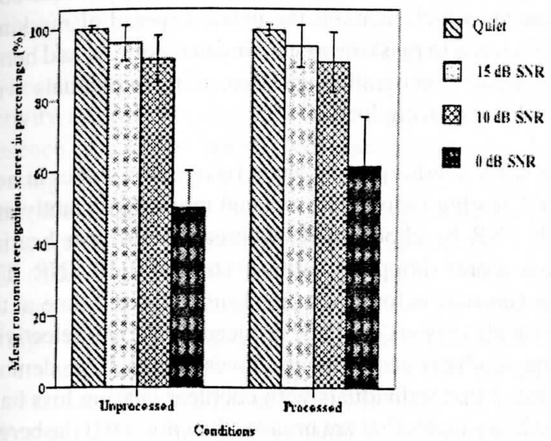

Figure 3: Paired't' test results in unprocessed and processed condition in normal hearing individuals. Error bars indicate SD.

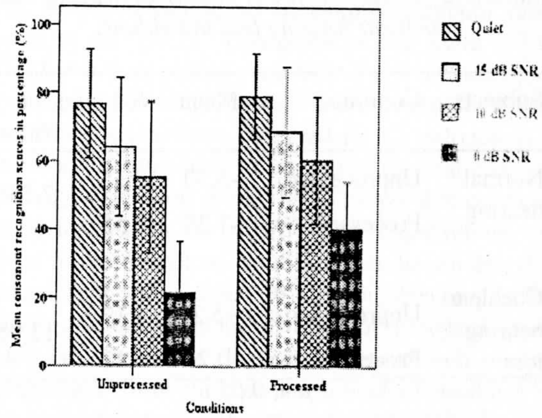

Figure 4: Paired 't' test results in unprocessed and processed condition in cochlear hearing loss individuals. Error bars indicate SD.

loss obtained lesser scores than those with normal hearing.

Repeated measure ANOVA was done to compare the unprocessed and processed consonant recognition scores across listening conditions (quiet, 15 dB, 10 dB and 0 dB SNR) in normal hearing individuals. Further, results showed significant difference across different listening conditions in unprocessed [$F_{(3,57)} = 300.032$, $p< 0.05$] and processed condition [$F_{(3,57)}= 120.159$, $p< 0.05$]. Further, paired't' test was performed to compare unprocessed and processed consonant recognition scores across each of the listening conditions (quiet, 15 dB, 10 dB and 0 dB SNR). Results revealed significant difference in the performance of normal hearing group in unprocessed and processed condition at 0 dB SNR only. Processed condition had an average of 12 % higher scores at 0 dB SNR ($p< 0.05$) than unprocessed condition. However, no significant difference was obtained in quiet ($p = 0.33$), 15 dB ($p = 0.57$) and 10 dB SNR ($p = 0.67$).

To compare the unprocessed and processed consonant recognition scores across listening conditions (quiet, 15 dB, 10 dB and 0 dB SNR) in cochlear hearing loss individuals, repeated measure ANOVA was carried out. Results showed significant difference across different listening conditions in unprocessed [$F_{(3,57)} = 122.178$, $p< 0.05$] and processed [$F_{(3,57)}= 84.548$, $p< 0.05$].

Among cochlear hearing loss individuals, paired't' test results revealed significant difference in unprocessed and processed consonant recognition scores at 15 dB, 10 dB and 0 dB SNR except quiet condition (Figure 4). Maximum improvement was obtained at 0 dB SNR (18.75 %) than 10 dB SNR (5.25 %) followed by 15 dB SNR (4.5 %) in processed over unprocessed condition.

Further, MANOVA was done to compare the consonant recognition scores between normal hearing and cochlear hearing loss individuals across different listening conditions (quiet, 15 dB, 10 dB and 0 dB SNR). Results revealed a significant difference in consonant recognition scores between the groups in quiet [$F(1, 38) = 51.790$, $p< 0.05$], 15 dB SNR [$F(1, 38) = 34.481$, $p< 0.05$], 10 dB SNR [$F(1, 38) = 43.622$, $p< 0.05$] and 0 dB SNR [$F(1, 38) = 24.270$, $p< 0.05$].

Sentence Recognition Threshold in Noise (Snr-50)

Sentence recognition threshold in noise (SNR-50) was obtained in both unprocessed and processed condition among individuals with normal hearing and cochlear hearing loss. Both the groups obtained lower SNR values in processed than unprocessed condition as shown in Figure 5.

