Effect of Spectral Bandwidth and Spectral Integration on Speech Perception in Listeners with Normal Hearing, Cochlear Hearing Loss and Auditory Dys-Synchrony

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Abstract

The present study aimed at finding whether the type of hearing loss has any effect on the bandwidth required to achieve minimum amount of speech identification scores with low and high center frequencies and also ability to integrate information from these two bandwidths. Participants included 29 individuals with normal hearing, 12 individuals with cochlear hearing loss and 17 individuals with auditory dys-synchrony. Two CSBs (Criterion Speech bandwidth) were obtained for all the participants. The first one for the low center frequency of 500 Hz and the second one for the higher center frequency of 2500 Hz. To determine the spectral integration abilities, words having both the CSBs were presented to the participants. Results showed that individuals with auditory dys-synchrony failed to achieve criterion score even at maximum bandwidth at 500 Hz center frequency. All the three groups differed significantly from each other for the normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at 2500 Hz. Individuals with auditory dys-synchrony showed significantly lower spectral integration scores from the other two groups and they showed two types of spectral integration scores. One group showed reduced spectral integration scores compared to the criterion score obtained at 2500 Hz center frequency. Another group showed marginal improvement. It was seen that individuals with cochlear hearing loss were as good as normal hearing individuals in their ability to combine the information across different frequency bands.

Keywords: *Spectral integration, Criterion Speech Bandwidth, center frequency*

Introduction

Speech is a complex signal. The components of speech vary in terms of frequency and intensity over time. Approximately 95% of the frequency components in speech lie between 300 Hz and 3000 Hz (Hamernik & Davis, 1988). To perceive and understand speech one needs to have normal hearing sensitivity within this frequency range. Hearing loss at any frequency within this frequency range will affect speech perception. The impact of hearing loss on speech perception is based on both type and configuration of hearing loss.

It is well established that different speech sounds have predominantly different energies across frequencies. For example nasals are predominantly lower in frequency, whereas fricatives are more of high frequency speech sounds. Thus, individual with low frequency hearing loss will have difficulty perceiving nasals and individuals with high frequency hearing loss will not be able to get the important features which are necessary to perceive fricatives. Hence, all these individuals would fail to comprehend speech.

Similarly, type of hearing loss has also different perceptual consequences (Zeng & Liu, 2006). A conductive type of hearing loss which is thought to attenuate the acoustic signal reaching to the cochlea is likely to have less impact on speech perception, whereas cochlear hearing loss would show deterioration in speech perception with the increase in severity of hearing loss. This is probably due to the loss of OHC's in the cochlea, which is responsible for fine discrimination. As the fundamental frequency, formant frequency and frequency transition are important features to understand speech, perception of these features will be affected due to lack of sharper tuning as a result of OHC damage. People with cochlear hearing loss usually have auditory filters that are broader than normal (Glasberg & Moore, 1986; Tyler, 1986). This means that their ability to determine the spectral shape of speech sounds and to separate components of speech from background noise is reduced. Impaired frequency resolution has been identified as the main reason for speech perception deficits in cochlear hearing loss with greater than moderate degree of hearing loss (Glasberg & Moore, 1989).

Another reason for impaired speech perception can be, reduced phase locking in these individuals. This may be due to fact that the propagation time of the travelling wave along the basilar membrane can be affected by the cochlear damage and this may disrupt the processing of temporal information by central mechanisms (Leob & White, 1983).

People with cochlear hearing impairment often complain that their greatest problem is understanding speech when background noise is present. The hearing impaired needs a higher signal-to noise ratio (SNR) to achieve the same level of performance (Plomp, 1994). This increase in signal to noise ratio ranged from 2.5 dB for mild hearing loss to 7 dB for moderate to severe

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hearing loss. An even larger SNR is required when the noise is fluctuating (Plomp, 1994).

Auditory dys-synchrony is another hearing disorder that has unique pathologies and perceptual consequences (Starr, Picton, Sininger, Hood & Berlin, 1996). It is a disorder characterized by abnormal or absent auditory brainstem responses (ABRs) and the presence of otoacoustic emissions (OAEs) and/or cochlear microphonics (CMs), indicating normal functioning of the outer hair cells (OHCs) (Starr et al., 1996).

It is difficult to localize the exact cause for auditory dys-synchrony. There may be multiple underlying causes (Rance, 2005). Auditory dys-synchrony (AN) may result from a loss of inner hair cells (IHC), dysfunction of the IHC-nerve synapses, neural demyelination, axonal loss or a possible combination of multiple sites. These pathologies may be present with the traditional cochlear loss involving outer hair cells and/or central processing disorders involving the brainstem and cortex, complicating the classification of auditory dys-synchrony (Rapin & Gravel, 2003).

One major characteristic of AN is an impaired capacity for temporal processing and difficulty in speech understanding, particularly in noise, that is disproportionate to the degree of hearing loss measured by pure-tone thresholds (Rance, Cone- Wesson, Wunderlich & Dowell, 2002; Rance, McKay & Grayden, 2004, Zeng, Kong, Michalewski & Starr, 2005). Zeng and Liu (2006) said that these individuals have poor pitch processing at low frequencies, excessive masking in noise, and inability to process interaural timing information. Most of the individuals with auditory dys-synchrony have a raising pattern of hearing loss indicating a low frequency hearing loss. This is mainly due to the auditory nerve fibers which are getting affected in them since the low frequency fibers are the longest ones they have more chances of getting involved and this results in poor pitch processing at low frequencies. Zeng, Oba, Garde, Sininger and Starr (1999) studied the frequency discrimination abilities of these individuals across frequencies and found that they have very poor discrimination at low frequencies. Even at signal to noise ratios of 10 to 15 dB, individuals with auditory dys-synchrony found it difficult to perceive speech which is due to the excessive masking.

