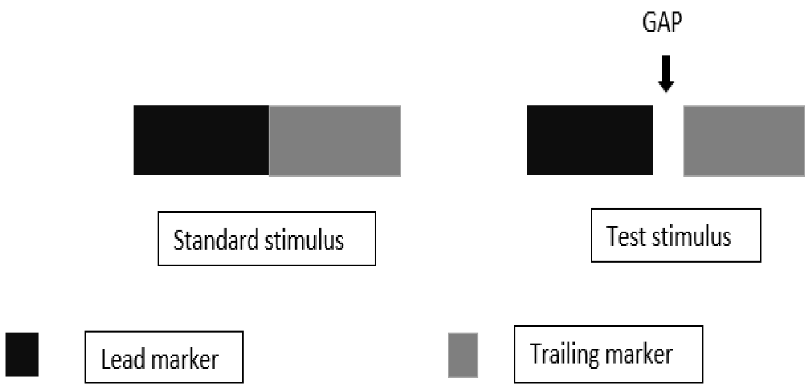
Introduction

Speech is a complex signal which the auditory system decodes by identifying the inherent fluctuations of the stimuli with respect to intensity and frequency over time. Humans are gifted with a remarkable capacity of spectral and temporal resolution which makes the complex process look simple andproficient. This resolution ability of the ear is achieved as it weighs the effect of any sound by an exponentially decaying factor so that more importance is given to the recent portions of the sound (Irwin & Kemp, 1976).

Over the years, there are many tests developed to study this resolving ability of the auditory system in humans. One such test which is commonly used to assess the temporal resolution is the Gap Detection Test. This test requires the listener to identify the just noticeableinterruption in otherwise a continuous stimuli. Conventionally, the listener is presented with a pair ofstimuli out of which one has agap. The smallest gap the listener is able to identify is considered the gap detection threshold (GDT). The stimulus with gap is the test stimulus and the other forms the standard stimulus.



According to the earlier psychophysical experiments done in this area, individuals with normal hearing abilities can identify a gap of ranging to a few milliseconds (Plomp, 1964; Moore, 1993). This is true when the lead and the trailing marker are of same frequency, which is the within channel (WC) gap detection. It is considered a simple task where the auditory system has to detect the discontinuity of the stimulus given in a single channel.In the day to day scenario, the environmental sounds heard comprises of multiple frequencies.And so, to resolve complex stimuli especially like speech, the gap detection is just not 'discontinuity detection' because, the gaps are not bound by similar markers on either side which requires across channel (AC) processing to detect the gap in the stimulus. Multiple attempts have been made to simulate a multi-channel processing and test the temporal resolution ability using gap detection task. It is usually performed using dissimilar frequency markers (the lead marker and the trailing marker of the stimuli belong to different frequencies) or with dichotic presentation (that is lead stimulus to one ear and lag stimulus to the other) (Formby, Gerber & Sherlock, 1998). Sucha gap is identified by the time difference between the offset of the first neural channel and the onset of an entirely new channel.A number of studieshave been carried out keeping ear and/or frequency as the dimension for across channel processing.By and large, it is found that the across channel GDT has a greater threshold when compared to within channel GDT because of the physiology involved. This is a general trend observed in individuals with normal hearing sensitivity.

Nevertheless, a compromised hearing can also influence gap detection ability in the individual.Any disruption in the process of hearingleads not only to loss of audibility, also interrupt the spectral and temporal processing (Moore 1996; Moore &Oxenham 1998; Nienhuys& Clark 1978; Oxenham& Bacon 2003; Prosen, Moody, Stebbins, & Hawkins, 1981; Ryan &Dallos 1975). However, the impact of hearing loss is also determined by the age of onset, degree and type of the problem.In Adults pathology restricted at the outer or middle ear level leads to conduction deficit which usually leads to audibility issues with little or no other perceptual consequences. On the other hand, in children with conductive hearing loss several authors have reported them to have poor temporal resolution ability compared to normal hearing typically developing children where as they even found that children with conductive hearing loss had same performance as of children with central auditory processing disorders. Therefore, authors concluded that conductive hearing loss in early age of development can results profound temporal processing deficits (Balen et al., 2009, Borges, Paschoal, Maria, & Iii, 2013,).If the pathology is at the inner ear, majorly spectral processing gets affected along with the audibility problem. With neural involvement in the pathology, temporal processing also gets altered significantly. Hence, the common complaint of person with hearing loss especially at the sensory or the neural level would be inability to hear which may accompany with inability to understand speech, especially in acoustically degraded environment.

Cochlear hearing loss (CHL) is one of the most common types of hearing loss which is caused due to pathology of the inner ear. The pathology more specifically damages the outer hair cells, effectively causing this type of hearing loss. The damage can also extend to the inner hair cells or can cause distortion of the stereocilia. The impact of these anatomical changes can bring about several perceptual changes like impaired frequency and temporal resolution in addition to reduced audibility (Preminger & Wiley, 1985; Glasberg& Moore, 1986; Tyler, Wood, &Fernandes, 1982; Lorenzi, Gilbert, Carn, Garnier, & Moore, 2006).

a) The frequency selectivity depends on the filtering that takes place at the level of cochlea (Evans, Pratt, & Cooper, 1989). Hence, in person with cochlear damage the frequency selectivity is poorer than normal. But the difference between persons with normal hearing and cochlear hearing loss tend to lessen at higher sound level (Moore, Laurence, & Wright, 1985; Stelmachowicz, Lewis, Larson, &Jesteadt, 1987). Several studies comparing psychophysical tuning curves(PTC) in subjects with normal hearing and cochlear hearing loss (Bonding, 1979; Carney & Nelson, 1983; Festen&Plomp, 1983; Florentine, Buus, Scharf, &Zwicker, 1980; Nelson, 1991) agree to a general conclusion that PTCs are broader than normal in persons with cochlear hearing loss. In addition to estimate frequency selectivity studies have been to estimate the Auditory filter shapes of subjects with cochlear impairments using notched-noise maskers (Dubno& Dirks, 1989; Glasberg& Moore, 1986; Leek & Summers, 1993; Leeuw&Dreschler, 1994; Peters & Moore, 1992; Sommers&Humes, 1993; Stone, Glasberg, & Moore, 1992; Tyler, Hall, Glasberg, Moore, & Patterson, 1984). The results generally agree in showing that auditory filters are broader than normal in hearing-impaired subjects and that, on average, the degree of broadening increases with increasing hearing loss.

b) The intensity discrimination is measured using ecxperimentts like DLI measurement, the detection of amplitude modulation and the detection of differences in intensity of separate pulsed tones. Persons with cochlear hearing loss perform as well as or better than normal when the comparison is made at equal sensation level (SL). However, when compared at equal sound pressure level (SPL), the performance of persons with cochlear damage is worse than normal (Buus, Florentine, & Redden, 1982; Glasberg& Moore, 1989; Schroder, Viemeister, & Nelson, 1994; Turner, Zwislocki, &Filion, 1989).

c) The temporal perception as a result of impaired cochlea is reduced and affects the speech perception (Schom&Zwicker, 1990). Thus, along with frequency and intensity, temporal perception is also extensively studied mainly to see the effect of configuration and degree of hearing loss made a change in temporal resolution in individuals with CHL. The usual finding is that, abnormal cochlea produces abnormal temporal characteristics. Irwin, R. J., Hinchcliff, L., and Kemp, S. (1981) found that listeners with cochlear hearing loss had poorer temporalacuity than normal hearing listeners; that is, the listeners with hearing loss required a longer gap in the presence of noise in order forit to be just detectable than did normal hearing listeners. Similar findings by Florentine andBuus, 1984 suggests that the individuals with CHL needed a larger duration to detect the minimum gap when compared to the normal hearing counterparts.The minimum detectable duration for a burst of noise was also observed to be increased in CHL individuals like seen for gap detection (Irwin & Purdy, 1981). All these studies conclude on similar remark that the impaired listeners exhibit a slower temporal processing in both temporal summation and temporal acuity when compared to normal hearing individuals.

Overall, reduced sensitivity and impaired frequency selectivity leads to a poor speech perception in individuals with CHL. Further damage in the neural pathway alone also does alter speech perception as seen in individuals with auditory dys-synchrony (AD).

