Perception of Spectral Ripples and Amplitude Compressed Speech by Individuals with Cochlear Hearing Loss

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Abstract

Spectral ripple discrimination test assesses the frequency resolution of an individual's auditory system. In this study, spectral ripple discrimination ability was investigated in normal and hearing impaired listeners. The task involved discriminating between two rippled noise stimuli in which the frequency positions of the decibel amplitude-spaced peaks and valleys were interchanged. The ripple spacing was varied adaptively from 1.000 to 11.31 ripple/octave, and the minimum ripple spacing at which a reversal in peak and trough positions could be detected was determined as the spectral ripple discrimination threshold for each listener. Results showed that, the spectral ripple discrimination was best, on average, in normal listeners compared to hearing impaired listeners. SNR loss for compressed speech was greater than that for original speech and also it was found that SNR loss for slow-acting compression was less, indicating good speech intelligibility compared to fast-acting compression in hearing impaired listeners. Results of the study revealed that spectral ripple discrimination method can be reliably used to study individual's frequency resolution ability and be used to predict SNR loss. Thus the ability to process fine structure information may lead to implications for the choice of compression speed in hearing aids.

Key words: *Spectral ripple discrimination, SNR loss, compression, temporal fine structure, envelope.*

Introduction

Human speech is highly redundant with spectral and temporal cues. Speech signals contain two forms of information; envelope and temporal fine structure (TFS). Envelope cues (also called as amplitude modulations) correspond to the slow amplitude variations that rate below 50 Hz and fine structure cues correspond to rapid frequency fluctuations that rate above 250 Hz (Rosen, 1992). Importance of these cues for speech recognition has been the research interest in the recent decades. The temporal envelope cues from 3 to 4 bands are sufficient for the speech recognition in quiet (Shannon et al., 1995). However, recent studies have indicated that the envelope cues alone are not sufficient for the robust speech recognition in noise (Fu & Shannon, 1999; Zeng & Galvin, 1999; Stickney, Zeng, Litovsky & Assmann, 2004; Nie, Stickney & Zeng, 2005). It has been found that adding fine structure cues along with envelope, significantly improves the speech recognition under background noise (Nie, Stickney & Zeng, 2005; Hopkins & Moore, 2008; Lorenzi & Moore, 2008).

Physiologically, information about both the envelope and the TFS is carried by the timing of the auditory nerve discharges. It is commonly believed that envelope cues are represented in the auditory system as fluctuations in the short-term rate of firing in auditory neurons, while TFS is represented by the synchronization of nerve spikes to a specific phase of the carrier (phase locking). In most mammals, phase locking is weak for frequencies above about 5000 Hz (Palmer & Russell, 1986), so TFS information is presumably not conveyed to the brain, or is conveyed with reduced accuracy, for frequencies above 5000 Hz. A reduced ability to use TFS information could explain some of the perceptual problems of hearing-impaired subjects (Lorenzi, Gilbert & Carn, 2006)

Recent research evidences suggest that cochlear hearing loss adversely affects the ability to use TFS information for speech perception (Qin & Oxenham, 2003; Stickney et al, 2005; Lorenzi et al., 2006; Hopkins, Moore & Stone, 2008; Lorenzi & Moore, 2008). This seems likely to be one factor that contributes to the difficulty experienced by cochlear hearing loss individuals when trying to understand speech in the presence of background especially when the noise is also modulated (Festen & Plomp, 1990; Hopkins et al., 2008). The ability to use TFS information can vary markedly across hearing-impaired individuals (Hopkins & Moore, 2009).

Henry, Turner and Behrens (2005) studied spectral peak resolution in normal hearing, hearing impaired, and cochlear implant listeners. The task involved discriminating between two rippled noise stimuli in which the frequency positions of the log-spaced peaks and valleys were interchanged. The ripple spacing was varied adaptively from 0.13 to 11.31 ripples/octave, and the minimum ripple spacing at which a reversal in

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peak and trough positions could be detected was determined as the spectral peak resolution threshold for each listener. The results revealed that the normal listeners had the best spectral peak resolution, with an average threshold across listeners of 4.84 ripple/octave and a range of 2.03-7.55 ripples/octave, while cochlear implant listeners had the poorest spectral peak resolution, with an average threshold across listeners of 0.62 ripples/octave, and a range of 0.13-1.66 ripples/octave. The average spectral peak resolution threshold of 1.77 ripples/octave for the hearing-impaired listeners was between those of the normal and the cochlear implant listeners. The results indicated that the degree of spectral peak resolution required for accurate vowel and consonant recognition in quiet backgrounds is around 4 ripples/octave, and that spectral peak resolution poorer than around 1-2 ripples/octave may result in highly degraded speech recognition. These results suggest that efforts to improve spectral peak resolution for HI and CI users may lead to improved speech recognition.