Several studies have tried to explain the reasons for poor speech perception abilities, especially in the presence of noise in the individuals with auditory dys-synchrony. Psychophysical studies have demonstrated poor temporal and spectral processing in participants with auditory dys-synchrony and they attributed this as the reason for poor speech perception (Rance et al., 2004; Starr et al., 2003; Zeng et al., 1999).

Vinay and Moore (2007) reported that their participants with auditory dys-synchrony had poor frequency resolution when compared to individuals with normal hearing. Kumar and Jayaram (2010) reported that the poor speech perception abilities are predominantly due to temporal processing deficit. They also saw a poor correlation between pure tone thresholds and speech perception abilities and concluded that audibility is not a major factor that causes impaired speech perception in individuals with auditory dys-synchrony.

Most of the studies in the literature aimed at relating the impaired speech perception to the deficits in phase locking, frequency resolution and temporal processing. A few other studies have seen the speech perception scores in the presence of noise. There are only a few studies which compared the ability to combine speech information from different frequency regions in individuals with hearing loss.

The ability to perceive speech on the basis of sparse cues that are separated in frequency could be important for speech understanding in noisy backgrounds. For example, when the signal to noise ratio is very low, a listener may not have access to the entire spectrum of a speech target and good performance may depend upon the ability to integrate speech fragments that are separated in frequency (Assmann & Summerfield, 2004).

Many studies in speech perception have used vocoders to simulate the spectral channels of cochlear implants. Shannon, Zeng, Kamath, Wygonski and Ekelid(1995), developed a noise-band vocoder to simulate CI speech processing for normal hearing listeners. They found that high level of speech recognition was possible with as few as four spectral channels of information. This result was obtained with simple sentence materials and in quiet listening conditions.

Mlot, Buss and Hall (2010) studied the development of the ability to combine speech information from different frequency regions. They also studied bandwidth required to achieve a low criterion level of speech identification for two frequency bands. They found that children required more bandwidth to identify the stimulus but their ability to integrate the information was similar to that of adults.

Grant, Tufts and Greenberg (2007) examined the intelligibility of speech filtered into relatively narrow spectral bands for both normal-hearing listeners and listeners with sensorineural hearing impairment. They found that ability to integrate the information across the bands was reduced in listeners with sensorineural hearing impairment compared to normals.

Hall, Buss and Grose (2008) considered bandwidth of speech centered either on 500 or 2500 Hz. They varied the bandwidth adaptively to determine the criterion speech bandwidth required to get a score of 15 to 25%. Speech recognition was assessed for low and high bands presented alone, and for the bands presented together. The speech material consisted of Bamford-Kowal-Bench sentences. There was no apparent relation between the criterion normalized bandwidths at the two center frequencies. There were relatively large individual differences in the bandwidth necessary for criterion performance in the hearing-impaired listeners, with criterion normalized bandwidth ranging from approximately 0.28 to 1.06 Hz at 500 Hz, and from approximately 0.14 to 0.54 Hz at 2500 Hz. The criterion speech bandwidths obtained for the hearing-impaired listeners were broadly similar to those obtained by the normal hearing listeners. They found that listeners with mild-moderate sensorineural hearing loss do not have an essential deficit in the ability to integrate across-frequency speech information as their results were comparable with that of individuals with normal hearing.

As is evident from the literature,there are only a few studies (Grant et al., 2007; Hall et al., 2008; Mlot et al., 2010) which have examined the ability to spectrally integrate information across frequencies. These studies have considered only individuals with cochlear hearing loss, and not individuals with auditory dys-synchrony. It is evident from the literature that individuals with auditory dys-synchrony also have poor speech perception abilities (Zeng et al., 1999; Rance et al., 2004) and also difficulty hearing in noise. So it is all the more important to study how the hearing impaired population combine the different spectral information to understand speech, even in noise.

Most of the studies (Hall et al., 2008; Mlot et al., 2010) have used sentences as stimuli which is more redundant. It would be better to use words which are less redundant in speech perception studies. The present study has used filtered words which makes it more difficult to get the redundant information. It is also seen that there is variability among the results of these studies. Hall et al. (2008) said that individuals with cochlear hearing loss has no difficulty in integrating information across frequencies whereas Grant et al. (2007) found that individuals with cochlear hearing loss has difficulty in integrating information across frequencies. Thus there is a need to study spectral integration abilities in individuals with cochlear hearing loss and also in individuals with auditory dys -synchrony.

The present study aimed at finding a criterion speech bandwidth which is necessary to get a minimum (15 to 25%) speech identification score separately for two center frequencies (500 Hz & 2500 Hz) in individuals with normal hearing, cochlear hearing loss and auditory dys-synchrony. The study further aimed at investigating the spectral integration abilities(improvement in speech identification ability that resulted when both bands were presented simultaneously) in all the three groups. Finally, the study intended to investigate if any relation exists between the spectral integration abilities and the speech identification scores in quiet without any modification to the speech stimulus.

Method

Participants

To achieve the goal, three groups of individuals were considered in the present study. The first group being the control group and the next two groups being the clinical groups. The control group consisted of individuals having normal hearing. Individuals having cochlear pathology formed the first clinical group and second clinical group was formed by individuals having auditory dys-synchrony.

