MEASUREMENT AND COMPARISON OF SPECTRAL RESOLUTION USING SPECTRO-TEMPORAL RIPPLE TEST WITH ERB SPACED RIPPLES IN INDIVIDUALS WITH NORMAL HEARING AND COCHLEAR HEARING LOSS

Mr. UDAY. N

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ALL INDIA INSTITUTE OF SPEECH AND HEARING

MANASAGANGOTRI, MYSORE- 570006

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CERTIFICATE

This is to certify that this dissertation, entitled **"Measurement and comparison of spectral resolution using Spectro-temporal ripple test with ERB spaced ripples in individuals with normal hearing and cochlear hearing loss"** is a bonafide work submittedin part fulfilment for the degree of Master of Science (Audiology) of the student Registration number P01II21S0086. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

Mysore

September 2023

Dr. M. Pushpavathi

Director

All India Institute of Speech and Hearing

Manasagangothri, Mysore- 570006

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Mysore

September 2023

Dr. Saransh Jain

Guide

Assistant Professor in Audiology

Department of POCD

All India Institute of Speech and Hearing,

Manasagangothri, Mysore- 570006

DECLARATION

This is to certify that this dissertation entitled “Measurement and comparison of spectral resolution using Spectro-temporal ripple test with ERB spaced ripples in individuals with normal hearing and cochlear hearing loss” is the result of my own study under the guidance of Dr. Saransh Jain, Assistant Professor in Audiology, Department of POCD, All India Institute of Speech and Hearing, Mysore and has not been submitted earlier to any other University for award of any other Diploma or Degree.

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LIST OF ABBREVIATIONS

STRt-NBN - Spectro-temporal Ripple Test with Narrowband Noise Carrier

STRt - Spectro-temporal ripple test

SRt – Spectral ripple test

ERB - Equivalent Rectangular Bandwidth

Log – Logarithmic

PTC - Psychoacoustic Tuning Curve

DLF - Difference limen for Frequency

DLC - Difference limen for complex tones

CI – Cochlear implant

ABSTRACT

Aim and Objectives: The present study aimed to measure the spectral resolution using the Spectro-temporal Ripple Test with Narrowband Noise Carrier (STRt-NBN test) with Equivalent Rectangular Bandwidth (ERB) and Logarithmically-spaced ripples in individuals with normal hearing and cochlear hearing loss. The thresholds were compared across the two for the subjects with normal hearing and cochlear hearing loss. The psychophysical tuning curves, which are considered a standard test for assessing spectral resolution, were measured, each at 500, 1000, 2000, and 4000 Hz center frequencies. Psychoacoustic Tuning Curves (PTCs) were correlated with spectral resolution thresholds obtained for STRt-NBN-ERB spaced and STRt-NBN-Log spaced ripple perception tests.

Methods: Two groups of adults were considered in the study. Group I consisted of individuals with normal hearing and Group II consisted of individuals with cochlear hearing loss. All the participants had undergone testing with STRt-NBN with ERB spaced ripples and Log spaced ripples and PTCs (500Hz, 1000Hz, 2000Hz and 4000Hz).

Results and Discussion: The STRt-NBN with ERB spaced ripple thresholds were significantly better than STRt-NBN with Log spaced ripple thresholds, for individuals with normal hearing and those with hearing loss. Between group comparison revealed that individuals with hearing loss had poorer SRT-NBN thresholds and broader PTCs compared to the normal hearing. This suggests that the cochlear hearing loss group had poorer spectral resolution. Correlation of STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with PTCs revealed that the STRt-NBN with ERB-spaced ripple thresholds were significantly correlated with PTCs of 1000, 2000 and 4000 Hz.

Conversely, correlation was found with PTCs and STRt-NBN with LOG-spaced ripples only at 4000Hz. The results suggested that ERB-spaced ripple stimuli can closely predict the spectral resolution than the Log-spaced ripple.

Conclusion: The STRt-NBN test with ERB spaced ripples better represents the spectral resolution of the cochlea in individuals with normal hearing and hearing loss. It can be used as a potential test to assess the spectral resolution abilities.

Keywords: Spectrotemporal ripple test, Spectral resolution, Equivalent rectangular bandwidth spaced ripple stimuli, Logarithmic spaced ripple stimuli, Psychophysical tuning curves, Cochlear hearing loss.