Furthermore, measurements of frequency resolution may be helpful in selecting listener appropriate hearing-aid characteristics (Thornton & Abbas, 1980; Hannley & Dorman, 1983; Tyler et al., 1984). Ability to process TFS may have implications for the choice of compression speed in hearing aids (Moore, 2008a). Compression is one of the essential components in hearing aids to fit the wide range of signal levels occurring in everyday life (Levitt, 1982) into the typically small dynamic range of the hearing-impaired person (Miskolczy-Fodor, 1960). An individual who has little or no ability to process TFS information will rely largely on temporal envelope cues in different frequency channels to understand speech. Even though compression offers comfortable hearing to hearing impaired individuals, it also has adverse effect on speech intelligibility by altering temporal envelope cues. Stone and Moore (2003, 2004, & 2008) have shown that fast-acting compression can disrupt the ability to use envelope cues more when compared to slow-acting compression.

Most important information that TFS carries is harmonics of the signal (Moore, Glasberg & Hopkins, 2006). Perception of harmonics are important for perception of pitch and thus for source segregation (Oxenham, 2008). Frequency resolving ability is one factor which determines the perception of harmonics and thus for stream segregation (Bernstein & Oxenham, 2006). Two stimuli (target and interferer) having different harmonic structure but unresolved at cochlear level may form single auditory stream and result in poor discrimination.

As discussed earlier when individual cannot perceive fine structure due to reduced frequency resolution, he/she might rely on envelope. So, clinicians must be cautious while prescribing compression parameters which are deleterious to envelope. Spectral ripple discrimination test assesses the frequency resolution of an individual's auditory system. The present study was conducted to investigate whether spectral ripple discrimination test can be used for prescription of compression time constants, and also to correlate between perceptions of spectral ripples with amplitude compressed speech by individuals with cochlear hearing loss. The aim of the study was to compare the spectral ripple discrimination sensitivity between individuals with normal hearing and cochlear hearing loss. The study aimed at measuring the SNR loss in three conditions namely original speech, speech stimuli compressed using slow-acting compressor and speech stimuli compressed using fast-acting compressor. The study also investigated possible correlation between SNR loss and spectral ripple discrimination sensitivity in cochlear hearing loss individuals.

Method

Participants

A total of 20 participants were recruited for the current study. All participants were native Kannada speaking adults. The participants were divided into two groups namely, control and clinical group. The control group comprised of 8 participants (N=15 ears) with normal hearing sensitivity. Normal hearing was defined as having pure-tone air conduction thresholds ≤15 dB HL at octave frequencies from 125 to 8000 Hz in the tested ear. They were age matched to compare spectral ripple discrimination threshold.

The clinical group comprised of 12 participants (N=17 ears) with hearing impairment. The hearing losses were diagnosed as sensorineural (and assumed to be of cochlear origin) based on the lack of an air-bone gap and tympanograms consistent with normal middle ear function. The ear with the better pure tone thresholds was selected as the test ear. The degree of hearing loss ranged from mild to moderate with flat audiometric configurations.

Stimuli

Spectral ripple discrimination: Ripple noises were generated using MATLAB as described by Won, Drennan and Rubinstein (2007). Two hundred pure-tone frequency components with the duration of 500 ms were summed to generate the rippled noise stimuli..

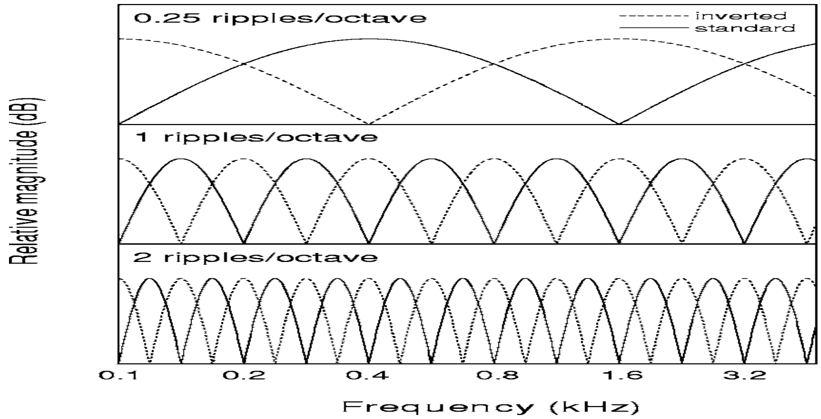

Figure 1: Rippled noise spectra. Standard and inverted peak positions for ripple frequencies of 0.25, 1 and 2 ripples/octave are shown.