To analyze whether mean differences between con-

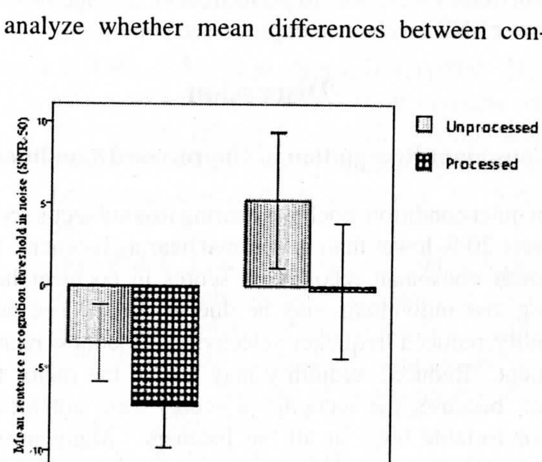

Figure 5: Mean and standard deviation (SD) of unprocessed and processed sentence recognition threshold in noise (SNR-50) in normal hearing and cochlear hearing loss group. Error bars indicate SD.

Table 1: Paired 't' test results for sentence recognition threshold in noise (SNR-50) in normal hearing and cochlear hearing loss individuals.

Subjects	Condition	Mean	SD	t value
Normal hearing	Unprocessed	-3.50	2.35	7.55*
	Processed	-7.25	2.55	
Cochlear hearing loss	Unprocessed	+5.25	4.12	15.98*
	Processed	-0.25	4.12	

*$p < 0.05$

ditions for both the groups reached significance, MANOVA was performed. Analysis revealed significant difference between both the groups in unprocessed [F (1, 38) = 67.85, P<0.05] and processed condition [F (1, 38) = 41.609, p< 0.05]. A comparison across the groups indicated that sentence recognition threshold in noise (SNR-50) for the group with normal hearing was lower than the group with cochlear hearing loss in both the conditions.

Sentence recognition threshold in noise (SNR-50) was compared between unprocessed and processed condition in both normal hearing individuals and cochlear hearing loss individuals using paired sample t-test. The results of the paired 't' test is given in Table 1.

From Table 1, it can be described that mean sentence recognition threshold in noise (SNR-50) is significantly lower in processed condition than in non-processed condition for both the groups. In the processed condition, normal hearing individuals are able to perform at an average of -3 dB to -4 dB lower SNR levels compared to unprocessed condition, whereas cochlear hearing loss individuals were able to perform at an average of -5 dB lower SNR levels than unprocessed condition.

Discussion

Consonant Recognition in Unprocessed Condition

In quiet condition, cochlear hearing loss subject's scores were 20 % lower than the normal hearing listeners. The lower consonant recognition scores in cochlear hearing loss individuals may be due to the reduced audibility, reduced frequency selectivity or loudness recruitment. Reduced audibility may not be the major factor, because, the recognition scores were obtained at comfortable level in all the listeners. Many investigators demonstrated no significant correlation between identification scores and frequency selectivity (Dubno& Schaefer, 1992). However, loudness recruitment may be one of the major causes which leads to reduced dynamic range and changes the amplitude variations in the speech signal. These changes involve increase in the amplitude of vowel more significantly than the consonants which increase the upward spread of masking. This leads to masking of consonantal portion, and hence consonant recognition is affected in individuals with cochlear hearing loss.

In noisy condition, consonant recognition scores in normal hearing individuals reduced more significantly at 0 dB SNR by about 40 %, whereas in cochlear hearing loss scores dropped to almost 16 % at 0 dB SNR. The precise reason for low scores is not known. Some of the possible reasons could be reduced frequency selectivity and loudness recruitment. Investigators have demonstrated that individuals with cochlear hearing loss have auditory filters that are broader than normal (Glasberg& Moore, 1986; Tyler et al., 1982). This means that, the ability to resolve the spectral components of speech sounds and to separate the components of speech from background noise is reduced. One mechanism by which impaired frequency selectivity could affect speech understanding in noise involves the perception of spectral shape. Broader auditory filters produce a more highly smoothed representation of the spectrum (the excitation pattern) than the normal auditory filter. Further, smoothened spectrum results in reduced formant frequency representation which causes imperceptions of the formants. Adding a noise background to speech, fills the valleys between the spectral peaks and thus reduces spectral prominence, exacerbating the problem of perceiving them for people with broadened auditory filter. Another reason is that, many recent investigators have demonstrated that cochlear hearing loss listeners depend more on envelop of speech signal than the fine structure and adding a noise would significantly alter the envelop of the signal that is., reducing the modulation depth and distorting the modulation. Because of the above mentioned reasons, individuals with cochlear hearing loss have more significant problem than those with normal hearing.