Auditory dys-synchrony (AD), the impairmentcaused by the dysfunction of the auditory nerve but preserved outer hair cells of the cochlea. This impairment is thus considered retro-outer hair cell pathology (Starr, Picton, Sininger, Hood & Berlin, 1996). It presents itself with a unique set of symptoms and perceptual difficulties. The usual complaint of individuals with AD is that they hear the sound but there is difficulty in understanding the same. This perceptual difficulty does not correlate with the degree of hearing loss as observed in individuals with cochlear hearing loss (Sininger& Oba, 2001; Zeng, Kong, Michalewski, & Starr, 2005). Multiple researchers have reported the behavioural data of the perceptual consequences of AD which mainly concentrates on frequency, intensity and temporal processing and in turn comment on the poor speech understanding ability.

a) The frequency discrimination ability studied in individuals with AD has shown significantly poor performance when compared to normal hearing counterparts, especially in the low frequency. Zeng et al. (2005) compared the frequency discrimination in 12 AD individuals where they found significantly poor frequency discrimination in low frequencies when compared to normal. But this difference was not observed in high frequencies.Rance et al (2004) observed that in AD individual difference limen at 4 KHz was 4.5 time higher than normal and at 500 HZ it was 11 time higher than the normal hearing group.

b) Intensity processing is relatively spared when compared to frequency and temporal processing in individuals with AD. Psychoacoustic intensity discrimination task was also carried out in two AD cases, where the client had to discriminate one different stimulus among the triad of stimuli. It was found that normal hearing required less than 1dB to discriminate, whereas the AD cases required 3 to 6 dB to discriminate (Starr et al, 1996). Similarly, Zeng (2001, 2005) studied intensity discrimination ability in these individuals and found that at lower intensities they required higher intensity differences to discriminate. However, at higher intensities the difference required did not differ much when compared to normal hearing counterparts.

c) Temporal processing is the first and most affected ability in these individuals. Previous researchers have extensively studied this area using multiple tests available like temporal integration, gap detection, temporal modulation transfer function, temporal masking and simultaneous masking. Starr et al (1991) were among the first researchers to study the processing of timing in these individuals. He reported that individuals with AD performed poorly when compared to normal in duration discrimination, gap detection and masking level differences. Similar findings were observed byZeng et al (2005) who studiedthe temporal ability in individuals with AD. Thus, gap detection which depends on the temporal processing is majorly affected in individuals with AD along with temporal integration, forward/backward masking, and temporal modulation detection (Zeng& Shannon, 1999; Zeng et al., 2001; Zeng et al., 2005 & Kraus et al., 2000).

Research on GDT in individuals with AD are mainly done with either broad band noise or narrow band noise in a within channel paradigm. These reports basically say that the gap detection ability are affected especially at higher SLs too where normals perform significantly better.

To conclude, a sensory or neural hearing loss though differently but definitely influences the gap detection thresholds. Along with these, other factors like age, the type of stimulus used for testing also could contribute for the overall thresholds.

Need for the study:

Gap detection thresholds have been found to be affected in individuals with hearing impairment. However, clinically GDT is not been used to assess the temporal ability of the individuals with hearing impairment with an exception of CAPD test battery. But, with the more recent research, the testing has started to use frequency specific stimuli for measuring the gap detection. Within channel gap detection test has been done by various authors to understand the temporal resolution abilities in normal, individuals with hearing impairment.

Aim:

The current study aims to evaluate across channel and within channel temporal resolution skills in individuals with normal hearing, sensorineural hearing loss and auditory dys-synchrony and correlate the same with their speech identification scores.

Objectives of the study

1. To assess the temporal resolution skills using within channel and across channel gap detection threshold by using dynamic adaptive test in individuals with

a) Normal hearing

b) Sensorineural hearing loss

c) Auditory dys-synchrony

2. To compare within channel and across channel temporal resolution skills in individuals with normal hearing, sensorineural hearing loss and auditory dys-synchrony.

3. To correlate the across channel temporal resolution skills with SIS within group:

a) Individuals with normal hearing

b) Individuals with sensorineural hearing loss

c) Individuals with auditory dys-synchrony

Null Hypothesis

1. There is no significant difference in temporal resolution skills using within channel and across channel gap detection threshold by using dynamic adaptive test in individuals with

a) Normal hearing

b) Sensorineural hearing loss

c) Auditory dys-synchrony

2. There is no significant difference in within channel and across channel temporal resolution skills in individuals with normal hearing, sensorineural hearing loss and auditory dys-synchrony.

3. There is no significant correlation between the across channel temporal resolution skills with SIS within group:

a) Individuals with normal hearing

b) Individuals with sensorineural hearing loss

c) Individuals with auditory dys-synchrony

Method

The objective of the present study was to assess the temporal resolution ability using across and within channel gap detection testing in population with AD, CHL and normal hearing ability. To obtain this, data was collected from the following participants who were assigned into following three groups.

Participants:

The participants were grouped based on the audiological findings. They were,

Group 1: *The control group*

1. Thirty individuals with hearing abilities within normal range were considered in this group who were in the age range of 15 to 50 years.
2. Their hearing sensitivity was within normal limits (four frequency average pure tone threshold, 500 Hz, 1000 Hz, 2000 Hz & 4000 Hz) and speech identification scores in noise was 60% or above at 0dB SNR.
3. Transient evoked otoacoustic emissions were present in all the participants.
4. ‘A’ type tympanogram with middle-ear acoustic reflexes (both ipsilateral&contralateral) and
5. Auditory brainstem responses were present for all the participants.

Group 2: *Individuals with cochlear hearing loss*

1. This group consisted of individuals diagnosed as having post lingual acquired cochlear hearing loss by the Department of Audiology, All India Institute of Speech and Hearing.

2. The pure tone thresholds ranged from mild to moderately severe hearing loss with speech identification scores proportionate to the degree of hearing loss.

Table: Demographic and Audiological details of subjects with cochlear hearing loss

Subjects (Age and gender)	**Test ear**	**Degree of hearing loss**	**Speech Identification Score at MCL**	**Tympanometry**
S1 (29yrs/male)	Right	Moderate hearing loss	88%	A
S2 (36yrs/female)	Left	Mild hearing loss	96%	A_S
S3 (46yrs/male)	Right	Mild hearing loss	92%	A
S4 (22yrs/female)	Right	Moderate hearing loss	92%	A
S5 (40yrs/male)	Left	Mild hearing loss	96%	A
S6 (35yrs/female)	Left	Moderate hearing loss	96%	A
S7 (50yrs/male)	Right	Moderate hearing loss	96%	A
S8 (51yrs/male)	Right	Mod-severe hearing loss	88%	A_s
S9 (45yrs/male)	Left	Mild hearing loss	92%	A
S10 (30yrs/female)	Right	Mild hearing loss	100%	A
S11 (40yrs/female)	Right	Mild hearing loss	100%	A_d
S12 (50yrs/male)	Left	Mild hearing loss	100%	A
S13 (47yrs/male)	Right	Mild hearing loss	100%	A
S14 (39yrs/female)	Left	Moderate hearing loss	100%	A
S15 (57yrs/male)	Left	Mild hearing loss	96%	A