Control Group-Individuals with normal hearing sensitivity: This group consisted of 29 individuals with normal hearing sensitivity in the age range of 18 to 50 yrs with a mean age of 28.12 yrs, matched for age with the participants in 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. Participants had greater than 90% speech identification scores in quiet and more than 60% speech identification scores at 0dB SNR.

Immittance evaluation showed type 'A' tympanogram with the presence of acoustic reflexes. None of them had any history of otological symptoms (ear discharge, ear pain, giddiness, or ototoxicity). They did not have any past or present history of neurological dysfunction that was relevant to the present study. All participants were fluent Kannada speakers and did not have any speech or language problems.

Clinical group 1-Individuals with cochlear hearing loss: Consisted of 12 participants in the age range of 18 to 50 years with a mean age of 30.3 years. The participants had acquired mild or moderate sensory hearing impairment as determined by air and bone conduction pure tone audiometry. The pattern of hearing loss was either flat across frequencies or gradually sloping (increase in threshold of around 5-12 dB per octave and the difference between the highest and lowest threshold being no more than 35 dB) from 250 Hz to 8000 Hz. All of participants had speech identification scores proportional to their degree of hearing loss indicating that the hearing loss was predominantly due to cochlear pathology.

Immittance evaluation showed type 'A' tympanogram with either presence, elevated or absence of acoustic reflexes. All participants had absent DPOAEs suggestive of outer hair cell dysfunction. Click evoked ABR was present (proportional to their degree of hearing loss) at

80 dBnHL with a repetition rate of 11.1 clicks/second. There was no past or present history of neurological dysfunction that was relevant to the present study. All participants were fluent Kannada speakers and did not have any speech or language problems.

Clinical group 2-Individuals with auditory dys-synchrony: Consisted of 17 participants in the age range of 18 to 50 years with a mean age of 25.95 years. All of them had bilateral acquired auditory dys-synchrony, with hearing loss not exceeding moderate degree (PTA of 41-55 dB HL). Their speech identification scores were either disproportionate to their degree and configuration of hearing loss or very poor speech perception in noise (SPIN) scores at 0 dB SNR.

Only those individuals who had speech identification scores more than 30% in quiet at 40 dB SL were selected for the present study as the present study required them to identify filtered words. All participants had absent auditory brainstem response (beyond that was expected with the degree of pure tone hearing threshold) at 80 dBnHL with a repetition rate of 11.1 clicks/second. All the participants had DPOAEs and/or cochlear microphonics present.

These participants had normal tympanometric findings with absent ipsilateral and contralateral acoustic reflexes. No other neurological abnormality was present, which was ruled out by an experienced neurologist. All participants were fluent Kannada speakers and did not have any speech or language problem.

Equipments

GSI 61, GSI-TS, Capella OAE analyzer, Biologic Navigator Pro were used to obtain the hearing thresholds, to check the middle ear functioning, OHC's functioning, and also to check retrocochlear involvement respectively. All the equipments were calibrated as per the standards specified by the manufacturer.

Test Environment

Recording of OAEs and all other audiological evaluations, including tests administered to collect data were carried out in a sound treated room. The ambient noise of the test rooms were within the permissible limits as recommended by ANSI (S3.1, 1999).

Test Procedure

All the participants underwent puretone audiometry, immittance audiometry, OAEs and ABR testing. All those participants who met the criteria were selected for the study. The experiment was carried out in three phases:*Preparation of the stimulus, obtaining the criterion speech bandwidth (ie., the minimum bandwidth required to get 15 to 25% SIS)*, and *determining the spectral integration score.*

Phase 1: Preparation of the stimulus

The speech stimuli used in this study was bisyllabic words developed by Sreela and Devi (2009) in Kannada. This test contains four lists, each list having 25 bisyllabic words which are phonemically balanced. All the 25 words in each list are equally difficult. For the present study, all the four lists were taken.

The words were recorded in an acoustically treated room. The words were spoken in conversational style by a female native speaker of Kannada. A unidirectional microphone kept at a distance of 10 cm from the speaker's mouth was used. The sampling rate of 44100 Hz and the resolution of 32 bits were used to record the speech stimuli. Each word was recorded thrice to select the best out of three.

Speech intelligibility rating: These recorded words were judged by five native speakers of Kannada. Only those words having good intelligibility were selected for the study.

*Filtering of the words:*Each word was filtered using Adobe Audition software (version 3). The slope of the filter was 60dB/ octave. All the words from all the lists were passed through a band pass filter having either 500Hz or 2500Hz center frequency. The first one was having a low frequency center frequency of 500 Hz and the second one was having a high frequency center frequency of 2500Hz respectively. These center frequencies were also used by Hall, Buss and Grose (2008) in their study on spectral integration. They had selected these center frequencies based on the rationale that frequency components in a speech spectrum predominantly lay between 300 to 3000 Hz. Thus, if a center frequency of 500 Hz and 2500 Hz are taken, these would lie at low and high portions of the speech spectrum respectively. This helps in finding the spectral integration across the speech spectrum. Each word list was filtered using two center frequency having different bandwidths.

Bandwidths considered: The number of bandwidths available for the two center frequencies were different. The words were first passed through a band pass filter with a 500 Hz center frequency. The bandwidth of the filter having 500 Hz as the center frequency was varied from 100 Hz till 1000 Hz in 100 Hz steps. Similarly the bandwidth of filter having 2500 Hz center frequency was also varied from 100 Hz till 3000 Hz in 100 Hz steps.