To summarize, individuals with cochlear hearing loss perform poorly in noise which may be due to reduced frequency selectivity, loudness recruitment and impaired ability in extracting envelop of speech signal in noisy condition.

Consonant Recognition in Unprocessed Versus Processed Condition

In the present study, spectral enhancement using companding strategy improved the consonant recognition scores in noise for individuals with normal hearing and cochlear hearing loss. To our knowledge, there are no studies that have utilized companding strategy in cochlear hearing loss individuals. Many studies which have used various other strategies to enhance spectral contrast have shown improvement in noise with enhancement (Baer et al., 1993; Yang et al., 2003; Frank et al, 1999). However, the above mentioned studies cannot be compared due to the larger differences in the signal enhancing strategies and rationale behind these strategies. The improvement with companding strategy can be because of two reasons: (i) reduced frequency selectivity affects the perception of the consonant in the presence of noise by reducing its spectral contrast. Increasing the spectral contrast of the consonant using spectral enhancement, thereby will compensate for reduced frequency selectivity and reduced spectral contrast (Baer et al., 1993; Watkins & Makin, 1996); (ii) envelop of a less intense consonants can be masked by high intense vowels resulting in the degradation of the envelop, leading to imperceptions of that particular consonant (Brokx&Nooteboom 1982; Turner, Souza & Forget, 1995). However, enhancing envelop of consonant prevent it from the upward spread of masking caused by vowels, due to increased amplitude of consonant portion. Because of the above reasons, cochlear hearing loss individuals perform better with processed recognition condition.

Sentence recognition threshold in noise (SNR-50)

In the present study, individuals with cochlear hearing loss required +7 dB higher SNR for sentence recognition threshold in noise (SNR-50) than the normal hearing individuals. These results are in agreement with those of previous studies (Plomp, 1994; Needleman &Crandell, 1995; Bacon et al., 1998). The reason for obtaining higher SNRs in individuals with cochlear hearing loss may be due to broader auditory filters, which degrades the spectrum of the speech signal (Glasberg& Moore, 1986; Tyler, et al., 1982). In addition to this, adding background noise further reduces the spectral prominence in the speech signal. Also, because of the loudness recruitment, speech sound with maximum energy can mask out the other speech sounds which are less intense. As a result, envelop of speech signal would be distorted which can result in reduced modulation depth. This can further impair the speech perception when an additional background noise is added to it. Because of the above mentioned reasons, individuals with cochlear hearing loss have more significant problem than those with normal hearing.

Using the spectral enhancement through companding strategy, both the groups obtained lower SNRs in processed than unprocessed condition. To our knowledge, many other studies (Baer et al., 1993; Yang et al., 2003; Franck et al, 1999) have also obtained similar findings using different strategies. But, these studies cannot be directly compared with the present study, due to the larger differences in the signal enhancing strategies employed.

In the unprocessed condition, the speech signal will be degraded in the presence of noise, making the listeners more difficult to identify the words in the sentences. This is because of reduced spectral contrast (Moore &Glasberg, 1983; Leek et al., 1987) and distorted envelop of the speech signal (Brokx&Nooteboom 1982; Turner et al., 1995). Bhattacharya and Zeng (2007) have shown that spectral contrast in the processed signal significantly enhanced compared to unprocessed condition. The improvement observed for CI individuals in their study is attributed to increased spectral contrast. Similarly, Oxenham et al. (2007) have demonstrated similar results. In the present study improvement observed in the processed condition, can be attributed to enhanced spectral contrast. In addition, the companding strategy also enhances the envelope of the signal which would have enhanced the less intense speech sounds, preventing it from the upward spread of masking by high intense vowels. Hence, subjects obtained lower SNRs in the processed than unprocessed condition.

To summarize, spectral enhancement improved consonant and sentence perception for both the individuals with normal hearing and cochlear hearing loss. The amount of improvement observed was higher for cochlear hearing loss than normal hearing listeners.

Conclusions

The major findings of the study indicated that spectrally enhanced speech through companding strategy improved the speech perception in noise among individuals with cochlear hearing loss to a much greater extent than do for normal hearing. The important clinical implication of the current study is that, the spectral enhancement using companding strategy has the potential to improve speech performance in the presence of noise among those with cochlear hearing loss individuals. Further, this strategy can be implemented in amplification devices for the benefit of speech recognition in adverse listening conditions.

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