The starting phases of the components were randomized for each presentation.

Speech identification task: The amplitudes of the components were determined by a full-wave rectified sinusoidal envelope on a logarithmic amplitude scale. The ripple peaks had equal space on a logarithmic frequency scale. The overall bandwidth of rippled stimuli was 100 to 5,000 Hz with a peak-to-valley ratio of 30 dB. The ripple stimuli were generated with 8 different densities, measured in ripples per octave, those were 1.000, 1.414, 2.000, 2.828, 4.000, 5.657, 8.000 and 11.314. For standard ripples, the phase of the full-wave rectified sinusoidal spectral envelope was created using 'sin' function and for inverted ripples, it was 'cos' function (Figure 1). The stimuli were ramped with 150 ms rise/fall times.

Compression algorithms were implemented using Adobe Audition 3 software with following parameters: A compression ratio of 3:1 was used for both fast-acting and slow-acting compression. An attack time and release time of <5ms and 50ms respectively were used for fast-acting compression (Walker & Dillon, 1982). Similarly an attack time and release time of around 500 ms (Plomp, 1988; Festen & Plomp 1990) were used for slow-acting compression.

The quick speech-in-noise sentence lists developed by Avinash, Meti and Kumar (2009) were used. Each list consisted of seven sentences recorded at +20, +15, +10, +5, 0, -5 and -10 respectively. The present study consisted of six lists of which four lists were digitally compressed. Among compressed lists two lists simulated slow-acting compression and two simulated fast-acting compression. The remaining two lists were retained (uncompressed). The speech identification was tested in uncompressed and compressed conditions. Under compressed condition, speech identification was assessed for both slow-acting compression and fast-acting compression.

Procedure

All subjects were tested in a sound treated room and noise levels within permissible limits as per ANSI (1991). The rippled noise and speech stimuli were presented to normal and hearing impaired listeners monaurally through calibrated two channel diagnostic audiometer (Madsen Model Orbiter 922 version 2) coupled with acoustically matched TDH 39 headphones housed in MX-41/AR. The presentation level for both speech and rippled noise stimuli was 40 dB SL for the normal-hearing listeners. The presentation level was set on an individual basis for each of the hearing impaired listeners' most comfortable level as determined in pilot test sessions.

Spectral ripple discrimination test: Ripple resolution thresholds were determined using a three interval forced-choice adaptive procedure, based on the method developed by Henry and Turner (2003). One interval contained stimuli with standard and reverse phase separated by 10 ms (we refer this as variable interval) where another interval contained stimuli with standard and standard or reversed and reversed phase (we refer this as standard interval). The position of the standard and variable interval were randomized across the presentation, and also variable interval position of standard and reverse phase stimuli was randomized. Highest ripple density at which phase reversal could be perceived by participants were estimated using simple up-down procedure (Levitt, 1971). Three numerically labeled buttons were displayed on the computer monitor, corresponding to the three intervals, and subjects were instructed to press the button corresponding to the interval that sounded 'different' (i.e., that contained the test stimulus), ignoring any loudness variation between intervals. Correct answer feedback was provided throughout the experiment. Each test run commenced at a ripple frequency of 1.000 ripples/octave, and the ripple frequency was varied in a one-down, one-up procedure. After each incorrect response the ripple frequency was decreased by a step, and it was increased after a correct response and thresholds corresponded to 50% point on psychometric function.

Speech identification task: The sentences were presented monaurally through the headphones across all three conditions. Prior to the test session, three prototype lists were administered at 40 dB SL or most comfortable level to familiarize the subjects with the task.