Group 3: *Individuals with Auditory Dys-synchrony*

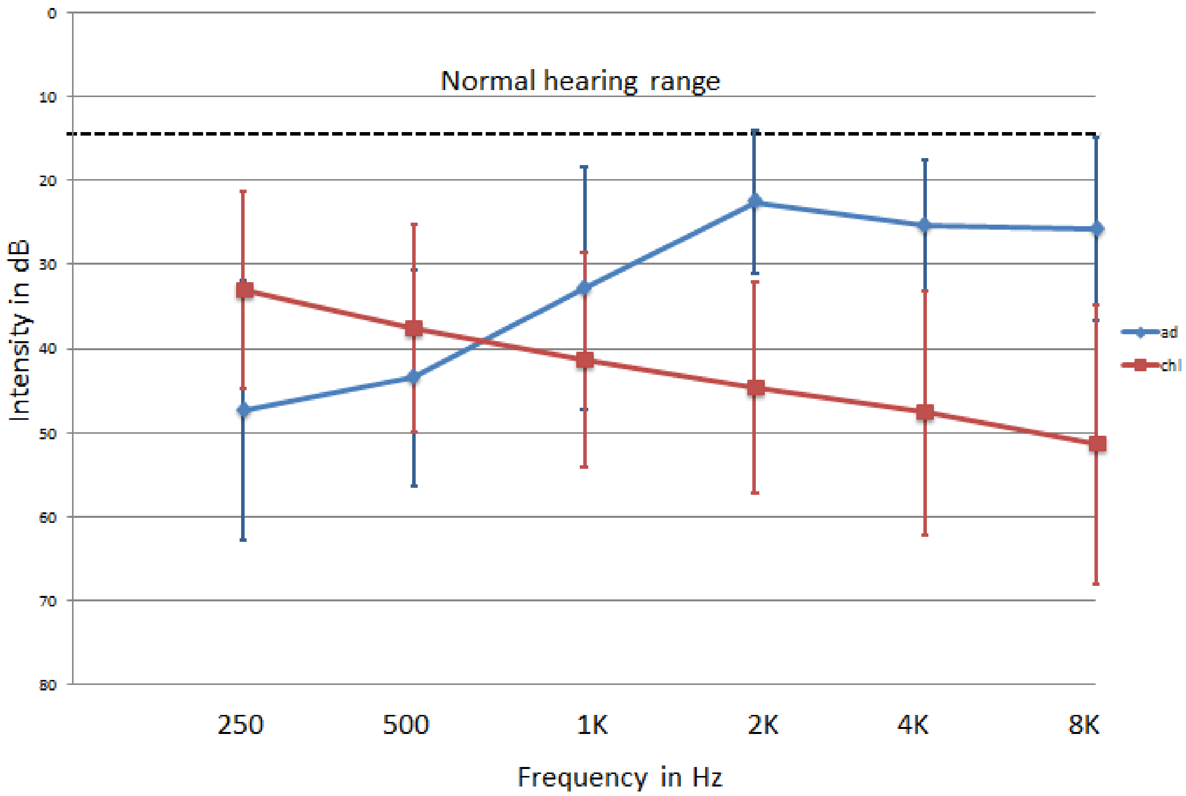
1. This group consisted of individuals diagnosed with auditory dys-sychrony by the Department of Audiology, All India Institute of Speech and Hearing.
2. All the participants reported to have acquired hearing loss, in terms of pure tone thresholds ranged from near normal hearing to moderate sensorineural hearing loss.
3. The speech identification scores were disproportionate to the degree of hearing sensitivity.

   None of the participants from the three groupsreported of any known speech and language deficits or any other associated neurological symptoms.

Table: Demographic and Audiological details of subjects with auditory dys-synchrony

Subjects (Age and gender)	**Test ear**	**Degree of hearing loss**	**Speech Identification Score at MCL**	**Tympanometry**
S1 (19yrs/male)	Left	Minimal hearing loss	92%	A
S2 (28yrs/female)	Right	Moderate hearing loss	48%	A
S3 (24yrs/male)	Right	Moderate hearing loss	64%	A
S4 (23yrs/male)	Left	Mild hearing loss	15%	A_s
S5 (35yrs/male)	Right	Mild hearing loss	40%	A
S6 (26yrs/female)	Left	Minimal hearing loss	80%	A
S7 (40yrs/female)	Right	Moderate hearing loss	20%	A_s
S8 (55yrs/male)	Right	Moderate hearing loss	84%	A
S9 (20yrs/female)	Right	Mild hearing loss	60%	A
S10 (16yrs/male)	Left	Minimal hearing loss	30%	A_d
S11 (19yrs/female)	Left	Minimal hearing loss	84%	A_d
S12 (20yrs/female)	Right	Minimal hearing loss	96%	A_s
S13 (21yrs/male)	Right	Mild hearing loss	68%	A
S14 (26yrs/male)	Left	Mild hearing loss	86%	A_d
S15 (22yrs/female)	Right	Mild hearing loss	45%	A
S16 (18yrs/male)	Right	Mild hearing loss	56%	A_s
S17 (18yrs/male)	Left	Mild hearing loss	96%	A

The following graph shows the mean threshold distribution across the tested frequencies for both the population.



Instrumentation:

- A calibrated dual channel diagnostic audiometer to carry out pure tone audiometry and speech audiometry.
- GSI- Tympstar middle ear analyser for Tympanometry and acoustic reflex assessment.
- Calibrated Oto dynamic ILO system to measure the distortion product otoacoustic emissions.
- Calibrated intelligent hearing systems to record ABR.

- The stimulus presentationcarried out through HP Pavilion g6 laptop loaded with Psycon V 2.18 experimental software.
- The stimulus from the laptop was routed through a calibrated audiometer (MA-53). In order to control the intensity of the stimulus. A Senheiser HD 200 headphone was used to deliver the stimulus.

Stimuli:

The stimuli used for the testing are narrow band noise with centre frequencies 1 KHz, 2 KHz and 4 KHz (with 1 equivalent rectangular bandwidth) and broad band noise. All these experimental stimuli were generated instantly with the sampling rate of 44100 from Psycon V 2.18 experimental software using AUX scripting (Kwon, 2012).

Test environment:

The testing was carried out in an air conditioned sound treated single room set-up. The noise level in the testing room was maintained within the permissible limits (ANSI S-3, 1991).

Testing procedure:

Threshold estimation using adaptive procedure in Psycon software was carried out for broad band noise, 1 kHz, 2 kHz and 4 kHz narrow band noise. Following threshold estimation, most comfortable level (MCL) for every stimulus was obtained. The testing was carried out using 2-down 1-up procedure giving 3 alternate forced choice options for all the stimuli (accuracy of hit rate being 70.8% by Levitt H, 1971). Using the same procedure, GDT for BBN was estimated for the listener's preferred ear at their MCLs and for NBNs in the following combinations.

Within channel combinations	Across channel combinations
1 KHz- 1 KHz	1 KHz- 4 KHz
	1 KHz- 2 KHz

For within and across channel GDT experiment, the duration of the lead marker was 300 ms which was kept constant throughout the testing. The duration of the trailing marker varied from 250 ms- 300 ms to take out the overall duration as a possible cue to identify the gaps. The overall stimulus duration remained constant within trials but varied across trials. All the stimuli had a 1msec ramping before and after the gap. The standard stimulus had one msec gap which was utilised as reference/ standard signal to reduce the spectral splatter in the stimulus. The test stimuli gap duration varied based on the subject’s response which started from the initial value being 50 msec for across channel GDT and 20 msec for within channel GDT. A highest gap of 200msec was set in this study. If any subject was not able to perform the task, the highest duration of 200msec was considered as their GDT for that particular condition. The schematic representation of stimulus is represented in figure 2.1.

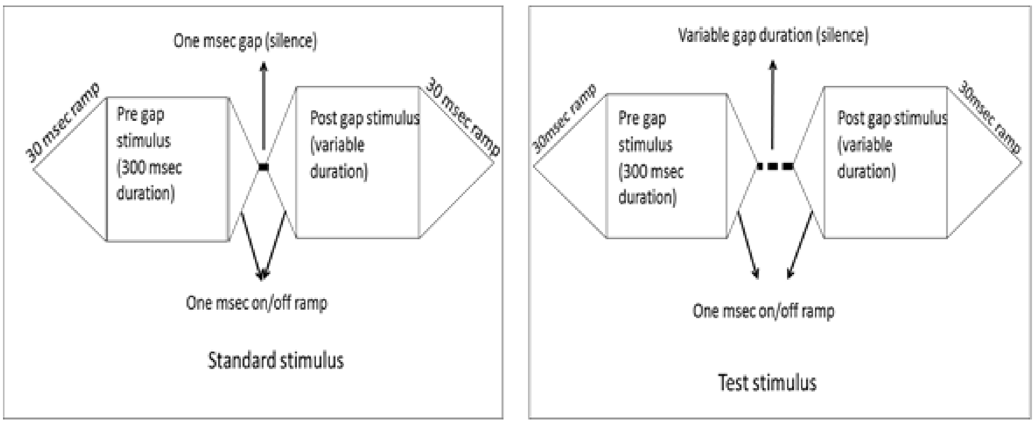


*Figure 2.1:*schematic representation of the stimulus used for the testing

GDT were obtained first for the broad band noise stimuli followed by the narrow band noise with within channel condition and across channel condition being the last. This order was maintained to follow the hierarchy of difficulty in the testing procedure.

The subjects were instructed to identify the stimulus which differed among the three options given. If they felt that the stimuli sounded similar, they were asked to point out to the particular stimulus which had the longest gap. The figure 2.2 shows the response screen with three choices to identify the target stimulus with the gap.

