Determining Temporal Fine Structure (tfs) Sensitivity in Individuals with Normal Hearing and Cochlear Hearing Loss through Frequency Discrimination of Complex Tones

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Abstract

In a band pass filtered complex signal, Temporal fine structure (TFS) refers to the rapidly fluctuating variations in the waveform amplitude close to the centre frequency of the band, and "Envelope" refers to slower modulation superimposed on this fine structure which occurs at a rate equal to F0 of the signal. A reduced ability to use TFS information could explain some of the perceptual problems of the hearing-impaired individuals. The ability to use TFS information can vary markedly across hearing-impaired individuals. The present study determined the extent to which individuals with normal hearing and individuals with cochlear hearing loss (minimal, mild & moderate degree) can use temporal fine structure information, by measuring the least amount of shift in the frequency (□F) that can be detected in the harmonic complex tone containing only TFS information. TFS1 software developed by Moore & Sek (2009) was used in the study, with the task being to discriminate between harmonic complex tone (H) and frequency-shifted Inharmonic complex tone (I) under conditions where temporal fine structure cues were available, but envelope and spectral cues were limited or absent. Results revealed that individuals with normal hearing could perform the discrimination task using the TFS cues implying a superior sensitivity to TFS cues especially in the F0 of 100, 200 & 400 condition. On the other hand, cochlear hearing impairment leads to a reduction in the ability to analyze and utilize TFS cues to perform the discrimination task. The present study concludes that cochlear hearing loss significantly affects the sensitivity of the auditory system to TFS.

Key words: *TFS, harmonic and inharmonic complexes, F0, cochlear hearing loss.*

Human auditory system is designed not only to pass on the external sounds to the brain but also to analyze them during the transmission. Analysis of the incoming sound starts with simple frequency analysis to very complex analysis of binaural inputs and extracting signals from the background noise. Many sounds in our environment, such as voiced speech, musical tones, and some animal vocalizations are complex. They are referred to as being harmonic, comprising frequencies that are all at, or close to, integer multiples of a fundamental frequency (F0).

When a complex broadband sound such as speech or a complex harmonic tone is analysed in the cochlea, the result is a series of bandpass-filtered signals, each corresponding to one position on the basilar membrane. Each of these signals contains two forms of information provided by the temporal analysis mechanism: fluctuations in the envelope (E) and fluctuations in the temporal fine structure (TFS) (Moore & Sek, 2009).

Temporal fine structure refers to the rapidly fluctuating variations in the waveform amplitude close to the centre frequency of the band, whereas "Envelope" refers to slower modulation superimposed on this fine structure, which occurs at a rate equal to *F*0 of the signal (Moore & Sek, 2009).

Complex harmonic tones are composed of resolved, partially resolved and unresolved harmonics. Experiments have revealed that performance of frequency discrimination tasks for complex tones containing only lower harmonics were markedly poorer than for complex tones containing only higher harmonics, suggesting that pitch was conveyed largely by higher unresolved harmonics (Hoekstra & Ritsma, 1977; Rosen, 1987; Moore & Glasberg, 1988). When a complex tone contains only unresolved harmonics, experiments involving frequency discrimination have shown the subjects use only TFS cues to perform the discrimination task (Moore & Moore, 2003b; Moore, Glasberg & Hopkins 2006b; Hopkins & Moore, 2008; Moore & Sek, 2009).

TFS information plays a vital role in the ability to lateralize sounds based on inter-aural time differences (Moore, 2003). There is also a general consensus that TFS information plays a role in the perception of pitch (Plack & Oxenham, 2005; Moore, Hopkins & Cuthbertson, 2009; Moore & Sek, 2009).

In listeners with normal hearing, considerable benefit was obtained from temporal fine structure cues which helped them in differentiating the signal from the fluctuating background noise to increase the

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SNR. But the hearing impaired seem to have little or no ability to use TFS cues to enhance signal perception, even when appropriate amplification is provided to ensure that the sounds in the fluctuating background are above the absolute threshold (Lorenzi, Gilbert, Carn, Garnier & Moore, 2006).