Scoring: One point was given for each of five key words repeated correctly in each sentence. Half credit was given for words close to the target word. The SNR-50 was calculated for each sentence using a formula as recommended by Avinash, Meti and Kumar (2009) for obtaining spondee thresholds:

$$\textit{SNR loss} = 28.67 - (\textit{total words correct})$$

Results

Shapiro-Wilk's test was administered to test whether data of spectral ripple discrimination thresholds from both the groups were normally distributed. Shapiro-Wilk's test for normality compared the distribution of current data against the normal distribution. Results revealed that data of spectral ripple discrimination threshold from both groups are normally distributed (Experimental group; $W=0.98$, $p=0.93$ & Control group; $W=0.88$, $p=0.06$). So, a parametric independent sample 't' test was chosen to investigate the main effect of hearing loss on spectral ripple discrimination threshold. Independent sample 't' test revealed that spectral ripple discrimination thresholds obtained from both groups are significantly different [$t(30)=-0.85$, $p<0.05$]. Levene's test for equality of variances indicated an equal variances between both groups ($F=0.01$, $p=0.92$). So, no adjustments were done to degrees of freedom. Spectral ripple discrimination thresholds were significantly better in normal hearing individuals (Mean=3.5 ripples/octave) when compared to individuals with cochlear hearing loss (Mean=1.6 ripples/octave) which can be observed from Figure 2. This result confirms the previous studies by Hopkins and Moore (2006), that individual with cochlear hearing loss has poor sensitivity to spectral fine structure.

Speech identification abilities by individuals with cochlear hearing loss were assessed using QuickSIN protocol (Killion, 1997). QuickSIN does not measure speech identification scores instead it measures SNR loss. SNR loss indicates loss in ability to understand speech at the SNR used by those with normal hearing (Killion, 1997). SNR loss was calculated for each individual using following formula as recommended by Avinash, Meti and Kumar (2009). SNR loss was measured for three conditions which are: (i) Speech stimuli compressed using fast-acting compressor hence forth this condition will be regarded as 'fast-acting compression' (ii) Speech stimuli compressed using slow-acting compressor, here after this condition will be regarded as 'slow-acting compression' and (iii) original speech which will regarded as 'original' in following section.

Gaussian nature of the data was assessed using Shapiro-Wilk's test for normality and the results revealed that SNR loss for all the three conditions are not normally distributed [fast-acting compression ($W=0.85$, $p=0.01$), slow-acting compression ($W=0.87$, $p=0.02$) and original ($W=0.74$, $p<0.001$)].

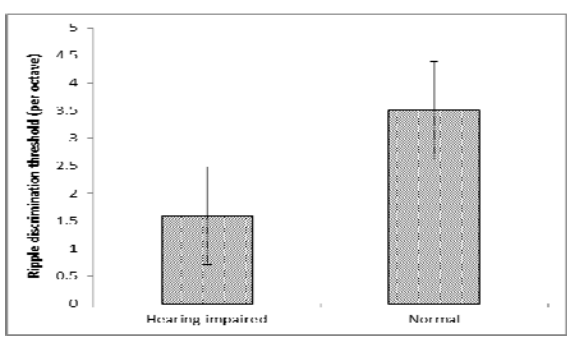

Figure 2: Bars represent mean ±1 SD Spectral ripple discrimination thresholds in individuals with normal hearing and hearing impairment.

Table 1: Median, range and inter quartile range for SNR loss in original, slow-acting compression and fast-acting compression conditions.

Conditions	Median (dB)	Range (dB) (Min-Max)	Inter-quartile range (dB) (Q1-A3)
Original	4.67	0.67-23.67	3.67-8.17
Slow acting compression	5.67	1.67-22.67	3.67-13.67
Fast acting compression	8.67	2.67-28.67	4.67-13.17

Since, data from all the three conditions are not normally distributed the non-parametric Friedman's test was used to investigate the main effect of compression on SNR loss. Friedman's test revealed that compression had significant main effect [$X^2(2)=6.89$, $p=0.03$] on SNR loss.

Pair-wise comparisons across the three conditions were performed using Wilcoxon signed rank test. Bonferroni's adjustments were made for each pair-wise comparisons to account for the multiple comparisons. Results of the Wilcoxon signed rank test was considered to be significant when, $p<0.016$ as the significance level was adjusted for Bonferroni's correction factor. Pair-wise comparison revealed that SNR loss for original signal was significantly different ($Z=-2.99$, $p=0.001$) from the SNR loss for fast-acting compression. SNR loss for original signal was lower when compared to fast-acting compression (Table 1). Even though median SNR loss for slow-acting compression was lower than the SNR loss for fast-acting compression (see Table 1), the difference was not statistically significant ($Z=-0.98$, $p=0.34$). Similarly, median SNR loss for original signal was lower than the SNR loss for slow-acting compression (Table 1) but statistically, the difference was not significant ($Z=-1.87$, $p=0.062$).