Figure 2.2: Response screen depicting the 3 choices

The next set of stimuli was presented after 1000 msec after the response was obtained. The inter-trial duration between the 3 forced choices was 500 msec. The mean threshold of last four reversals was considered as GDT of that particular condition. The thresholds obtained for BBN condition was saved in the folder named BBN, for within channel condition, in WC (1k-1k), for the two across channel conditions, in AC (1k-2k) and AC (1k-4k) respectively. For further reference, the thresholds of each stimulus condition will be referred with the same names

In addition to the GDT scores, speech perception scores were obatined at MCL of the participants using PB word list in Kannada language developed by Yathiraj and Vijayalakshmi (2005). The obtained GDT scores (in msec) were compared across each testing condition and were also compared across three groups of population. The speech identification scores were compared to the GDT scores for each stimulus condition for all the three groups.

Results

The focus of the current study was to understand how the ear with pathologies (sensory and neural) processes the temporal information and try to understand the within channel and across channel temporal acuity skills, and to compare the same with the processing that happens in the ears with normal functioning. The second objective was to correlate the across channel temporal resolution skills with SIS for the normal hearing population and in individuals with hearing impairment. To study these, gap detection thresholds were obtained from 30 normal hearing individuals, 17 individuals diagnosed with AD and 15 individuals diagnosed with cochlear hearing loss in four different stimulus conditions.

The mean gap detection thresholds across four stimulus configurations obtained was considered for analysis. The analysis was carried out using SPSS (version 20) software. The distribution of data showed variability and not all of them followed a normal distribution according to Shapiro-Wilk’s test. Figure 3.1 shows the threshold distribution across all stimulus conditions in all the population. The thresholds which were greater than 1.5 times the interquartile range formed the outlier population. However, the outliers were retained for the statistical analysis as their performance was within the range for the BBN condition. Non parametric tests were chosen for analysis based on all these observations. Following is the illustration of the data and tests run on them.

Independent variable (groups)	Three groups a) Normal (30) b) CHL (15) c) AD (17)
Dependent variable (GDT)	GDT in 4 different conditions a) BBN b) WC (1k-1k) c) AC (1k-2k) d) AC (1k-4k)
Kruskal Wallis test	To compare the gap detection thresholds across population within each stimulus condition
Mann-Whitney test	To compare the groups pairwise if there is a significant effect of the stimulus condition across the three groups
Friedman's test	To compare the gap detection thresholds within population across different stimulus condition
Wilcoxon's test	To compare the GDT pairwise if there is a significant effect of stimulus condition within the three groups

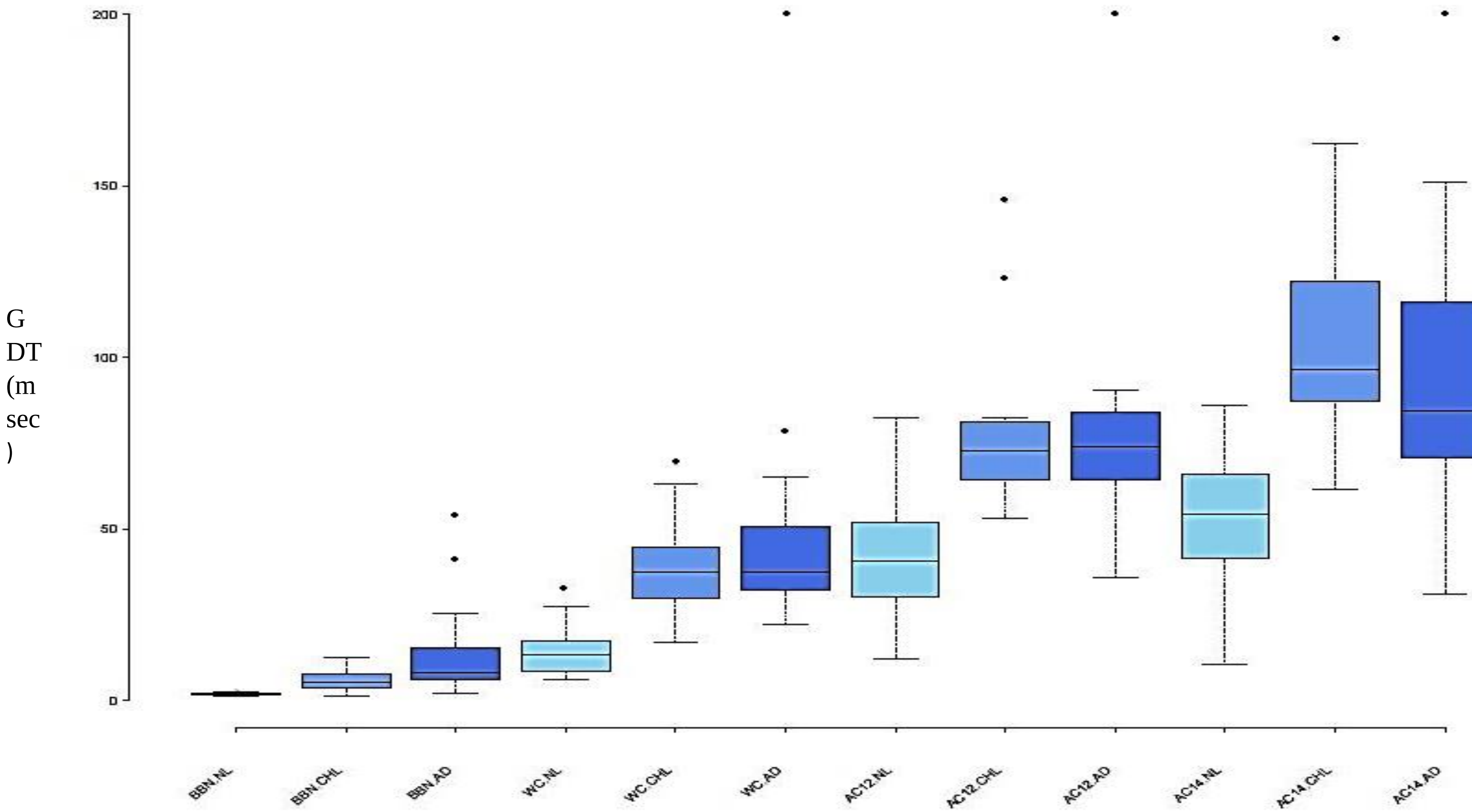


Figure 3.1: boxplot represents the mean threshold distribution of the three groups across all the stimulus conditions. The GDT values 1.5 times higher than the interquartile range are represented as the outliers.

The results are discussed under the following headings:

1. Comparison of gap detection thresholds across different population within each of the 4 stimulus condition.
2. Comparison of gap detection thresholds across different conditions within each of the three populations.
3. Correlation of gap detection thresholds with different stimulus conditions with speech identification ability of the three populations.

Comparison of gap detection thresholds across different population within each of the 4 stimulus condition:

From figure 3.1 it can be observed that pathological group performed poorly when compared to the controls. However, in all the population, a common trend of least GDT in BBN stimulus condition was observed. Also, the trend of threshold increase was also similar across all the three population with maximum scores observed in across channel (1k-4k) condition. The increase in thresholds from BBN condition to AC (1k-4k) were almost by 30 folds in controls, 25 folds in individuals with CHL and by 13 folds in individuals with AD.

Table 3.1: Descriptive statistics values obtained for the four stimulus condition across three populations

		Mean	Median	SD	Min	Max	Range
AD	BBN	13.565	8.000	14.0232	2.0	53.7	51.7
	1k-1k	59.571	37.300	54.6556	22.3	200.0	177.7
	1k-2k	91.394	74.000	53.4613	35.8	200.0	164.2
	1k-4k	105.518	84.500	53.3484	30.8	200.0	169.2
CHL	BBN	5.760	5.300	3.2443	1.3	12.5	11.2
	1k-1k	40.307	37.300	15.7508	17.1	69.3	52.2
	1k-2k	78.607	72.800	24.8176	53.0	145.3	92.3
	1k-4k	108.513	96.500	34.7654	61.5	192.8	131.3
Control	BBN	1.827	1.700	.4034	1.0	2.8	1.8
	1k-1k	14.507	13.500	6.6973	6.0	33.0	27.0
	1k-2k	41.617	40.750	16.1466	12.0	82.3	70.3
	1k-4k	53.617	54.350	18.5121	10.3	86.0	75.7

Kruskal-Wallis test was performed on this data to compare the thresholds across different population within each stimulus condition. The results revealed that the three groups were significantly different in all the four stimulus conditions. The results of this test are given in table 3.2

Table 3.2: χ^2 values along with significance level obtained for different stimulus conditions

Stimulus condition	χ^2 value	*p* value
BBN	38.6	0.00
WC (1kHz-1kHz)	41.6	0.00
AC (1kHz-2kHz)	32	0.00
AC (1kHz-4kHz)	29.4	0.00

The test however does not give the details about the group difference if significant pairwise for the groups. To get this information, Mann-Whitney test was administered, results of which is given in table 3.3.