Cochlear hearing loss has various physical, physiological and psychoacoustical consequences. The several perceptual consequences that appear correspond to the changes observed physiologically (reduction in compressive non-linearity) due to the cochlear hearing loss. These perceptual consequences include loudness recruitment, poorer-than-normal frequency resolution, poor temporal resolution, along with the loss of lateral suppression and generation of distortion products and changes in various aspects of masking (Moore, 1995; Moore & Oxenham, 1998). These changes affect both pitch perception as well as speech perception abilities in these individuals.

A reduced ability to use TFS information could explain some of the perceptual problems of the hearing-impaired inviduals (Lorenzi *et al.*, 2006). Recent evidence suggests that cochlear hearing loss adversely affects the ability to use TFS information for lateralization of sounds (Lacher-Fouge`re & Demany, 2005) and perception of pitches created by binaural interaction for the perception of monaural pitch (Moore & Moore, 2003a; Moore et al., 2006b; Hopkins & Moore, 2008), and for speech perception (Qin & Oxenham, 2003; Lorenzi et al., 2006; Hopkins, Moore & Stone, 2008).

TFS seems likely to be one factor that contributes to the difficulty experienced by hearing-impaired people when trying to understand speech in background sounds, especially fluctuating background sounds (Festen & Plomp, 1990; Peters, Moore & Baer, 1998; Lorenzi et al, 2006; Hopkins & Moore, 2008). The ability to use TFS information can vary markedly across hearing-impaired individuals (Hopkins & Moore, 2008).

TFS plays an important role in masking, pitch perception, and speech perception. Most of these studies describing this role concentrated on normal hearing individuals, with relatively fewer studies dealing with hearing impaired individuals leading to a dearth of studies dealing with TFS abilities in individuals with cochlear loss. Also there is a need to understand whether the TFS deficits in cochlear hearing loss is due to the reduction in the audibility only, or do TFS deficits exist even when the audibility of stimulation is controlled.

Moore and Sek, (2009) revealed that preliminary results using hearing-impaired subjects indicated that some hearing impaired individuals can use TFS cues and some cannot (Moore & Sek, 2009).

The earlier investigators have not controlled the degree of hearing loss, which may affect results when studying the processing of a signal. With the emerging importance of TFS in the various aspects of signal perception, there is a need to study the factors affecting the perception of TFS in the hearing impaired individuals across various degrees of hearing loss, keeping in mind the role it has in enhancing signals and resolving complex sounds in the presence of background noise in everyday life. Hence the present study was designed with the objectives of investigating the sensitivity of individuals with normal hearing to TFS information, sensitivity of individuals with cochlear hearing loss to TFS information, effect of change in the F0 of the complex tone in individuals with normal hearing and cochlear hearing loss and comparison of TFS sensitivity across various degrees of cochlear hearing loss, (minimal to moderate cochlear hearing loss).

Method

The present study was conducted with the aim of determining temporal fine structure sensitivity (TFS) through frequency discrimination of complex tones in individuals with normal hearing and audiologically confirmed cochlear hearing loss. To achieve the aim, two groups of participants were taken.

Participants: A total of 41 participants participated in this study. The participants were divided into two groups viz control group and experimental group. The control group included 17 participants (N=34ears) with normal hearing sensitivity with no history of middle ear pathology or any other neurological symptoms, in the age range of 18-25 years with a mean age of 20 years. Whereas the experimental group included 24 participants (N=30 ears) with audiologically confirmed cochlear hearing loss with no history of middle ear pathology or any other neurological symptoms, in the age range of 18-40 years with a mean age of 27 years. A total of 30 ears were chosen. The participants with cochlear hearing loss were divided into three subgroups; minimal (N=10 ears), mild (N=10 ears) and moderate (N=10 ears) based on the degree of hearing loss.