CHAPTER 1

INTRODUCTION

Spectral resolution refers to the ability of the auditory system to resolve spectral components of a complex signal. It plays a significant role in speech perception and discrimination of complex signals. Degradation of spectral resolution is often associated with cochlear damage(Moore, 1985; Pick, 1977; Zwicker et al., 1982) Damage to the cochlea results in the widening of auditory filters by up to three to four times, thereby reducing the spectral resolution (Glasberg & Moore, 1986) and affecting speech recognition(Festen & Plomp, 1983; Patterson et al., 1982; Plomp & Dreschler, 1980; Stelmachowicz et al., 1985)

Tests of spectral resolution incorporate the ability to detect or discriminate spectral ripples, employing a white noise or a wide band noise carrier modulated using a sinusoidal function, giving rise to spectral ripples. Ripple density or spectral modulation rate is the number of ripples for linearly spaced ripples and ripples per octave for logarithmically spaced ripples. The highest ripple density at which the ripples can be detected or discriminated helps in assessing spectral resolution abilities(Henry et al., 2005; Supin et al., 1994; Won et al., 2007).

Spectral resolution can be assessed using detection (Litvak et al., 2007) or discrimination (Supin et al., 1998) tasks. Spectral ripple test (SRt), incorporating a discrimination task, measures the highest value of ripple density of the target at which the task could be performed at a spectral modulation depth. Aronoff and Landsberger (2013) proposed a method using a modified version of the SRt, called the spectro-temporal ripple test (STRt). In their method, the phase of spectral modulation varied over time. In both SRt and STRt, a wide band carrier is used, which assesses the information over a wide range of frequencies (Drennan et al., 2014; Henry et al., 2005; Won et al., 2007). However, several researchers have suggested that this process occurs at the level of auditory filters, which are responsible for the perception of the peak frequencies alone. Thus, information using a broadband carrier may overestimate the spectro-temporal resolution in some auditory filters and underestimate other auditory filters. Therefore, Narne et al. (2020) modified the stimulus using a narrow-band carrier at 0.5, 1, 2, and 4 kHz and compared the scores of STRt-Narrow Band Noise with STRt-Broad Band Noise. It was found that STRt-NBN correlated more positively with Psychophysical Tuning Curves at 0.5, 1, 2, & 4 kHz than STRt-BBN.

1.1. **Need for the Study**

Narne et al. (2020) found that STRt-NBN correlated well with PTCs. However, a potential limitation of their study was the logarithmic spacing of the ripples. As these ripples measure the spectral resolution of the cochlea, where auditory filters are spaced based on equivalent rectangular bandwidth (ERB) scale, in other words, ERB gives a better representation of auditory filter shape than logarithmic scale, arranging the ripple based on ERB scaling may better represent the spectral resolution of the auditory filter.

The non-linear spacing in the ERB filtering corresponds more closely to the way the human ear perceives frequency differences, giving more resolution in lower frequencies and broader resolution in higher frequencies. Log-spaced filters are spaced evenly on a logarithmic scale. This spacing aligns with the fact that our perception of pitch is based on frequency ratios, not absolute differences. Log-filters are more evenly spaced in terms of perceived pitch, but they do not account for the varying bandwidths of auditory filters in the same way as ERB-filters. Thus, ERB-filters provide a more accurate representation of how the human auditory system processes sound. They capture the varying sensitivity of the ear to different frequencies and are particularly useful for tasks that involve detecting and discriminating between frequency components in complex sounds.

Various auditory processing tasks use ERB-filter, for example, in cochlear implant signal processing, coding audio signals, and other psychoacoustic research. It provides a reasonable representation for modelling auditory perception and explaining as how our ears perceive different frequencies. Thus, in the present study, the spectral resolution was measured using the STRt-NBN test, where the ripples were placed as per ERB spacing, and the results were compared with the STRt-NBN test with logarithmically spaced ripples. These thresholds were correlated with that of PTCs.

1.2. **Aim:**

The present study aimed to measure the spectral resolution using the STRt-NBN test with ERB-spaced ripples in individuals with normal hearing and hearing loss.

1.3. **Objectives of the Study:**

1.3.1 To compare the spectral resolution abilities using STRt-NBN stimuli with ERB-spaced ripples in individuals with normal hearing and hearing loss.

1.3.2 To compare the spectral resolution abilities using STRt-NBN stimuli with logarithmically spaced ripples in individuals with normal hearing and hearing loss.

1.3.3 To compare the psychoacoustic tuning curves in individuals with normal hearing and hearing loss.

1.3.4 To compare the spectral resolution thresholds obtained for STRt-NBN-ERB spaced with that of STRt-NBN-Log spaced stimuli in individuals with normal hearing and hearing loss.

1.3.5 To find the relationship of spectral resolution thresholds obtained for STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with PTCs.

1.4. **Hypothesis**

1.4.1 There will be no effect of hearing loss on spectral resolution thresholds measured using STRt-NBN-ERB spaced stimuli.

1.4.2 There will be no effect of hearing loss on spectral resolution thresholds measured using STRt-NBN-Log spaced stimuli.