Table 3.3: |Z| values across different stimulus conditions for pairwise comparison for all the population

	|Z| values across stimulus condition			
Population	**BBN**	**WC (1k-1k)**	**AC (1k-2k)**	**AC (1k-4k)**
Control-CHL	4.4	5.1	4.7	4.9
Control-AD	5.5	5.4	4.5	3.8
CHL-AD	2.2	0.6	0.1	0.6

Note: shaded area represents $p<0.05$

From the table it can be noted that there was a significant difference in performance of controls when compared to both the pathological groups, i.e., the control group performed significantly better than both the pathological groups. In BBN stimulus condition, normal threshold was almost 5 times better than individuals with AD and 3 times better than individuals with CHL. In other three stimulus conditions, the increase from the pathological groups was similar to both the pathologies i.e., controls were twice as better than pathological group in WC (1k-1k) condition and better by one fold in both the AC conditions.

Between CHL and AD, the difference in performance was significantly different only when BBN was used as stimulus, i.e., the CHL group performed significantly better in the BBN stimulus condition. For the other stimulus conditions, the difference in performance was not statistically significant. However, in WC (1k-1k) condition, CHL group performed better than the AD group, but was not statistically significant. Whereas, in AC (1k-4k) condition, the AD group performance was better than the CHL group. From these test findings, it is clear that the different groups behave differently for given stimulus condition. To check if there was difference within each population, further statistical testing was carried out.

Comparison of gap detection thresholds across different stimulus conditions within population:

Friedman's test was run to see if there was any effect of stimulus on GDT within each group. The test revealed that there was a main effect of stimulus in all the groups tested (p<0.05). The same is tabulated in the table 3.4.

Table 3.4: χ^2 values along with significance values across the three population

Population	χ^2 **value**	*p***value**
Control	41.3	0.00
CHL	40.5	0.00
AD	83.3	0.00

Further analysis was continued to check for the effect of stimulus pairwise in each population. To see the same, Wilcoxon's test was run on the data. The |Z| values of the same are as shown in the table 3.5.

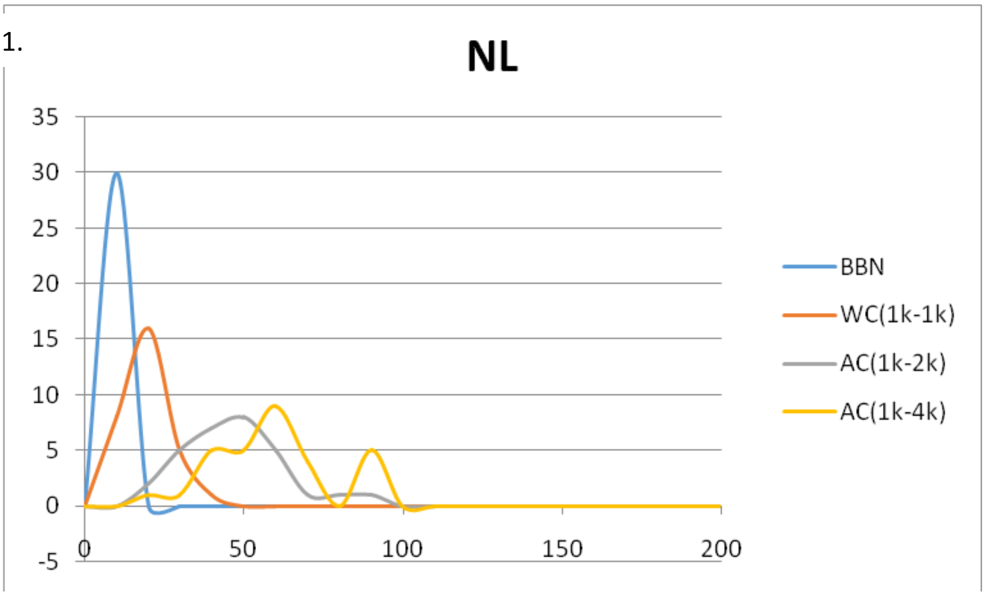
Table 3.5: |Z| values of pairwise comparison of different stimulus across the population.

Population	BBN - WC(1k-1k)	BBN – AC (1k-2k)	BBN – AC (1k-4k)	WC-AC (1k-2k)	WC-AC (1k-4k)	AC (1k-2k)- AC (1k-4k)
Control	4.9	4.9	4.8	4.8	4.8	4.1
CHL	3.4	3.4	3.4	3.4	3.4	3.3
AD	3.6	3.6	3.6	2.9	3.1	2.2

Note: $p<0.05$ in all conditions

This shows that in each group, the gap detection thresholds were significantly different for all the stimulus conditions. The thresholds for BBN were less for all the population which significantly increased for WC (1k-1k) condition and further the thresholds increased as the frequency difference increased in across channel condition. The frequency distribution (i.e. number of people whose GDT obtained was within the particular bin; bin width considered=20) of mean thresholds of each group is given in the following graphs.

1.



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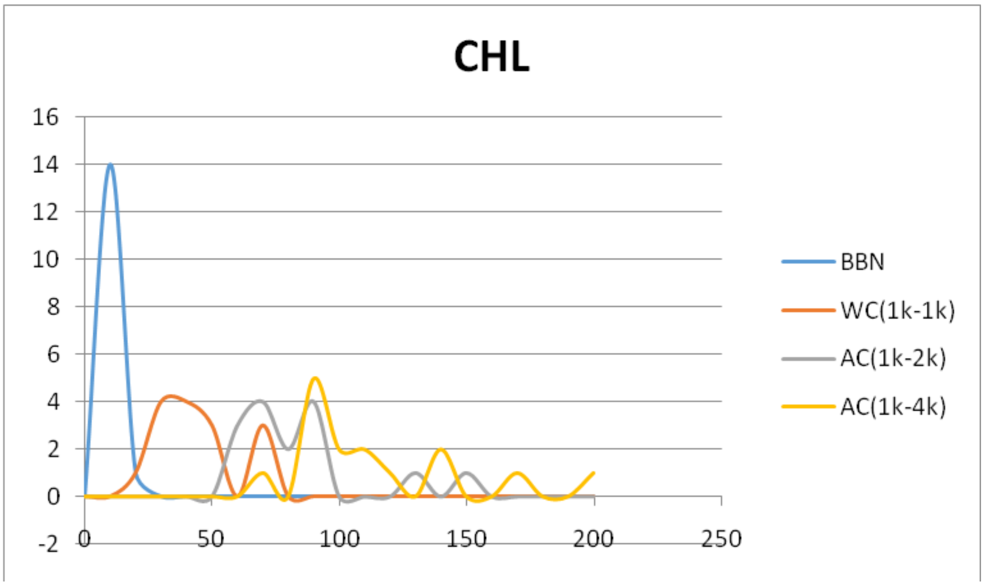

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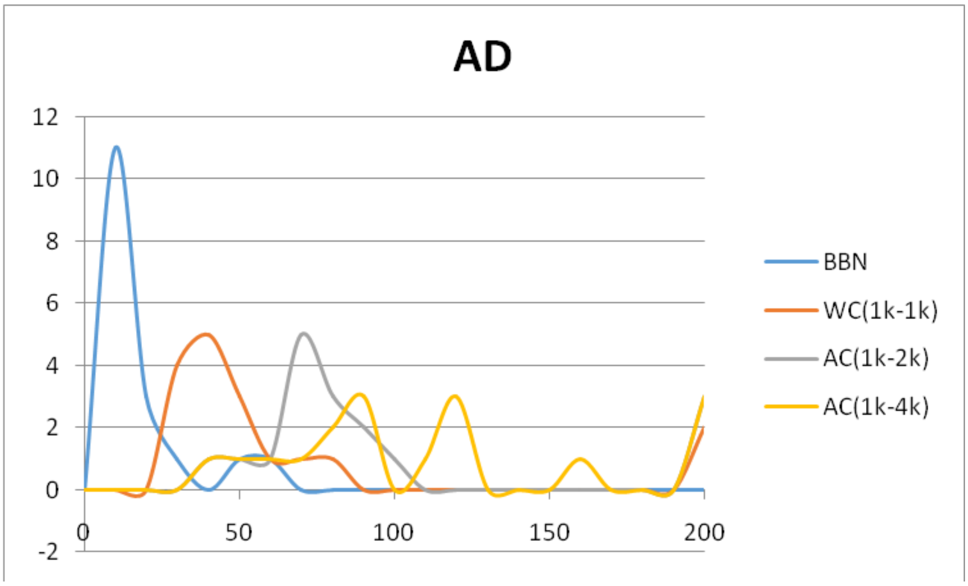


Figure 3.2: Graphs 1, 2 and 3 showing the frequency distribution of the gap detection thresholds across 4 stimulus conditions for controls, CHL and AD respectively.