Initially a pilot study was done on 5 native speakers of Kannada. Initially, filtered speech materials having either low center frequency or higher center frequency were presented to the participants, with the minimum bandwidth. Gradually the bandwidth of the filtered speech was increased. The minimum bandwidth at which the individuals obtained 15 to 25% speech identification scores was noted. This is called as criterion speech bandwidth (CSB) as suggested by Hall et al. (2008).

In the pilot study it was seen that filtered words having 500 Hz center frequency with bandwidths of 100 or 200 Hz was not sufficient for individuals with normal hearing to achieve the criterion score of 15 to 25%. Thus, these two bandwidths were not considered for the study. Similarly for the filtered words having 2500 Hz center frequency bandwidths till 1100 Hz was not sufficient for normal hearing individuals to achieve the criterion score of 15 to 25%. Thus, bandwidths till 1100 Hz were not considered in the study. Table 1 shows the details of bandwidths of two different center frequencies considered for the study.

Maximum bandwidth considered for 500 Hz and 2500 Hz center frequency was 1000 Hz and 3000 Hz respectively. This was not increased further because it would lead to overlapping of bandwidths. For example, if 3100 Hz was considered it would contain frequency components between 950 to 4050 Hz and this will overlap with the 500 Hz center frequency having a bandwidth of 1000 Hz (0-1000 Hz).

Table 1: Bandwidths used for the study having two different center frequencies

500 Hz center frequency		2500 Hz center frequency	
Frequency range (Hz)	Bandwidth (Hz)	Frequency range (Hz)	Bandwidth (Hz)
350-650Hz	300Hz	1900-3100	1200
300-700Hz	400Hz	1850-3150	1300
250-750Hz	500Hz	1800-3200	1400
200-800Hz	600Hz	1750-3250	1500
150-850Hz	700Hz	1700-3300	1600
100-900Hz	800Hz	1650-3350	1700
50-950Hz	900Hz	1600-3400	1800
0-1000Hz	1000Hz	1550-3450	1900
-	-	1500-3500	2000
-	-	1450-3550	2100
-	-	1400-3600	2200
-	-	1350-3650	2300
-	-	1300-3700	2400
-	-	1250-3750	2500
-	-	1200-3800	2600
-	-	1150-3850	2700
-	-	1100-3900	2800
-	-	1050-3950	2900
-	-	1000-4000	3000

Phase 2: Obtaining Criterion Speech Bandwidth (CSB)

Criterion Speech Bandwidth was established using two steps. Step one was to obtain initial bandwidth for CSB and the second step to establish the CSB.

Step to obtain Initial Bandwidth for CSB: To obtain the initial level the stimuli were presented through a calibrated 2 channel diagnostic audiometer GSI-61 with TDH 50P earphones. Presentation level was kept at 40 dB SL for all the participants and it was monitored through audiometer. Responses were obtained from the participants by instructing them either to repeat or write the words. Participants were instructed to guess the words if it was not clearly perceived. Only one ear was considered for all the participants to reduce the practice effect. The ear which fulfilled the criteria was selected for testing. If both the ears of a single subject passed the criteria then their right ear was considered for testing. Experimenter didn't give any feedback regarding their responses during the testing.

With the goal of predicting the CSB, filtered words were presented to the participants. At first filtered words having center frequency of 500 Hz were presented. An initially filtered word with largest bandwidth of 1000 Hz was presented for familiarization. Two filtered words were presented at each bandwidth. If the participants failed to identify both the words, then bandwidth was increased by 100 Hz and the next set of filtered words were presented. For example, in the Table 2, after familiarizing the participants by presenting filtered word with largest bandwidth, filtered words having a bandwidth of 300Hz were presented. Since the participant could not identify both the words at this bandwidth, the bandwidth was increased by 100 Hz ie, 400Hz and again two filtered words were presented. When the participants were able to identify both the words at a particular bandwidth, this was considered as initiation bandwidth for CSB. In the Table 2, at the bandwidth of 500 Hz, the

Table 2: Procedure to obtain initiation bandwidth for CSB

Bandwidth (center frequency 500 Hz)	Response(Word identification-two words at each band width)	
	1st word	2nd word
1000 Hz, for familiarization	present	present
300 Hz	absent	absent
400 Hz	absent	absent
500 Hz	present	present

participant correctly identified the filtered words. Thus the initiation bandwidth for CSB is 500Hz.

The same procedure was also followed for the 2500 Hz center frequency to obtain the initiation bandwidth for CSB. This procedure was followed to minimize the presentation of full list to obtain CSB.

Phase 3: Step to obtain CSB

Criterion speech bandwidth was the minimum bandwidth required to get 15 to 25% word identification scores. Thus, in the next step of the study a full list of 25 filtered words were presented to the participants at their initiation bandwidth for CSB's for both the center frequencies to see whether it could give the criterion score of 15 to 25%. Each correct word was given a score of 4%, thus 25 words in a list makes a total of 100%. Hall et al. (2008) also considered criterion score of 15 to 25%. In case they failed to obtain 15 to 25% score at their initiation bandwidth for CSB then the bandwidth was increased at the order of 100 Hz and again a full list of 25 filtered words was presented. Bandwidths were increased till the criterion score was achieved. The bandwidth at which the score of 15 to 25% was obtained was considered as the CSB.

The relatively low criterion of 15 to 25 % was considered to ensure that performance is below 100% when both the bands are presented together.