1.4.3 There will be no effect of hearing loss on spectral resolution thresholds measured using PTCs.

1.4.4 There will be no difference in the spectral resolution thresholds obtained using STRt-NBN-ERB spaced stimuli and that using STRt-NBN-Log spaced stimuli.

1.4.5 There will be no correlation between spectral resolution obtained using STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with PTCs.

CHAPTER 2

REVIEW OF LITERATURE

The ability of the auditory system to distinguish the frequencies in a complex signal is referred to as spectral resolution (Moore, 1985). Spectral resolution plays a crucial role in speech perception as it decomposes the incoming sound waves into constituent frequencies and analyses the information in those frequencies to perceive speech sounds (Davies-Venn et al., 2015a). If the spectral resolution is good, one can distinguish closely spaced frequencies, which helps in perceiving fine details in the speech signal. On the other hand, if the spectral resolution is poor, one might have difficulty distinguishing between similar speech sounds characterized by slight differences in frequency composition.

The cochlea helps differentiate between frequencies of sound. The cochlea's basilar membrane is stiffer and narrower at the base and becomes broader and more flexible at the apex. This gradient of stiffness and width along the basilar membrane leads the basilar membrane to respond maximally to different sound frequencies. The specific region of the basilar membrane that vibrates most depends on the frequency of the incoming sound wave. High-frequency sounds cause the basal region to vibrate most vigorously, while low-frequency sounds cause the apical region to vibrate most vigorously. As the basilar membrane vibrates, it creates travelling waves along its length. These waves peak at specific points along the basilar membrane corresponding to the frequency of the incoming sound. It is the critical physiology behind spectral resolution.

Several tests and methods are used to assess the spectral resolution of the cochlea. Psychophysical tuning curves are the gold standard for testing spectral resolution. This method involves presenting pure tones of varying frequencies in masking noise (simultaneously or forward masking) to a listener and measuring the threshold for detection or discrimination at each frequency (Tyler et al., 1984). The PTCs are determined by a fast method developed by (Sęk et al., 2005). PTCs were obtained for 12 subjects with hearing loss and 10 with normal hearing. PTCs obtained in patients with normal hearing were comparable across the two methods (standard and fast-PTC methods). PTCs acquired using the fast-tracking approach demonstrated high reproducibility for participants with dead regions. The shape of the resulting curve can provide insights into the cochlea's ability to resolve different frequencies (Florentine, 1992).

Moore and Glasberg (1981) investigated five normal listeners using the fast-tracking approach and the conventional method using the PTC paradigm with simultaneous and forward masking at various test tone levels and frequencies. Compared to the simultaneous masking paradigm, the PTCs obtained using the forward masking paradigm had sharper tips and steeper slopes. They concluded that PTCs obtained using the simultaneous masking paradigm could be affected by beats, lateral suppression, and combination tones. However, PTCs obtained using the forward masking paradigm could be affected by off-frequency listening and the masker's decaying effect.

Moore and Alcantara (2001) tested the PTCs of five participants with sensorineural hearing loss who were considered to have dead regions. For each PTC, the amplitude and frequency of the sinusoidal signal were predetermined, and calculations were made as a function of masker frequency to determine the degree of narrowband noise masker required to silence the signal. With increased signal strength and a partial drop in the frequencies at the tips, PTCs with frequency-shifted tips (indicating dead regions) were found for all people.

Nelson and Fortune. (1991) assessed the psychophysical tuning curves (PTCs) for 1000 Hz probe tones at various probe levels for listeners with cochlear hearing loss and normal hearing. At similar masker levels close to the PTC tips, comparisons were made between PTCs with normal hearing and those with hearing loss. The extraordinarily broad PTCs mainly caused the lowered high-frequency slopes of these PTCs in 10 hearing-impaired ears. Only listeners with hearing losses greater than 40 dB HL displayed this aberrant downward spread of masking. These results imply that some, but not all, cochlear hearing impairments beyond 40 dB HL affect the fine-tuning abilities often associated with outer hair cell function.

Summers et al. (2003) tested 17 individuals with moderate-to-severe high-frequency hearing loss using the PTC and TEN tasks, and they discovered that in 10 out of 17 cases, the results from the two tasks agreed on whether or not dead regions existed at all tested frequencies.

Carney and Nelson. (1983) obtained simultaneous psychophysical tuning curves from listeners with normal hearing and hearing loss by using probing tones at either the same sound pressure or sensation level for the two listener categories. Depending on the frequency range of the probing tone and the frequency characteristics of the hearing loss, the tuning curves from the listeners with hearing loss were flat, irregular, broad, or inverted. Tuning curves from listeners with normal hearing were as precise as expected at low SPLs.