From the above graphs it is clear that the thresholds for BBN is the least followed by WC (1k-1k), and maximum thresholds is obtained for AC (1k-4k). Also, the variability in the thresholds is least for BBN condition and most for across channel (1k-4k) condition. Both these trends are similar in all the three population. The variability observed was most in AD group followed by the CHL group in all the stimulus condition. The least variability was noted in the normal hearing group for the BBN stimulus condition.

Correlation of gap detection thresholds with different stimulus conditions with speech identification ability of the three populations

To see if there exists a relation between speech identification ability of an individual and their gap detection thresholds, Spearman's correlation was run for the SIS and GDT data for the three groups. For all the three groups, the results obtained did not show any significant correlation between any of the stimulus conditions and the SIS of the individuals. In the current study, a relation between speech identification and GDT could not be established.

A difference in gap detection thresholds for all stimulus conditions were calculated to get various measures of within and across channel differences for all the population (e.g., WC (1k-1k)-AC (1k-2k)). The results of this showed no significant relation between the two parameters for any of the groups. Further, the AD group was divided into good and poor performers based on the median SIS of 60%. Both the groups had 7 individuals [3 subjects for whom thresholds could not be established (GDT>200msec in any condition) were eliminated for this analysis). No statistically significant correlation was obtained with SIS in any of the conditions in both the groups. However, a strong positive correlation ($r = +0.7$, $p=0.06$) was obtained between SIS in quiet and [WC (1k-1k) – BBN] condition i.e., within channel versus multiple channels for the good performers only. It is to be noted that this failed to reach statistical significance. The graph below explains the correlation between the SIS and difference in GDT in AD population for good and poor performers.

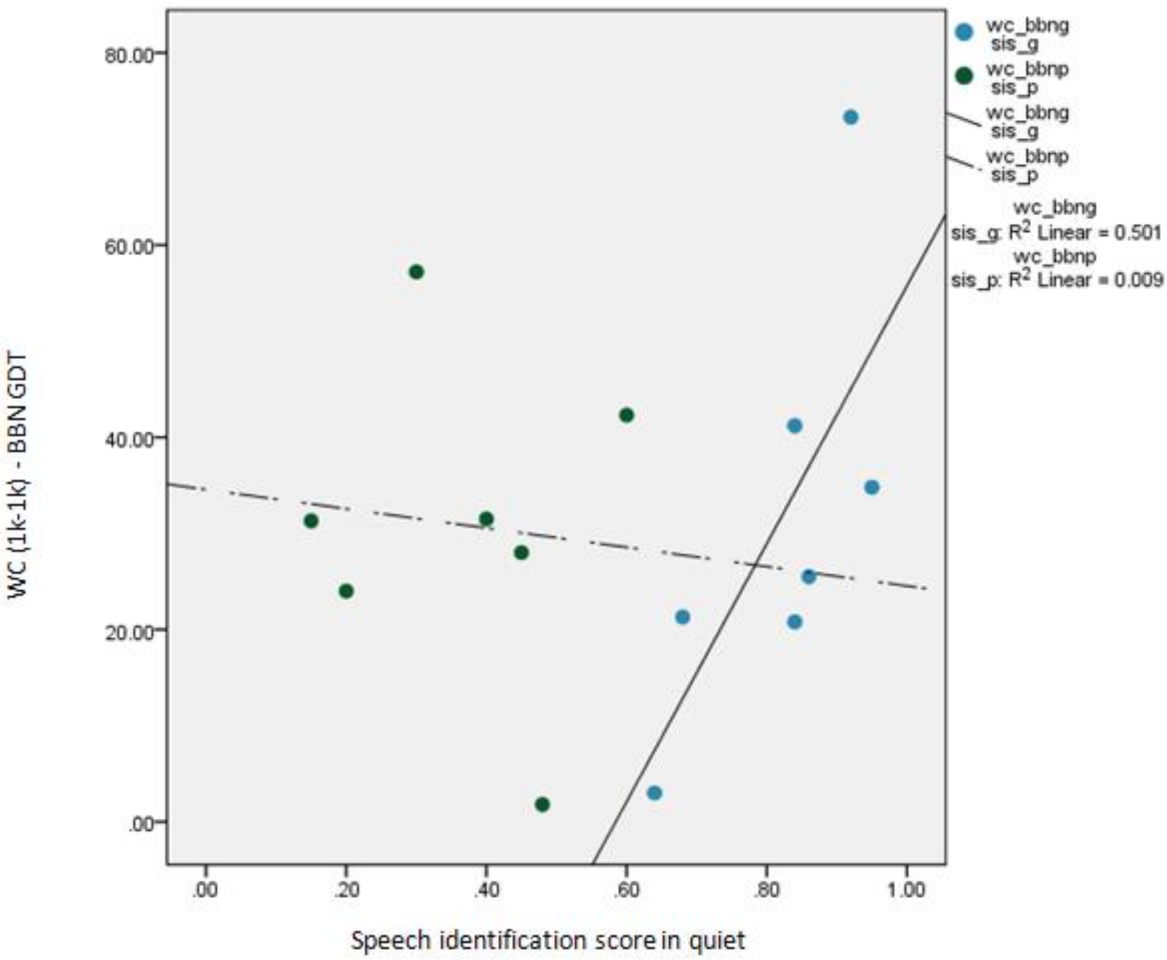
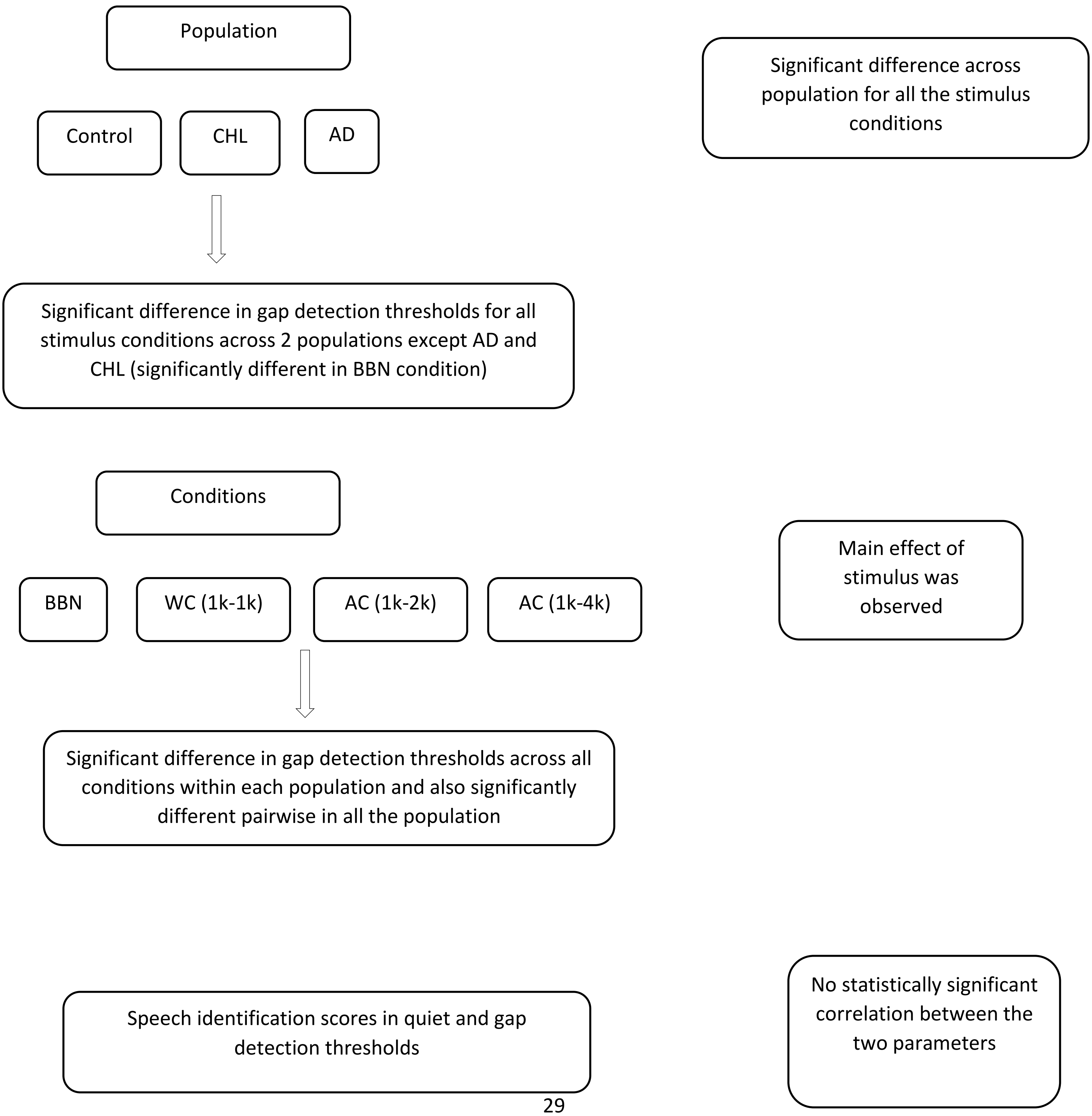