Determining the Spectral integration: Two CSBs were obtained for all the participants. The first one for the low center frequency of 500 Hz and the second one for the higher center frequency of 2500 Hz. To determine the spectral integration abilities, words having both the CSB's were presented to the participants. A full list of 25 words was used and the word identification scores were calculated.

Results

For each participant, CSB's for 500 Hz center frequency and 2500 Hz center frequency was noted. These CSB's were then divided by their respective center frequencies to obtain normalized CSB. Speech identification scores were obtained by presenting words having both the CSBs. These values were taken for comparison across groups.

Within group statistical analyses were done for comparing the parameters within the same group. Paired t-test was carried out to determine whether a significant difference existed between normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at low and high center frequencies, within each group. A Pearson correlation was done to see the correlation between the spectral integration scores and the speech identification scores obtained in quiet without any modification to the speech stimulus.

Between group statistical analyses were done to compare parameters across the groups. Independent t- test was carried out to see the group differences for normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at 500 Hz, between individuals with normal hearing and individuals with cochlear hearing loss. One way ANOVA was not done for group comparison of normalized bandwidth at 500 Hz because individuals with auditory dys-synchrony could not get minimum speech identification scores even at the maximum bandwidth at the 500 Hz center frequency used in the study. One way ANOVA was done to see whether a significant difference existed between normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at 2500 Hz, across the three groups .One way ANOVA was also done to see whether a significant difference existed between spectral integration scores obtained across the groups. Duncan's post hoc analysis was done to see the pairwise differences when the ANOVA results were significant.

Individuals with Normal Hearing

The mean and the standard deviation for the normalized minimum bandwidth required to achieve minimum speech identification scores (normalized CSB) at 500 Hz, 2500 Hz center frequency and for the speech integration scores were calculated for all the 29 individuals with normal hearing sensitivity. Details are given in Table 3.

From the table it can be seen that the normalized minimum bandwidth achieving minimum speech identification scores at 500 Hz center frequency was greater than the bandwidth required at 2500 Hz center frequency. Paired t- test was carried out to determine whether a significant difference existed between normalized bandwidth at these two center frequencies. Results showed that there was a significant difference [t= (3.73), 28 $p<0.001$] between normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at low and high center frequencies.

Table 3: Mean, Standard Deviation (SD), minimum and maximum values for the normalized criterion speech bandwidths at two different center frequencies and also speech integration scores obtained in individuals with normal hearing sensitivity

	Mean (kHz)	SD	Min	Max
Normalized CSB at 500 Hz	0.76 (N=29)	0.2	0.68	0.83
Normalized CSB at 2500 Hz	0.61 (N=29)	0.08	0.58	0.64
Spectral integration	90.34% (N=29)	3.30	89.09%	91.50%

Correlation between the spectral integration scores and speech identification scores obtained in quiet without any modification to the speech stimulus was not done in this group, since all the participants in the group got 100% speech identification scores in quiet without any modification to the speech stimulus.

Individuals with Cochlear Hearing Loss

The mean and the standard deviation for the normalized minimum bandwidth required to achieve minimum speech identification scores (normalized CSB) at 500 Hz, 2500 Hz center frequency and for the speech integration scores were calculated for all the 12 individuals with cochlear hearing loss. Details are given in Table 4.

Table 4: Mean, Standard Deviation (SD), minimum and maximum values for the normalized criterion speech bandwidths at two different center frequencies and for the speech integration scores obtained in individuals with cochlear hearing loss

	Mean (kHz)	SD	Min	Max
Normalized CSB at 500 Hz	0.92 (N=12)	0.29	0.73	1.1
Normalized CSB at 2500 Hz	0.74 (N=12)	0.17	0.63	0.84
Spectral integration scores	92.3% (N=12)	3.17	90.31%	94.84%

Table 4 shows that normalized bandwidth required for 500 Hz is more than that required for 2500 Hz center frequency. Paired t- test was carried out to determine whether a significant difference existed between normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at low and high center frequencies. Results showed that there was no significant difference (t= (1.96), 11 $p>0.05$) between normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at low and high center frequencies.

Pearson correlation was done to see the relationship between the spectral integration scores and the speech identification scores obtained in quiet without any modification to the speech stimulus in individuals with cochlear hearing loss. Results of the correlational analysis showed that there was no significant correlation between the spectral integration scores and the speech identification scores obtained in quiet without any modification to the speech stimulus in individuals with cochlear hearing loss ($r=0.35$, $p> 0.05$).

Individuals with Auditory Dys-synchrony

Mean for the normalized minimum bandwidth required to achieve minimum speech identification scores (normalized CSB) at 500 Hz was not calculated as none of the individuals with auditory dys-synchrony could get a minimum speech identification score of 15 to 25%, even at the maximum bandwidth of 500Hz center frequency used in the study.

Table 5: Mean, Standard Deviation (SD), minimum and maximum values for the normalized criterion speech bandwidths at 2500 Hz center frequency and also speech integration scores obtained in individuals with auditory dys-synchrony

	Mean (kHz)	SD	Min	Max
Normalized CSB at 2500 Hz	1.08 (N=17)	0.15	1	1.16
Spectral integration scores	30.11% (N=17)	13.71	23.06%	37.17%

The mean and the standard deviation for the normalized minimum bandwidth required to achieve minimum speech identification scores (normalized CSB) at 2500 Hz and for the speech integration scores were calculated for all the 17 individuals with auditory dys-synchrony. Spectral integration scores were calculated by presenting filtered words having both CSBs (500 Hz and 2500 Hz center frequency). As none of the individuals with auditory dys-synchrony could get a minimum speech identification scores even at the maximum bandwidth of 500 Hz center frequency, for calculating spectral integration scores maximum bandwidth at 500 Hz center frequency was presented along with the CSB obtained at 2500 Hz center frequency. Details are given in Table 5.