Equipment: A Calibrated two channel diagnostic audiometer Grason-Stadler Model GSI 61 coupled with acoustically matched TDH 39 headphones housed in MX - 41/AR and Radio ear B-71 bone vibrator were used to estimate the Pure tone threshold, Speech Recognition Thresholds (SRT), Speech Identification Scores (SIS), and Uncomfortable level for speech (UCL). Audiometer was calibrated according to ANSI 1996 standards. A

Calibrated middle ear analyzer GSI- Tympstar version 2 was used for tympanometry and reflexometry. The otoacoustic emissions were measured using ILO 292 Echoport Plus. To record and analyze ABRs IHS Smart EP version: 3140 (Intelligent hearing systems, Florida, USA) was used with Eartone 3A insert earphones to deliver the stimuli.TFS1 software developed by Moore and Sek (2009), was used to generate and present the complex tones and calculate ΔF (minimum amount of frequency shift detectable). All stimuli were digitally generated using a sampling rate of 48,000 Hz. The signals were routed to the headphones through GSI-61 audiometer. Toshiba Portege` laptop with Pentium IV processor connected to audiometer through auxiliary input for presenting the stimuli.

Testing environment: All the audiological tests were carried out in a sound treated double room and noise levels were within permissible limits as per ANSI S3.1 (1999).

Stimuli: The stimuli used were harmonic complex tones (H), with fundamental frequency F0. Nominal *F*0's of 100, 200, and 400 Hz were used in the present study. For the harmonic complex, multiple harmonics of the *F*0 were added, each starting in sine phase. The inharmonic complex (I) was formed in the same way as the harmonic complex except that each component was shifted upwards in frequency by an amount ΔF in Hertz (Hopkins & Moore, 2007). Stimulus generation and subsequent modifications were accomplished by the TFS1 software (Moore & Sek, 2009). For example, For an F0 of 100 Hz, tone (H) might contain components at 800, 900, 1000, 1100, 1200, 1300, and 1400 Hz, while tone (I) might contain components at 825, 925, 1025, 1125, 1225, 1325, and 1425 Hz; the value of ΔF in this example is 25 Hz.

The tones (H) and (I) were passed though a fixed bandpass filter having a centre frequency. The filter had a central flat region with a width of 5F0 and skirts that decreased in level at a rate of 30 dB/octave to reduce spectral cues (Moore & Sek, 2009). The value of the centre frequency of the band pass filter was set to 11F0. This meant that all components within the passband were unresolved when the filter was centered at 11F0 with the lowest harmonic being the 9th harmonic (Hopkins & Moore, 2008; Moore & Sek, 2009).

Threshold equalizing noise (TEN Noise): TEN noise (Moore et al, 2000), extending from 50 to 11,050 Hz, was used to mask combination tones and to mask components falling on the skirts of the bandpass filter described above. The TEN level was specified as the level in a 1-ERBN (equivalent rectangular bandwidth) wide band centered at 1000 Hz. The recommended level of the TEN was 15 dB below the overall level of the complex-tone signal. This level is set by default in the software.

Procedure: The participants who were clinically diagnosed as having cochlear hearing loss were included in the study. To confirm OHC dysfunction TEOAE's were recorded. Transient otoacoustic emissions evoked by clicks presented at 85 dBSPL for the linear/ non-linear clicks were recorded. The probe with an appropriate sized tip was positioned in the external ear canal and was adjusted to give flat stimulus spectrum across the frequency range. The response was acquired using the linear averaging method. The two averaged TEOAE waveforms of each memory buffer composed of 260 accepted click trains, were automatically cross-correlated and used to determine the reproducibility of the measured TEOAEs by the software. The response was considered to be present when the emission amplitude was 3 dB more than the noise floor and had reproducibility more than 70 %. The absence of TEAOE's or reproducibility less than 70% and reduced overall amplitude in the presence of hearing loss were considered as indicators of hearing loss. Auditory brainstem responses (ABR) for click stimuli were recorded using the protocol given in Table 1.

Table 1. Shows the protocol used for ABR recording

Stimulus	**Clicks**
Band pass filter	100-3000 Hz
Montage	Inverting- A1 /A2, Non inverting- Fz Ground- A2/A1
Transducer	Insert ear phone
Repetition rate	11.1/s and 90.1/s
Gain	1,00,000
Polarity	Rarefaction
Intensity	80 dBnHL
Number of stimuli	1500
Analysis time	10ms

The actual testing for temporal fine structure sensitivity involved a task in which the participants were instructed to discriminate a harmonic complex tone **(H)**, with fundamental frequency F0, from a similar tone in which all components are shifted up by the same amount in Hertz, ΔF, so as to create an inharmonic tone **(I)**. In one interval of a trial (selected randomly), there were four successive bursts of tone H, separated by 100 ms (H) (H) (H) (H). In the other interval, tones H and I are alternated, with the same 100- ms inter-burst interval, giving the pattern (H) (I) (H) (I). The task of the subject was to choose the interval in which the sound changed (fluctuated) across the four tone bursts within an interval.