Figure 3.3: Correlation between speech identification scores and difference in GDT for good and poor performers in AD group

The results obtained can be summarised as follows:



Discussion

The objective of the study was to compare the across channel and within channel gap detection thresholds in individuals with cochlear hearing loss, auditory dys-synchrony and relate the same with the thresholds of normal hearing individuals. GDT was obtained for four different stimulus [BBN, WC (1k-1k), AC (1k-2k), and AC (1k-4k)] conditions from normal hearing individuals, individuals with CHL, and AD to achieve the objective of the study. The thresholds from all the conditions were compared across all population and also within each group. The obtained results from different statistical analysis are discussed in the current section.

Comparison of gap detection thresholds across different population within each of the 4 stimulus condition

Gap detection threshold was significantly different in all the three population for all the stimulus conditions. Controls had the best scores in all the conditions when compared to both the pathological groups. Between CHL and AD, a significantly better performance by CHL was observed only when BBN was used as stimulus. For the WC and AC conditions, both the groups performed similarly.

The ability to detect minute changes in the stimulus is cued by temporal fine structure which the individuals with normal hearing are able to extract easily. In the current study, the GDT for BBN obtained in the normal group ranged between 1-2.8msec. Multiple studies have been carried out on estimation of gap detection thresholds in normal which reports that they are able to perceive brief gaps by utilising changes in stimulus over time (Plomp, 1964; Penner, 1977; Moore, Peters &Glasberg 1993). Though there are variations in the threshold owing to change in the methodology, on an average, for BBN, the threshold is roughly around 2-3 msec in normal population (Moore, 1996; He N., Horwitz A.R., Dubno J.R. & Mills J.H, 1999; Wiegrebe&Krumbholz, 1999) which is in consensus with the present findings. In the case of CHL group, due to the underlying pathophysiology, they are not able to extract the cues which are present in a stimulus. It has been well established that individuals with CHL are not able to use the temporal fine structure information as efficiently as normal can (Moore &Skrodzka, 2002; Moore, 2003; Hopkins & Moore, 2007). The exact reason for this inability is still unclear, however, widened auditory filters, change in the travelling wave as opposed to normal travelling wave, reduced phase locking abilities can be the reasons leading to an increased GDT for BBN in this population. Individuals with AD obtained a much poorer score on GDT for BBN stimulus in the present study. Neural dys-synchrony is known to significantly impair the temporal processing. GDT a test which purely relies on a person's ability to detect a change over time will be hampered the most in case of this population. These underlying reasons could have led to the increased thresholds for BBN in AD when compared to normal group and the CHL group. This is in consensus with the previous studies done on individuals with AD who obtained a poorer gap detection threshold when compared to normal (Starr et al, 1996; Zeng et al, 1999; Zeng et al, 2001).

In WC (1k-1k) condition, similar to BBN condition a better score was obtained for normal group when compared to other groups. It is expected that the thresholds become slightly poorer with a frequency specific stimulus when compared to white noise as the bandwidth of the stimulus is reduced which has a direct relation with the GDT (Buus and Florentine, 1985; Shailer & Moore, 1985, 1987; Moore et al, 1993). In the current study, a mean GDT of 13.5msec was obtained. Previous researches on normal hearing individuals with WC stimulus condition reports a lesser threshold of around 10msec (Philips & Smith, 2004) and around 7msec (Taylor et al 1999). These variations in the obtained findings can be attributed to the stimulus bandwidth, stimulus duration used in the testing, training given and other methodological differences. The CHL group performed significantly poorer than normal group in this stimulus condition. Almost, a reduction of thresholds by 3 folds was observed in the current study when compared with the control group. The reason for this could be attributed to their failure to extract the spectro-temporal cues of the stimulus to detect the changes in the stimulus. The AD group also performed poorly when compared to normal group; however the performance was relatable with the CHL group. Though the pathophysiology is different for the two groups i.e., at sensory level and at neural levels, the effect produced on WC GDT was not significantly different in the current study. But, by a small amount, CHL performed better than the AD group. The reason for this finding could be that the frequency considered in this study was 1 KHz for WC condition where it is known that there is abnormal frequency resolution for the AD group (Zeng et al 2005). However, it was not statistically significant which could be due to the degree of dys-synchrony in the considered AD population was relatively spared (which is reflected by good speech identification score) which might have allowed them to perform on par with the CHL group. On the other hand, this might also be because of the stimulus considered which was 1KHz, given the testing was done at 500 Hz, the results might have indicated a difference between the two population as it is known that the consequence of AD is more at lower frequencies when compared to higher frequencies.

In the AC (1k-2k) and AC (1k-4k) conditions, an expected increase in thresholds was observed in all the population. Out of which, least thresholds was noted in the control group followed by the pathology groups. Also, the ranges of the obtained thresholds were high in all the three groups. The reason for such increase can be reasoned out as the task is more complex in this condition i.e., it involves identification of the time difference between the offset of the first neural channel activated to the onset of an entirely new channel. Though an increase in threshold is found across many studies on the same topic, the present study obtained a higher threshold than the earlier ones. The reasons could be that previous studies which have reported a lesser threshold has a fixed duration of stimulus (Philips & Smith, 2004; Phillips et al 1997, 1998) and the listeners might have resorted to the overall duration of stimulus as a cue to detect the gap. In addition, AC (1k-4k) had the highest thresholds which are in agreement with the findings by Formby et al (1998a), Hanekom and Shannon (1999) who reported that there would be an increase in the GDT as the distance between frequencies of post gap and pre gap increased. The pathological groups did not achieve a significant difference in performance for both the AC conditions; however, in the AC (1k-4k) condition the AD group performed slightly better than the CHL group. This might be due to the frequency of the post gap stimulus which was 4 KHz, at which the frequency resolution in AD group is known to be normal (Zeng et al 2005) whereas the CHL group has an affected resolution at that frequency (Moore, 2003). However, the reason for the poor thresholds in both the population could be because there might be a deficit in integration of information across filters at sensory level and/or neural level which are reflecting as an increase in the thresholds. Hence, the null hypothesis stating 'there is no significant difference in temporal resolution skills using within channel and across channel gap detection threshold by using dynamic adaptive test in individuals with

a) Normal hearing

b) Sensorineural hearing loss

c) Auditory dys-synchrony

is rejected.

Comparison of gap detection thresholds across different stimulus conditions within population

GDT obtained by varying the frequency dimension of the stimulus revealed that there is a main effect of the same for all the three groups. The threshold was least for BBN, followed by WC GDT. The maximum threshold was obtained for AC (1k-4k). This trend was observed in all the groups.

Amount of threshold shift from one stimulus condition to other varied in every group. Maximum shift in threshold from BBN condition to AC condition was noted in individuals with AD.