There were 2 different patterns of integration seen in these individuals. This included negative spectral integration and poor spectral integration (marginal im-

Table 6: Scores/ Criterion scores obtained at 500 Hz and 2500 Hz center frequencies and also the spectral integration scores in individuals with auditory dys-synchrony

Participants	500 Hz center frequency with max bandwidth of 1000 Hz	Crit. score at 2500 Hz	Spectral integrat-ion score	SI scores in quiet with-out stimulus modification
1	4%	24%	12%	32%
2	8%	24%	16%	32%
3	0%	20%	16%	36%
4	0%	24%	4%	36%
5	0%	20%	16%	36%
6	8%	20%	28%	32%
7	8%	24%	40%	88%
8	0%	20%	32%	88%
9	8%	24%	40%	60%
10	8%	20%	32%	40%
11	4%	24%	52%	88%
12	0%	20%	52%	80%
13	0%	24%	40%	92%
14	0%	20%	24%	68%
15	12%	16%	36%	100%
16	0%	20%	36%	76%
17	0%	20%	32%	76%

provement). Negative spectral integration means when both the low and high center frequency bands were presented together to the participants instead of getting a better integrated score by combining the information in both the bands, these individuals got a poorer score than the criterion score obtained at 2500 Hz center frequency CSB. Out of the 17 individuals with auditory dys-synchrony 5 had negative spectral integration. The remaining 12 individuals had less advantage of spectral integration (marginal improvement). The details are given in Table 6.

From the Table 6, it is evident that none of the individuals could achieve a criterion score of 15 to 25% at the 500 Hz center frequency. All of them achieved a criterion score at 2500 Hz center frequency. When the information in both the bands was presented together first 5 participants got poorer scores, even poorer than their criterion scores obtained at 2500 Hz center frequency indicating a negative spectral integration. All these five participants had poor speech identification scores in quiet without any modification made in the speech stimulus with their scores ranging from 32% to 36%.

The remaining 12 participants with auditory dys-synchrony got better spectral integration values when compared to the first five participants with the scores ranging from 28% to 52%. Among the 12 participants, 10 had speech identification scores in quiet of 60% or above. Only the participants 6 and 10 had speech identification scores less than 50% in this group.

Pearson correlation was done to see the relationship between the spectral integration scores and the speech identification scores in quiet without any modification to the speech stimulus. The results showed that there was a significant positive correlation between the spectral integration scores and the speech identification scores obtained in quiet without any modification to the speech stimulus ($r=0.641$, $p<0.01$). This means that, better the Speech identification scores in quiet without any modification made in the speech stimulus, better the spectral integration scores and vice-versa.

Across Group Comparisons

Mean, Standard Deviation of normalized criterion speech bandwidths at 500 Hz and 2500 Hz center frequencies were compared across the groups. The results are given in the Figure 1.

None of the individuals with auditory dys-synchrony could achieve a criterion score even at maximum bandwidth at 500 Hz center frequency. It is seen that individuals with normal hearing obtained the criterion scores with least CSBs at both 500 Hz and 2500 Hz center frequencies followed by individuals with cochlear hearing loss and then the individuals with auditory dys-synchrony (CSB at 2500 Hz). The variability was relatively great among the individuals with cochlear hearing loss for the CSBs at both 500 Hz and 2500 Hz center frequencies. The mean and standard deviation for spectral integration scores were also compared across the groups. The details are given in Table 7.

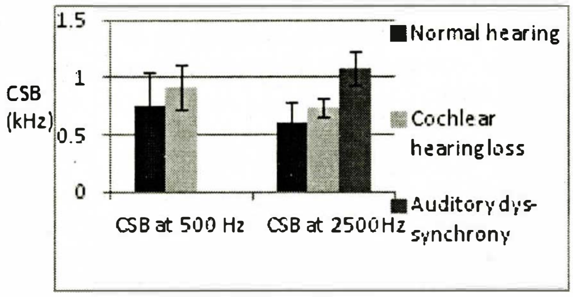

Figure 1: Mean, Standard Deviation (SD) at two different center frequencies obtained across all the three groups.

Table 7:

When the spectral integration scores were compared across the groups it was seen that both normal hearing individuals and individuals with cochlear hearing loss performed almost equally. Individuals with auditory dys-synchrony had very less spectral integration scores compared to the other two groups and also the variability was more in this group which is evident from the larger standard deviation value.

Normalized minimum bandwidth required to achieve minimum speech identification scores (normalized CSB) at 500Hz was compared across two groups (between individuals with normal hearing and those with cochlear hearing loss) since the individuals with auditory dys-synchrony could not achieve the criterion score even at the maximum band width of 500 Hz center frequency. Hence, at 500 Hz bandwidth an independent t-test was used to compare the normalized minimum bandwidth required to achieve minimum speech identification scores (normalized CSB) across individuals with normal hearing and those with cochlear hearing loss. Results showed that there was no significant difference in normalized minimum bandwidth required to achieve minimum speech identification scores at 500Hz center frequency between the two groups ($t= 2$, $p>0.05$).