The participants were asked to indicate the interval (1 or 2) in which the sound appears to fluctuate and to point out which of the two intervals contained the stimulus with the fluctuating tone by clicking one of the two response boxes labeled 1 and 2. Feedback was provided after each trial by colored blinking response boxes. Green lit response box indicated a correct response (i.e., when HIHI tone sequence was chosen as fluctuating), and a red lit response box indicated an incorrect response (i.e., when HHHH tone sequence was chosen as fluctuating).

By default, the duration of each interval was set to 200 ms and the two intervals were separated by 300 ms. The background TEN started 300 ms before the first tone burst in interval one, and ended 300 ms after the last tone burst in interval two of each trial. The tones were presented 20 dB above the pure tone average of the individual (i.e 20dB SL).

The ΔF of (I), was varied from trial to trial using a 2-down 1-up procedure (Levitt, 1971), to estimate the value of ΔF leading to 70.7% correct score. A run was usually started with a relatively large value of ΔF (usually the maximum value of 0.5F0), chosen to make the task easy at the start of a run. Following two correct responses in a row, the value of ΔF decreased, while following one incorrect response it was increased. The 'threshold' value of ΔF was estimated as the geometric mean of the values of ΔF at the last six turn points. The greatest difference between the H and I tones occurs when ΔF was 0.5F0 Hz. Hence, the software does not allow ΔF to exceed 0.5F0. The "threshold" or the minimum ΔF values were noted and tabulated for each F0 value for both control and experimental groups.

Statistical Analysis: The ΔF values obtained were divided by the corresponding F0 values and expressed as ΔF/F0 (relative frequency shift). Both the ΔF and ΔF/F0 values were considered for analysis. The means and standard deviations for both the control group and the experimental group across the F0s were calculated. Appropriate statistical analysis using Statistical Package for the Social Sciences (SPSS) version 17.0 software was done to compare ΔF/F0 values in the control and experimental groups, and also across different degrees of hearing loss in the experimental group.

Results and Discussion

The task in the present study was to discriminate between harmonic complex tone and frequency-shifted complex tones under conditions where temporal fine structure cues are available, but envelope and spectral cues are limited or absent. The minimum value of ΔF where discrimination between the (H) and (I) tones occurred was measured. Only the ΔF values leading to or greater than 50 % correct score in the adaptive procedure were considered. The ΔF values obtained were absolute values because they specified the actual physical difference between the harmonics that were needed to discriminate the two harmonic complexes. ΔF values obtained were not similar in all F0 conditions measured as they varied from one F0 condition to another. In other words, the size of ΔF depended on the size of F0. Hence a relative value that considers both ΔF and the starting value of F0 was considered and expressed as ΔF/F0 which represented the relative frequency shift of threshold.

Hence this relative value (ΔF/F0) was subject to further analysis instead of absolute ΔF values. Comparison of ΔF/F0 values between the groups and within the groups was carried out. The experimental data collected were subjected to statistical analysis using Statistical Package for the Social Sciences (SPSS) version 16.0 software.

Performance of normal hearing participants in terms of ΔF and ΔF/F0 values in each F0 condition

The least amount of frequency shift detectable between the two complex tones (ΔF values) were measured for each ear across F0 conditions in the control group. The mean, standard deviation (S.D) and range for ΔF and ΔF/F0 values obtained in individuals with normal hearing were calculated and the results are outlined in Table 2.