A well-known property of the normal ear is the ability to detect even a slight cessation in the stimulus which corresponds to its temporal acuity. The same tested using gap detection paradigm with BBN as stimulus produced a mean threshold of 1.8 msec which is very close to previously reported studies on the same parameter (Plomp, 1964; Penner, 1977; Moore, Peters &Glasberg 1993). GDT tested a using 1 kHz stimulus which forms within channel condition showed a slight increase in the thresholds when compared to BBN. The physiology involved in within channel gap detection is that a single neural channel is monitored and discontinuity in the stimulus is identified. The mean GDT obtained in the current study is 13.5 msec which is slightly higher than previous studies on WC GDT. These discrepancies in the results could be partly due to difference in the testing parameters. Also, the previous studies have usually considered small number of highly trained subjects which might lead to a more reduced score when compared to the current results. GDT of untrained listeners in a study by Philips D and Smith J, 2004 was around 10msec which is close to the mean GDT obtained in the current study. The AC GDT was studied by varying the post gap stimuli. The thresholds were highest for this condition [AC (1k-4k)] when compared to the other stimulus conditions. The reason could be due to the complexity involved in the detection of the gap. The activity of one neural channel till its offset has to be monitored and the onset in a completely different channel should be identified. The relative time difference between these two is identified as the gap. Thus, the thresholds observed were high for this condition; also, the variability was observed to be high [AC (1k-2k): 40.7msec, range=12-82.3; AC (1k-4k): 54.3 msec, range=10-86]. This is in consensus with previous study by Lister et al (2015). But the thresholds are larger when compared to the study by Lister and Roberts (2005) who obtained a threshold ranging between 8-76msec with a mean of 31msec. These differences can be due to equipment used and other methodological variations.

Cochlear hearing loss which affects the spectro-temporal perception of the individuals is expected to cause an increase in the GDT too. However, the stimulus effect in this population was similar to that of the normal hearing population. Narrowing the stimulus bandwidth from BBN to NBN increased the thresholds considerably. The obtained mean for WC (1k-1k) in the current study is around 37 msec which is almost 7 times higher than their GDT obtained in BBN condition. The reason for such increase could be that the ability to retrieve the temporal cues from the stimulus is severely affected. When the post gap stimulus was increased by an octave and two octaves to measure the AC perception, the results were poorer as expected. This could be due to their poor ability to process the stimulus fluctuations. The results are in consensus with previous studies which has reported higher thresholds for AC condition in individuals with CHL (Grose& Hall, 1996). Also, the shift in the threshold when compared to WC condition is higher than that seen in the normal hearing population. This is an established finding where an increased disparity between frequencies produced a greater shift in the GDT in CHL when compared to the normal counterparts (Grose& Hall, 1996). This could be due to slower temporal summation and decay in the impaired ears.

AD known to affect the temporal processing first in the individuals has a greater effect on the results of GDT when compared to other groups. Due to dys-synchronised firing and reduced discharge, the ability to detect or utilise minute changes in any stimulus can be difficult. In the current study, results in similar terms were obtained. Though the stimulus effect was observed in this group too, the amount of change in the thresholds was higher than compared to normal or the CHL group. By changing the stimulus from BBN to NBN (WC condition), one case could not perform the task. This could be due to severity of the underlying pathology which does not allow them to utilise the cues available to detect the changes in the stimulus. 2/17 cases were not able to perform in AC condition which exhibits their inability to extract information across filters at the neural level. These three individuals had a comparatively good SIS in quiet which shows that there might be no significant correlation between their performance in GDT and their speech comprehension. Hence, an individual with AD with good speech perception might face difficulty in processing the temporal fine structure cues which should be considered cautiously as it could give a hint on prognosis and management of the case. Hence, the null hypothesis stating 'there is no significant difference in within channel and across channel temporal resolution skills in individuals with normal hearing, sensorineural hearing loss and auditory dys-synchrony' if rejected.

Correlation of gap detection thresholds with different stimulus conditions with speech identification ability of the three populations

There was no significant correlation between the gap detection ability, the differences in thresholds between conditions and their speech identification scores in quite environment.

The current study did not show a significant correlation between speech perception ability and the gap detection thresholds in all the three population. This could be due to:

a) The individuals with normal hearing sensitivity and the subjects who formed the CHL group had a considerably good SIS (poorest being 88%), which is a skewed data. Hence, this might be a reason for the correlation to be not present in this population. In addition, speech identification ability in noise would have been a better tool to establish correlation.

b) The thresholds for gap detection were not found to be predictive of SIS in individuals with AD in the current study. Previous researchers have found a good correlation between the slope of TMTF and speech perception ability in individuals with AD (Narne&Vanaja, 2007; Kumar &Jayaram, 2005; Rance,McKay, &Grayden, 2004; Starr et al., 1996; Zeng etal., 1999). It is possible that the difference in GDT across conditions may be a more useful parameter than the thresholds in itself. Indeed, a WC (1k-1k) –BBN threshold difference showed a positive correlation with the SIS in AD (good performers) but not in the poor performers. This suggests that the mechanism leading to AD in the two groups may be different.

Though no conclusion can be drawn based on these finding, it can be observed that one might not be able to predict how a person with CHL or AD with good SIS might perform in GDT and vice versa. It is also possible that the supra-threshold measures like gap duration discrimination (GDD) may yield valuable information along with threshold measure like GDT (Grose, J. H., Hall III, J. W., & Buss, E 2001). Hence, the null hypothesis stating 'there is no significant correlation between the across channel temporal resolution skills with SIS within group:

a) Individuals with normal hearing

b) Individuals with sensorineural hearing loss

c) Individuals with auditory dys-synchrony'

is accepted.

To summarise, the GDT obtained by the normal group was significantly better than the pathological groups irrespective of the stimulus conditions. The reason could be that the normal ear can extract the temporal information in the stimulus effectively which the affected ear fails to do so. This inability to extract or utilise the available cues is reflected as an increase in the gap detection threshold in both the pathological groups.

In addition, the mechanisms involved in the processing WC and AC stimuli which are proposed to be two different physiologies was again confirmed by these results which obtained a significantly different result for each condition. This trend in result was also seen in the pathological groups (both sensory and neural) confirming that though the pathology hinders the ability to utilise the cues effectively, processing of these stimuli happen on similar grounds as observed in normal population.

Summary and Conclusion

Hearing involves a complicated online processing of sounds which are the vibrations distributed over time. Multiple studies have been carried out to understand how temporal processing happens in the auditory system. One such ability of the ear is to detect the order of the streams, silence between the streams if present or to just detect that there are two sounds in a row with a gap. This ability to resolve is susceptible to the pathologies in the ear. With this phenomenon in mind, the current study was designed with an aim to understand how the process of within channel and across channel gap detection happens in normal hearing and also the influence of sensory and neural pathology on the same.

To fulfil the aim, gap detection thresholds were estimated for 30 normal hearing individuals, 17 individuals with AD and 15 individuals with CHL. Four stimulus conditions were considered to simulate within channel and across channel processing in all these population. The stimulus conditions were BBN, within channel condition with 1 KHz NBN as lead and lag stimulus, across channel condition with 1 KHz NBN as lead stimulus and 2 KHz and 4 KHz as the lag stimuli respectively. The thresholds obtained were compared across and within conditions and groups. The statistical analysis of these revealed that

1. There was a main effect of stimulus frequency.
2. There was a significant difference between all the three groups for all the conditions
3. There was a significant difference between all the conditions within a group.
4. There was a high correlation between the differences in performance of GDT conditions (BBN and WC (1k-1k)) with the SIS in quiet in the good performers of the AD group but was not statistically significant.
5. No correlation was obtained with SIS in quiet and GDT for the normal hearing and the CHL groups.

Conclusion:

Minimum gap detection assessment is one of the common tests done to assess the temporal resolution ability of an individual. It is well established that a pathological ear, be it sensory or neural exhibits impaired temporal processing. However, this study is an attempt to know if there is any direct implication of changing frequency of stimuli on the gap detection performance of the individuals with hearing impairment. The current study was also designed to know if temporal resolution thresholds could be correlated with speech identification ability in these individuals.

The conclusion cannot be drawn directly from this study on what we wanted to know. But, this is a stepping stone for further planning in this area to study in detail about the temporal processing with across and within channel stimulation and correlate with speech perception ability. Though there was a correlation between the same in good population of AD, it cannot be generalised for the whole population with similar pathology.

Implication:

This study was an attempt to know if there is any direct correlation that can be obtained to show the relation between speech perception and temporal resolution ability. It can now be said that the changing frequency of the stimulus made a difference in performance for both cochlear and neural pathology, a direct correlation could not be drawn from the current tests performed.

Nevertheless, this is an initial attempt and future tests can be designed by taking these findings into consideration to better understand the relation between speech and temporal processing in individuals with sensory and neural pathologies.

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