To investigate the possible association between the types of compression and SNR loss Spearman's rank correlation analysis was performed. Results of the Spearman correlation was considered to be significant when $p<0.016$ due to multiple correlations. Correlation analysis revealed that there is no association ($r_s=-0.33$, $p=0.097$) between spectral ripple discrimination threshold and SNR loss for original speech, which means that spectral fine structure sensitivity or frequency selectivity did not play a major role in perception of original speech in the presence of noise.

There was a negative correlation observed between spectral ripple discrimination threshold and SNR loss for fast compression ($r_s=-0.54$, $p=0.013$) as well as between spectral ripple discrimination threshold and SNR loss for slow-acting compression ($r_s=-0.69$, $p=0.001$) which can be seen in Figure 3 and Figure 4 respectively. As the spectral ripple discrimination threshold increases SNR loss decreases for compressed speech. In other words, if the frequency selectivity or spectral fine structure sensitivity is better, SNR loss will be smaller. Statistically significant correlation suggests that, spectral fine structure sensitivity had played a role in perception of speech in the presence of noise under compressed conditions.

Linear regression analysis was performed to investigate whether SNR loss can be predicted from spectral ripple discrimination threshold. Linear model well suited to describe the relationship between spectral ripple discrimination threshold and

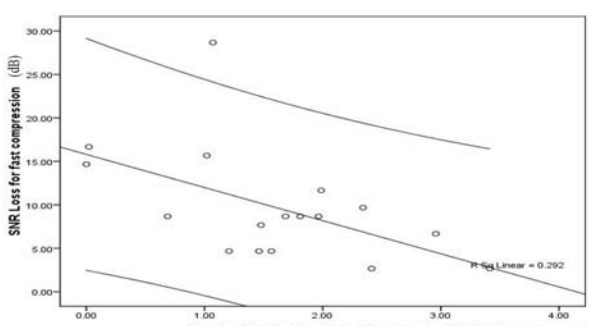

Figure 3: Scatter plots showing a linear relationship between spectral ripple discrimination threshold and SNR loss for fast-acting compression conditions.

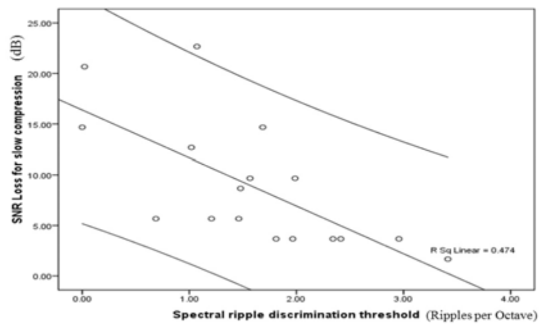

Figure 4: Scatter plots showing a linear relationship between spectral ripple discrimination threshold and SNR loss for slow-acting compression conditions.

SNR loss for fast-acting compression [$F(1,15)=6.19$, $p<0.05$]. Similarly, regression analysis revealed that SNR loss for slow-acting compression can be predicted from spectral ripple discrimination threshold using linear model [$F(1,15)=13.50$, $p<0.05$]. Regression equations are as follows:

$$\text{SNR loss } fc = 15.80-3.81*Srdt$$
$$\text{SNR loss } sc = 16.38-4.72*Srdt$$

In the above equations '*fc*' stands for fast-acting compression, '*sc*' stands for slow-acting compression and '*Srdt'* stands for spectral ripple discrimination threshold.

Observation of R^2 values suggested that 47% variance in SNR loss for slow-acting compression could be attributed to the variability in spectral ripple discrimination threshold. Similarly, 29% variance in SNR loss for fast-acting compression could be attributed to the variability in spectral ripple discrimination threshold.