From Table 2 it can be observed that the variability across subjects, was greater for the F0100 Hz condition and F0 400Hz condition than for the other F0s. The highest ΔF/F0 threshold value that could be obtained was 0.5F0. Group data revealed that ears in the control group obtaining the highest ΔF/F0 value of 0.5F0, was significantly higher (88%, i.e. 15 out of 17 ears) in F050 Hz than F0100Hz (35%, i.e.12 out of 34 ears) and F0400Hz (15%, i.e. 5 out of 32 ears) conditions with no subjects reaching the maximum ΔF value in F0200Hz condition.

Also from Table 2 it can be noticed that as F0 increases mean ΔF values increase but mean ΔF/F0 values decrease slightly in the control group remaining constant at F0200 and F0400 condition. Further statistical analysis was doneto check for variation in ΔF/F0 within the control group.

To find out whether the ΔF/F0 values varied significantly across F0 condition paired sample t test was performed. The results of paired sample t-test done for the pair wise comparison of ΔF/F0 values for different F0s in the control group were obtained and are outlined in table. Comparison of the ΔF/F0 values across the F0s using the paired sample 't' test showed (Table 3) significant difference between the

Table 2. Shows the Mean, SD and Range of ΔF and ΔF/F0 values obtained in individuals with normal hearing in each F0 condition

FOs	Control group							
	ΔF values in Hz				ΔF/F0 values in Hz			
	N	Mean	S.D	Range	N	Mean	S.D	Range
F050	17	24.21	2.25	17.30-25	17	0.48 F0	0.04	0.35-0.5F0
F0100	34	33.81	15.59	12.80-50	34	0.33 F0	0.15	0.08-0.45F0
F0200	34	52.89	16.57	25.7-82.5	34	0.26 F0	0.08	0.13-0.5F0
F0400	32	108.87	50.68	34.8-200	32	0.27 F0	0.12	0.09-0.5F0

Table 3. Shows the t-values and significance level for ΔF/F0 values for different F0 conditions in the control group

Control Group	't'	p
F050 - F0100	-1.750	0.099
F050 - F0200	-5.901	0.000
F050 - F0400	-7.728	0.000
F0100 - F0200	-5.012	0.000
F0100 - F0400	-7.672	0.000
F0200 - F0400	-5.918	0.000

F0 pairs, indicating that the ΔF/F0 values of one F0 condition varied significantly from that of the other F0 condition, except for the pair of F0 50 & F0 100. Performance for F0=50 Hz in the control group was generally poorer than for higher F0s. This is consistent with the finding of Moore and Sek (2009), using a similar test of sensitivity to TFS, wherein they reported that all normal hearing subjects could perform the task for F0s of 100 and 200 Hz, but that for F0=50 Hz only about one-half of their subjects could perform the task. They attributed this poor performance to the difficulty of the auditory system in accurately estimating long interspike intervals, associated with low F0s.

In the control group ΔF/F0 values obtained for F0=400 Hz had more variability with a range of 0.09-0.5F0 (i.e ΔF threshold values ranging from 34.5 Hz to 200 Hz) with two of the normal hearing subjects not able to perform the task in the present study. This may be due to the fact that phase locking weakens at high frequencies in normal hearing individuals (Palmer & Russell, 1986). It is usually assumed that in mammals the information becomes unusable for frequencies above about 5000Hz; (Heinz, Colburn & Carney, 2001). The assumption that sensitivity to TFS in humans is lost above 5000 Hz is mainly based on behavioral data showing changes in the perception of sinusoids when their frequencies fall above 5000 Hz (Moore, 2003). Hence the high threshold values obtained in F0400 condition in the control group.

Performance of individuals with cochlear hearing loss in terms of ΔF and ΔF/F0 values in each F0 conditon: The mean, S.D and range for ΔF and ΔF/F0 values obtained in individuals with cochlear hearing loss (experimental group) were calculated and the results are outlined in Table 4.

From Table 4 it can be seen that in the experimental group as F0 increases ΔF/F0 values remain largely constant at the F0 conditions measured with absolute ΔF values increasing with increasing F0. To find out whether ΔF/F0 values varied significantly within the experimental group further statistical analysis was done.