One way ANOVA was done to see whether a significant difference existed between normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at 2500 Hz, across the three groups. Results showed that there was a significant difference across groups [$F(2,55)=77.4$ $p<0.001$]. Duncans post hoc analysis was done to see if all the three groups differed significantly from each other for the normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at 2500 Hz. It was found that all the three groups differed significantly from each other ($p< 0.05$).

One way ANOVA was done to see whether a significant difference is present across the groups for the spectral integration scores. It was found that there was a significant difference [$F(2,55)=356.86$, $p<0.001$] across the groups. Duncans post hoc analysis was done to see if all the three groups differed significantly from each other for spectral integration scores. It was found that individuals with auditory dys-synchrony were significantly different from the other two groups in terms of spectral integration scores ($p<0.05$).

Table 7: Mean, Standard Deviation (SD) for the speech integration scores obtained across all the three groups.

Groups	Mean	SD
NH	90.34%	3.30
CH	92.3%	3.17
AD	30.11%	13.71

Discussion

Results showed that, for individuals with normal hearing the normalized CSB at 500Hz center frequency ranged from 0.68 to 0.83 and for individuals with cochlear hearing loss it ranged from 0.73 to 1.1. This is larger in comparison to the previous studies. Hall, Buss and Grose (2008) in their study said that for individuals with normal hearing the criterion normalized bandwidth at 500 Hz center frequency ranged from 0.27 to 0.57 and for individuals with cochlear hearing loss it ranged from 0.28 to 1.06. The difference in the present study from the study by Hall et al. (2008) might be due to the type of stimuli used. They used filtered sentences whereas, in the present study filtered words was used as stimuli and this is probably because sentences are more redundant than words.

There was no significant difference in normalized bandwidth required to achieve minimum speech identification scores at 500 Hz center frequency between individuals with normal hearing and individuals with cochlear hearing loss. However there was more variability in individuals with cochlear hearing loss. Similar results were also discussed by Hall et al. (2008). This can be explained with the degree and pattern of hearing loss considered in the present study. The current study has taken only individuals with flat or gradually sloping hearing loss of mild-moderate degree. Glasberg and Moore (1989) said that individuals with cochlear hearing loss of only more than moderate degree have major problems with frequency resolution. Thus, most of the participants in cochlear hearing loss group would not have had a problem with their frequency resolution and temporal coding that much which could bring a significant difference between individuals with normal hearing and individuals with cochlear hearing loss.

Individuals with auditory dys-synchrony could not achieve the criterion score even at the maximum bandwidth at 500 Hz center frequency. This can be attributed to their poor frequency resolution at low frequencies (Zeng & Liu, 2006) due to which their speech perception was severely affected at low center frequency.

Results showed that, for individuals with normal hearing the CSB at 2500 Hz ranged from 0.58 to 0.64 and for individuals with cochlear hearing loss it ranged from 0.63 to 0.84 and in individuals with auditory dys-synchrony it ranged from 1 to 1.16. The bandwidth required by individuals with normal hearing and also individuals with cochlear hearing loss at both the center frequencies in the current study were larger in comparison to the previous studies. Hall et al. (2008), in their study said that for individuals with normal hearing the criterion normalized bandwidth at 2500 Hz center frequency ranged from 0.22 to 0.48 and for individuals with cochlear hearing loss it ranged from 0.14 to 0.54. Mlot, Buss and Hall (2010) have also reported similar results as that of Hall et al. (2008). The difference in the present study from the previous studies can be again explained by the type of stimuli used.

All the three groups differed significantly from each other for the normalized bandwidth required to achieve minimum speech identification scores having 2500 Hz center frequency. This can be explained with the explanation given by Lorenzi, Gilbert, Cam, Gamier and Moore (2006) who reported that individuals with cochlear hearing loss has difficulty using the fine structure cues which are of high frequency information. So speech processing varies based on the frequency resolution at a particular frequency and also it varies across listeners. Thus in the present study, individuals with cochlear hearing loss would have had poorer frequency resolution at high center frequency due to which they required wider CSB than that of normal hearing individuals. Whereas, individuals with auditory dys-synchrony required the widest band width among the three groups to achieve minimum speech identification scores (normalized CSB) at 2500 Hz center frequency. Though temporal processing is majorly affected in these individuals they also have spectral processing difficulties (Zeng , Oba, Garde, Sininger & Starr, 2001; Rance, McKay & Grayden, 2004; Starr et al., 2003). Vinay and Moore (2007) reported poor ability in individuals with auditory dys-synchrony to detect tones in presence of noise and they also attributed this to the poor phase locking in these individuals. Therefore all these reasons would have contributed for poorer performance in this group.

Results also showed a significant difference between normalized bandwidth required to achieve minimum speech identification scores at 500 Hz and 2500 Hz center frequencies in individuals with normal hearing. This finding is in accordance with the study done by Mlot, Buss and Hall (2010) where they found that normalized CSB was significantly smaller for the band centered on 2500 Hz than that for the band centered on 500 Hz. This result can be explained with frequency band importance. The greater importance of the higher frequency band may explain the fact that it carries more information essential for determining consonant place, which is more essential in enabling the listener to discriminate among words (Kasturi, Loizou, Dorman & Spahr, 2002).

In individuals with cochlear hearing loss there was no significant difference between normalized bandwidth required to achieve minimum speech identification scores at 500 Hz and 2500 Hz center frequencies. This result is in contrary to the results discussed by Hall et al. (2008). He found that even individuals with cochlear hearing loss require lesser CSB at 2500 Hz center frequency compared to 500 Hz center frequency. In their study they had given a high frequency boost to the high frequency band to ensure the constant audibility and also to reduce the effect of upward spread of masking among hearing impaired listeners, which was not done in the present study. Another reason might be the type of the stimuli used in both the studies. Hall et al. (2008), had used filtered sentences where as the present study used filtered words as stimuli.