Discussion

Spectral ripple discrimination thresholds revealed that individuals with cochlear hearing loss required less ripple density to perceive the phase reversal when compared to individuals with normal hearing. Mean spectral ripple discrimination threshold for normal hearing individuals is 3.5 ripples/octave and mean spectral ripple discrimination threshold for hearing impaired individuals is 1.6 ripples/octave. This result suggests that frequency resolving ability of individual with cochlear hearing loss is worse than normal hearing individuals. In the phase reversal task both the stimuli have same spectral band but opposite positions of spectral maxima and minima on the frequency scale. The phase reversal effect will be detected only if the rippled structure of the spectrum can be resolved. If the fine structure of the spectrum is unresolved, phase reversal cannot be detected (Supin, Popov, Milekhina & Tarakanov, 2003). As the ripple density increases, position between the maxima and minima decreases hence, becoming irresolvable at cochlear level. Since cochlear hearing loss results in broadening of auditory filter (Tyler et al., 1984; Glasberg & Moore, 1986; Dubno & Dirks, 1989; Laroche, Quoc, Josserand & Glasberg, 1992; Peters & Moore, 1992; Stone, Glasberg & Moore, 1992; Leek & Summers, 1993; Sommers & Humes, 1993; Leeuw & Dreschler, 1994), they require less ripple density to perceive the phase reversal. Similarly, Henry, Turner and Behrens (2005) also reported that spectral ripple thresholds were poor in hearing impaired individuals when compared to normal hearing listeners. Normal hearing individuals obtained threshold of 4.84 ripples/octave and hearing impaired individuals obtained threshold of 1.77 ripples/octave. The values obtained in the current study are slightly worse when compared to results of Henry, Turner and Behrens (2005). This might be due to the age effect; participants in the current study are slightly older than the previous study. Other reason could be technique used to generate spectral ripples. Current study used the spectral ripples which were sinusoidal in decibel amplitude space, whereas the former study used the spectral ripples which were sinusoidal in a linear amplitude space.

SNR loss in hearing impaired individuals was measured for following three conditions; original speech, fast-acting compression and slow-acting compression. For original speech, hearing impaired subjects required 4.67 dB (median) more SNR than normal hearing subjects. This finding confirms previous several other studies (Plomp, 1978, 1986; Dreschler & Plomp, 1980; Humes, Dirks & Kincaid, 1987; Zurek & Delhorne, 1987; Lee & Humes, 1993; Glasberg & Moore, 1989) that individual with cochlear hearing loss perform poor in the presence of background noise. Spectral differences especially the difference in F_0 help the individual to perceptually segregate the target speech and competing speech maskers. When the individual is unable to utilize the spectral differences between target speech and competing speech, he/she may not form separate perceptual streams for target speech and masker (Oxenham, 2008). Poor spectral ripple perception by the participants of the study indicated that they had poor spectral resolution, which would have disabled them from utilizing the spectral difference between the target and masker.

SNR loss for compressed speech was greater than for original speech. Median SNR loss for slow-acting compression was 5.67 dB and for fast-acting compression is 8.67 dB indicating, worst performance with fast-acting compression among the three conditions. In the present study, it was found that SNR loss for slow-acting compression was less, indicating good speech intelligibility compared to fast-acting compression. Poor performance with compression could be attributed to the reduced dip listening ability. Listener ability to take advantage of dips in the background sound when trying to understand a target signal is denoted as dip listening (Gatehouse, Naylor, & Elberling, 2003). Dip listening is important in situations where communication takes place in the presence of modulated background noise, like current study where multi-talker babble was used. Use of compression reduces the temporal contrast or modulations thus resulting poor dip listening (Stone & Moore, 2004, 2008). It reduces intensity contrasts and the modulation depth of speech, which may have an adverse effect on the perception of certain speech cues, especially when high compression ratios are used (Plomp, 1988).

Moore (2008b) reported that, the benefit obtained from listening in the dips may be related to the ability to process the TFS of sounds. Changes in the TFS during dips in the background help the listener to determine that target speech is present and to determine what the properties of the target speech are (Moore, 2008b). Difference in TFS cues enables the listener to form separate perceptual streams for target speech and competing speech (Nie, Stickney & Zeng, 2005). There is evidence that moderate cochlear hearing loss reduces or abolishes the ability to process TFS (Hopkins & Moore, 2007; Moore, Glasberg, & Hopkins, 2006). Most important information that TFS carries is harmonicity of the signal (Moore, Glasberg & Hopkins, 2006). Perception of harmonics are important for perception of pitch and thus for source segregation (Oxenham, 2008). Auditory frequency selectivity and the resolvability of harmonics can predict pitch discrimination, suggesting that peripheral filtering is important for pitch coding (Bernstein & Oxenham, 2006). Resolvability of harmonics in hearing impaired participants would have been affected by their poor frequency selectivity, thus resulting in poor speech perception in the presence of noise.