Wilcoxon's signed rank test was done to check for significant difference in ΔF/F0 values calculated in each F0 condition (50 Hz, 100 Hz, 200 Hz and 400 Hz) across different F0s. The results of Wilcoxon's signed rank test across different F0s were obtained and are summarized in table 5. Since ΔF/F0 values could not be obtained in F050 condition, this condition was not considered for the test.

From Table 5 it can be inferred that except for the pair (F0200 - F0100), F0s of pairs (F0400 - F0100) and (F0400 - F0200) did not differ significantly from each other, thus indicating that only the ΔF/F0 values of F0200 differed from that of F0100. Also no significance between the F0s in the pairs (F0400 - F0100) and (F0400 - F0200) could be due to small number of ΔF/F0 values in F0400 condition compared to that of F0100 and F0200 conditions. As revealed by Table 4, in the F050 condition none of the subjects could perform the task. This may be due to the fact that cochlear hearing impairment leads to highly reduced precision or absence of phase locking (Woolf et al., 1981).

Table 4. Depicts the mean, S.D and range of ΔF and ΔF/FO values for individuals with cochlear hearing loss in each F0 condition

	Experimental group							
	ΔF values in Hz				ΔF/F0 values in Hz			
F0s	N	Mean	S.D	Range	N	Mean	S.D	Range
F050	------	-------	-------	-----	----	--------	--------	-------
F0100	14	44.72	7.00	31.6-50	14	0.44 F0	0.07	0.32-0.5F0
F0200	17	90.62	10.98	71.6-100	17	0.45 F0	0.05	0.36-0.5F0
F0400	4	180.25	25.32	147-200	4	0.45 F0	0.06	0.37-0.5F0

Table 5. Shows the Z values and significance level for ΔF/F0 values across different F0 conditions in the experimental group

Experimental Group	'Z'	p
F0200 - F0100	-3.304	0.001
F0400 - F0100	-1.826	0.068
F0400 - F0200	-1.841	0.066

This could probably explain the total lack of ability of the individuals with cochlear hearing loss in the present study to perform the task when F0=50Hz.

The frequent high threshold values and the total lack of ability to perform the task in F0400 condition can be due to damage to outer hair cells resulting in a broadening of the auditory filters in cochlear hearing loss across the frequencies (Glasberg & Moore, 1986).

Performance of individuals with cochlear hearing loss in terms of ΔF and ΔF/F0 values in each F0 condition across different degrees of hearing loss

ΔF values were measured in each degree of hearing loss (minimal, mild and moderate degree). The mean and the standard deviation for ΔF values obtained in the minimal and the mild degree of cochlear hearing loss of the experimental group were calculated and the results are outlined in Table 6. In the moderate degree performance was very poor and no values could be obtained.

It can be noticed from table 6 that the mean ΔF values increase with the increase in F0. Also the mean ΔF values in each F0 condition increase with an increase in the degree of cochlear hearing loss, with moderate degree of cochlear hearing loss leading to total lack of ability to use TFS information.

The mean and the standard deviation for ΔF/F0 values obtained in the minimal and the mild degree of cochlear hearing loss of the experimental group were calculated and the results are outlined in Table 6. As indicated earlier it does not include values for moderate degree of hearing loss, since the performance was very poor with the values having a high probability of chance factor and falling below the criteria 50 % correct score. ΔF/F0 threshold values for minimal and mild degree are given below.

It can be observed from the Table 7 that the mean ΔF/F0 values increase with the increase in F0. Also the mean ΔF values in each F0 condition increase with an increase in the degree of cochlear hearing loss, with moderate degree of cochlear hearing loss.

Mann Whitney U test was done to check for significant difference in ΔF/F0 values in each F0 condition across the degrees of cochlear hearing loss. The results of the Mann Whitney U test comparing minimal and mild degrees for F0100 and F0200 conditions were obtained. There was no comparison in F0400 condition since ΔF/F0 values could not be obtained for F0400 in mild degree of cochlear hearing loss.