Comparison between normalized bandwidth required to achieve minimum speech identification scores (normalized CSB) at 500 Hz and 2500 Hz center frequencies was not made in the group with auditory dys-synchrony as none of them could achieve the criterion score even at the maximum bandwidth at 500 Hz center frequency.

Results showed that individuals with normal hearing and individuals with cochlear hearing loss performed similar in spectral integration scores (with both groups having more than 90% scores when both bands were presented together). Similar findings have been reported in individuals with normal hearing and individuals with cochlear hearing loss by Hall et al. (2008). However the amount to which integration of the information occurred was different in the present study in individuals with normal hearing and individuals with cochlear hearing loss. Hall et al. (2008) in their study found that when the individual band which gives a criterion score of 15-25% were presented together spectral integration scores were better than 70%. Resuts of Mlot et al. (2010) also closely agrees with that of Hall et al. (2008) finding. In the present study when the low and the high frequency bands were presented together both the individuals with normal hearing and individuals with cochlear hearing loss got spectral integration scores of more than 90%. In their studies they obtained criterion score of 15-25% at smaller CSBs than that of the present study. In the study by Hall et al. (2008) the CSBs for low and high center frequencies were 0.41 and 0.35 respectively for normal hearing adults. On contrary in the present study CSBs for low and high center frequencies were 0.76 and 0.61 respectively for normal hearing adults. Thus when a two large spectral bands are presented together integration occurs across many frequencies than when smaller bands are presented together. This might have resulted in better integration scores of more than 90%.

Individuals with auditory dys-synchrony had significantly poor spectral integration scores than individuals with normal hearing and individuals with cochlear hearing loss.This can be explained based on the degree of dys-synchrony in these individuals. It is evident from the literature that these individuals have poor phase locking abilities which results in poor pitch processing mainly at low frequencies (Zeng & Liu, 2006). Thus those five individuals who had negative spectral integration would have had very poor pitch processing at low frequencies to the extent that it even interrupted their processing of high frequency information when both the CSBs were presented together. In other words they have failed to utilize the information at and around 500 Hz center frequency, rather the energy of this level would have caused upward spread of masking leading to the masking of high frequency signal which resulted in reduced performance. Individuals with auditory dys-synchrony also shows excessive masking effect (Zeng, Kong, Michalewski & Starr, 2005) which would further enhance the upward spread of masking and this would have resulted in poorer spectral integration scores, even poorer than their criterion scores obtained at 2500 Hz center frequency when the information in both the bands was presented together. This can be further supported by the fact that all the five participants had poor speech identification scores (32% - 36%) in quiet without any modification made in the speech stimulus.

Remaining 12 participants had poor spectral integration. Both the individuals with normal hearing and individuals with cochlear hearing loss, the spectral integration scores were greater than 90%, where as in individuals with auditory dys-synchrony the spectral integration scores ranged from 28%-52%.

The reason for poor performance compared to other two groups can be again explained using the poor pitch processing in individuals with auditory dys-synchrony. Reduced pitch processing in individuals with auditory dys-synchrony limits them from combining the information across the frequency bands effectively as in case of individuals with normal hearing and also of cochlear hearing loss. However these 12 individuals got better spectral integration scores compared to the other 5 individuals with auditory dys-synchrony. This might be because the degree of dys-synchrony was milder in this group. This is supported by the fact that 10 individuals among the 12 individuals with auditory dys-synchrony had their speech identification scores greater than 60% in quiet without any modification made in the speech stimulus, which suggests lesser degree of dys-synchrony. Results showed no correlation between the spectral integration scores and speech identification scores obtained in quiet without any modification made in the speech stimulus in individuals with cochlear hearing loss.

A positive significant correlation between the spectral integration scores and speech identification scores obtained in quiet without any modification made in the speech stimulus was seen in individuals with auditory dys-synchrony. In individuals with auditory dys-synchrony, only those individuals who had good speech identification had better spectral integration scores. This can be explained based on the frequency resolution at low frequencies. Those individuals who had better frequency resolution could obtain better speech identification scores in quiet which in turn resulted in improved ability to combine information across frequency bands.

Conclusion

These findings of the study are helpful while selecting hearing aid features for these individuals. Most of the individuals with moderate sensorineural hearing loss of flat or slightly sloping pattern will benefit from multi channel hearing aids as they have very good ability to combine the information across the frequencies. In individuals with auditory dys-synchrony it is better to select a hearing aid with lesser number of channels as they already have very poor abilities to combine information across the frequencies. It is also best to give them a hearing aid with best noise reduction strategies which will help to remove noise which are mainly of low frequencies. Even while prescribing them channel specific gain it is wise to give lesser gain at low frequencies to reduce the upward spread of masking, which can cause deleterious effect, as seen in the present study.

This study can be used as a tool to study the spectral integration abilities in different clinical groups. This can be used as a tool to assess the speech perception abilities in difficult listening situations as we are using filtered words. This study can also be used to differentiate between individuals with cochlear hearing loss and those with auditory dys-synchrony.This can be used to explain physiological basis for the speech perception abilities of different clinical groups to some extent. Further studies on CSBs required for speech perception may assist us in selection of hearing aids by helping us decide about the optimum number of channels required for each individual.

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