Better performance under slow-acting compression could be attributed to the fact that the deleterious effect on temporal envelope is minimal. This finding was in accordance with a study done by Drullman, Festen, and Plomp (1994), where they reported limited distortion in temporal envelope. Also, the envelope fluctuations at syllabic rates are preserved when using slow-acting compression systems, thus may be important for maintaining speech intelligibility. Poor performance of fast-acting compression could be attributed to the fact that it induces greater distortion in temporal envelope while preserving some amount of fine structure information. This was confirmed by previous studies which suggested that fast-acting compression reduces the temporal contrast to greater extent than slow-acting compression resulting in impaired speech perception (Plomp, 1994; Noordhoek & Drullman, 1997). It was also reported that it could introduce spurious changes in the shape of the temporal envelope of sounds (e.g., overshoot and undershoot effects; Stone & Moore, 2008). Therefore, it can be speculated that, in individuals with moderate cochlear hearing loss, the ability to use fine structure information is reduced and hence they rely more on information carried in the temporal envelope of speech signal. A recent study by Moore, Glasberg & Hopkins, (2006) confirms reduced ability to process fine structure information in individuals with moderate cochlear hearing loss. Hence, in the current study SNR loss for slow-acting compression is relatively better than fast-acting compression. The role of fine-structure information in speech perception remains somewhat controversial. While envelope information in a few frequency bands appears sufficient to give reasonably high intelligibility for speech presented in quiet (Shannon et al., 1995), the perception of speech in noise, especially modulated noise, seems to depend at least partly on the use of fine structure information (Lorenzi et al., 2006; Hopkins et al, 2008; Hopkins & Moore, 2008; Lorenzi & Moore, 2008b).

Results of the study revealed that spectral ripple discrimination method can be reliably used to study individual's frequency resolution ability and be used to predict SNR loss. Individual with good spectral ripple threshold can be fitted with fast-acting compression since they can utilize spectral differences to differentiate speech and noise. But individual with poor spectral ripple threshold, slow-acting compression may be preferred as they may have to rely more on information provided by the envelope rather than the spectral fine structure. Rippled noise has been used to estimate frequency selectivity in neurophysiological single-unit studies (Bilsen & Wieman, 1980; Evans, 1975), in psychophysical studies using a masking paradigm (Houtgast, 1974, 1977; Pick et al., 1977; Pick, 1980), and in studies of pitch perception of complex sounds (Yost, Hill & Perez-Falcon, 1977; Bilsen & Wieman, 1980; Yost, 1982). However, to study the frequency resolving power dependence on frequency, measurements can be made using narrow-band noises of various central frequencies. Thus, frequency resolving power data can be used to derive the auditory filter bandwidth. According to Supin et al., (1994), equivalent rectangular bandwidth (ERB) is given by the simple expression:

$$ERB \approx 0.71 \times F_0/D$$

where the ERB is given in Hz, 'F_0'is the central frequency, kHz and 'D' is the rippled density expressed in number of ripples per kHz, which determines the limit of resolvable ripple density.

Conclusions

Overall, it can be concluded that normal hearing individuals perform spectral ripple discrimination task using TFS cues implying the superior ability to process TFS information. On the other hand, individuals with cochlear hearing loss show difficulty in processing TFS information. Therefore, it can be concluded that hearing loss significantly reduces the ability to analyze and utilize TFS cues to perform spectral ripple discrimination task. Hence, individuals with cochlear hearing loss rely more on temporal envelope cues rather than TFS for understanding speech. Fast-acting compression induces greater distortions in the temporal envelope and preserves TFS information which results in significant difficulty in speech perception compared to slow-acting compression.

In summary, the results demonstrate a dramatic loss of the ability of hearing-impaired subjects to use TFS cues for speech perception. The conclusion from all this is that measures of the ability to use TFS information might be useful in determining the most appropriate speed of compression for a hearing-impaired individual. It is possible that the ability to process TFS is related in a more general way to the speed and accuracy of neural processing in the brain. If this were the case, the ability to process TFS could be related to cognitive abilities. This might explain the link between cognitive abilities and the benefit of fast-acting compression for listening in the dips (Gatehouse, Naylor, & Elberling, 2003).

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