From the results it was inferred that ΔF/F0 values for F0100 condition differed significantly across minimal and mild hearing loss. But in F0200 condition there was no significant difference between the two degrees of hearing loss. F0400 condition was not considered since ΔF values could not be obtained in the mild degree of cochlear hearing loss. Moderate degree could not be compared owing to very poor performance and absence of ΔF values. Also no ΔF values could be obtained in F050 condition across all degrees of hearing loss owing to very poor performance. ΔF values for F0100 condition showed a significant difference when minimal and mild degree was compared. This could be due to the progressive reduction in the precision of phase locking for low frequencies as the degree of cochlear hearing loss increases (Woolf, Ryan, & Bone, 1981).

Table 6. Mean SD and range of ΔF obtained in the minimal and mild degree of cochlear hearing loss

	Minimal Cochlear Hearing loss ΔF values in Hz				Mild Cochlear Hearing loss ΔF values in Hz			
F0s	N	Mean	S.D	Range	N	Mean	S.D	Range
F0100	7	39.70	6.87	31.6-50	7	49.74	0.55	49.70-50
F0200	10	89.41	12.41	71.6-100	7	92.35	9.20	92.30-100
F0400	4	180.47	25.14	147.3-200	-----	-----	-----	-----

Table 7. Shows the mean, SD and range of ΔF/F0 obtained minimal and mild cochlear hearing loss

	Minimal cochlear hearing loss				Mild cochlear hearing loss			
F0	N	Mean	S.D	Range	N	Mean	S.D	Range
F0100	7	0.39	0.06	0.32-0.5F0	7	0.49	0.00	0.49-0.5F0
F0200	10	0.44	0.06	0.36-0.5F0	7	0.46	0.04	0.40-0.50F0
F0400	4	0.45	0.06	0.37-0.5F0	----	-----	------	--------

The high threshold values seen in the minimal degree in F0400 condition reflects different abilities to use TFS information among hearing impaired subjects with broadly similar audiometric thresholds (i.e. in each degree of hearing loss). The differences seen in ΔF and ΔF/F0 values across degrees of cochlear hearing loss could be due to gradual reduction of the ability of the individuals with cochlear hearing loss to use TFS information. This pattern of results was consistent with earlier work by Hopkins and Moore, (2008) they showed that the ability to use TFS information varies markedly across hearing-impaired subjects.

From the results, it's clear that as the degree of hearing loss increases, the TFS processing degrades. From this we can conclude that as the degree of hearing loss increases, the ability to process TFS information degrades. On the whole we can conclude that individuals with cochlear hearing loss most often have degraded coding of F0 and its harmonics and this is more pronounced for a high degree of hearing loss.

Comparison of performance between the control group and the experimental group: The mean, S.D and range of ΔF values measured across F0 conditions in the control group and the experimental group are outlined in Table 8.

It can be seen from Table 8 that the mean threshold values (ΔF) were higher in individuals with cochlear hearing loss across all FOs compared to the control group. In the experimental group ΔF values were not obtained for F0 = 50 Hz owing to inability of the subjects to perform the discrimination task at this F0. The fact that individuals with cochlear hearing loss usually show a poor ability to discriminate the pitch of complex sounds, even when the sounds are presented well above the detection threshold consistently when compared with normal hearing individuals (Moore & Carlyon, 2005) supports the findings in the experimental group.

The mean, S.D and range for ΔF/F0 values calculated from ΔF values obtained for the control group and the experimental group are outlined in Table 8.

From the Tables 8 and 9 it can be noticed that in the control group as F0 increases mean ΔF values increase but mean ΔF/F0 values decrease slightly and remain constant at F0200 and F0400 condition. On the other hand in the experimental group as F0 increases absolute ΔF values increase but ΔF/F0 values remain largely constant at the F0 conditions measured. To check whether there was any significant difference between the ΔF/F0 values of the control group and that of the experimental group further statistical analysis were done.

Non-parametric tests were used to check for significant difference between the control group and the experimental group (groups I and II) due to the unequal sample size. Mann Whitney U test was used to check whether the ΔF/F0 values in each F0 of the experimental group differed significantly from that of the control group. The results of the Mann-Whitney U test (Table 10) for the pair wise comparison of ΔF/F0 values of the experimental group and the control group for the F0 conditions of 100Hz, 200Hz and 400Hz were obtained and are outlined in table 10. F050 Hz condition was not compared since ΔF values were not obtained for the experimental group. Results revealed significant difference in the ΔF/F0 values between the control and the experimental groups when the F0 was 200Hz and 400Hz.

Table 8. Mean, S.D and range of ΔF values for both control group and experimental group in each F0 condition

F0s	Control group ΔF values in Hz				Experimental group ΔF values in Hz			
	N	Mean	S.D	Range	N	Mean	S.D	Range
F050	17	24.21	2.25	17.30-25	------	-------	-------	-----
F0100	34	33.81	15.59	12.80-50	14	44.72	7.00	31.6-50
F0200	34	52.89	16.57	25.7-82.5	17	90.62	10.98	71.6-100
F0400	32	108.87	50.68	34.8-200	4	180.25	25.32	147-200

Table 9. Mean, S.D and range of ΔF/FO values for both control group and experimental group in each F0 condition

F0s	Control group ΔF/F0 values in Hz				Experimental group ΔF/F0 values in Hz			
	N	Mean	S.D	Range	N	Mean	S.D	Range
F0 50	17	0.48 F0	0.04	0.35-0.5F0	-----	--------	--------	-------
F0 100	34	0.33 F0	0.15	0.08-0.45F0	14	0.44 F0	0.07	0.32-0.5F0
F0 200	34	0.26 F0	0.08	0.13-0.5F0	17	0.45 F0	0.05	0.36-0.5F0
F0 400	32	0.27 F0	0.12	0.09-0.5F0	4	0.45 F0	0.06	0.37-0.5F0

However the test revealed that there was no significant difference when the F0 was 100 Hz compared to normal hearing, despite the mean ΔF value of F0=100Hz in experimental group being higher than that of the control group.

Table 10. Shows the Z values and the significance level for ΔF/F0 values in each F0 condition across the groups

F0 (Control v/s Experimental group)	Z	p
F0100	-1.757	0.079
F0200	-5.387	0.000
F0400	-2.374	0.018

Overall it can be concluded that individuals with cochlear hearing loss performed poorly than normal hearing individuals. These high threshold values in the experimental group and significant differences can be partly attributed to damage to outer hair cells resulting in a broadening of the auditory filters in cochlear hearing loss (Glasberg & Moore, 1986). This could lead to a reduced ability to use TFS information.

Conclusions

From the results of the present study, it can be concluded individuals with normal hearing could perform the discrimination task using the TFS cues implying a superior sensitivity to TFS cues especially in the F0s of 100, 200 & 400 condition. On the other hand cochlear hearing impairment leads to a reduction in the ability to analyse and utilize TFS cues to perform the discrimination ask. Thus it can be inferred that cochlear hearing loss significantly affects the sensitivity of the auditory system to TFS. Also the deficits in the processing of TFS information increase with the increase in the degree of hearing loss. Furthermore moderate degree of cochlear hearing impairment leads to very little or no ability to utilize TFS cues. On the whole it can be concluded that damage to the OHCs leading to broadening of the auditory filters and reduced precision of phase locking of the auditory nerve fibers can result in reduced abilities to perceive pitch and discriminate the complex tones using TFS cues.

Testing the sensitivity to TFS may be useful for characterizing and understanding the temporal coding abilities of the human auditory system and its dependence on various stimulus and subject related factors. The present findings on TFS deficits, as well as preserved auditory abilities, may serve as constraints for future models of the impaired auditory system. Furthermore, they may help in defining an auditory profile for listeners with impaired hearing. Measures of the ability to use TFS information might be useful in deciding the most appropriate speed of compression in the hearing aid for a hearing-impaired individual. For an individual with little or no ability to process TFS information, slow-acting compression might be more effective than fast-acting compression (Moore & Sek, 2009).

For a hearing-impaired individual who retains some ability to process TFS, fast-acting multi-channel compression may lead to improved intelligibility of speech in the presence of sounds with spectral and/or temporal dips for such an individual. TFS stimuli may be useful in evaluating impaired hearing and in guiding the design of cochlear implants. The lack of ability to use TFS cues probably also limits the ability of people with cochlear implants to understand speech when background sounds are present. Improving the ability to use TFS should be a goal for designers of hearing aids and cochlear implants.

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