Mason et al. (1981) obtained psychophysical tuning curves from listeners with moderate-to-severe sensorineural hearing loss using a forward masking paradigm that included a 300 ms masker, a 20 ms probing tone at 10 dB SL, and a 10 ms delay. They discovered that listeners with hearing loss had broader PTCs than normal hearing individuals compared to the exact measurements (same sensation levels).

Kluk and Moore. (2009) used "classical" and "fast" methods, respectively, to assess the psychophysical tuning curves for simultaneous masking (320-Hz wide noise masker) and forward masking (sinusoidal masker). Tests were performed on 14 individuals who had high-frequency dead regions (DR). They chose a signal frequency that fall inside the DR for PTC measurement, and to get the values of the center frequencies (*f*e), the PTCs' tip frequencies were collected. The values of *f*e obtained from the PTCs in simultaneous masking and forward masking (both fast and classical techniques) were often close but occasionally somewhat higher when compared to the values of *f*e acquired from the TEN (HL) tests. They advised utilizing fast PTCs assessed in simultaneous masking in clinical practice since they are quick to administer and accurately estimate *f*e.

In listeners with normal hearing and those with sensorineural hearing loss, the PTCs were simultaneously measured using a 400-ms masker's temporal center or onset, where the 20-ms signal was displayed. It was found that sensorineural hearing loss listeners had abnormally flat PTCs (Kimberley et al., 1989).

Stelmachowicz et al. (1985) compared high-level PTCs in individuals with hearing loss and those with normal hearing. The tuning properties of healthy ears (Q10) were discovered to be independent of probe level. Moreover, HI had flatter low-frequency slopes. The propagation of stimulation from low frequencies to high frequencies is reflected in low-frequency slopes and findings suggest that masking in individuals with hearing loss spreads abnormally upward.

Pitch discrimination or frequency difference limen is the traditional test for measuring spectral resolution (Moore & Peters, 1992). It includes presenting two tones closely spaced apart in frequency and asking the listeners to decide whether the tone has a higher or lower pitch. In a more straightforward task, they must indicate whether the two tones are different in pitch (Wier et al., 1977). The ability to discriminate between closely spaced frequencies indicates good spectral resolution.

Moore and Peters (1992) assessed frequency difference limen for pure tones (DLFs) and complex tones (DLCs) in four groups of subjects- young people with normal hearing, young people with hearing loss, older people with near-normal hearing, and older people with hearing loss. In prior studies, it was discovered that for all center frequencies (50-4000 Hz), the DLFs for both impaired groups were higher than for the young normal group. The notched noise technique was utilized to evaluate the individual's auditory filters for center frequencies (*f*c) of 100, 200, 400, and 800 Hz. The DLFs at any given frequency were often not substantially correlated with the sharpness of the auditory filter at that frequency, and some individuals with broad filters had near-normal DLFs at low frequencies. Several elderly subjects in the normal group showed highly significant DLFs at low frequencies while having virtually normal auditory filters. These results suggest that pure tonal frequency selection and frequency discrimination can be partially separated. The DLCs for the two damaged groups were higher than those for the young normal group at all fundamental frequencies examined (50, 100, 200, and 400 Hz).

Notched noise masking is another popular test where the ability to detect a tone in the presence of a notched noise is assessed. A notched noise has a "notch" or gap in its spectrum. The width of the notch can be adjusted to determine the smallest frequency separation at which the listener can still detect the tone (Patterson, 1976). Smaller notches correspond to better spectral resolution. Listeners must change a comparison tone's frequency to match a target tone's pitch to complete pitch-matching trials (Clarke et al., 2016). The difference between the two frequencies can provide insight into the listener's ability to discriminate between different frequencies.

Festen and Plomp (1983) studied eight listeners with normal hearing and fifteen with mild to severe sensorineural losses. The auditory filter forms at center frequencies of 0.8, 1.6, and 3.2 kHz were calculated using a notch-noise masking paradigm, and auditory filter bandwidth was determined. The findings demonstrated minimal association between the auditory filter bandwidth at different frequencies and the speech reception threshold for unsmeared speech.

Glasberg et al. (1984) used the notched noise method to evaluate the auditory filter's shape and asymmetry over a greater dynamic range. Two 800 Hz wide noise bands' thresholds for 2 kHz sinusoidal signals were examined. The signal frequency was surrounded by noise bands that were both symmetrically and asymmetrically positioned, with a noise spectrum level of 45 dB (re: 20 μ Pa). In six people, ages 22 to 74, it was discovered that the auditory filters varied between patients and had some degree of asymmetry, with steeper slopes on the high-frequency side.

Spectral resolution can be assessed using detection (Litvak et al., 2007) or discrimination (Supin et al., 1998) tasks. (Litvak et al., 2007) measured spectral detection thresholds on ten normal hearing subjects to evaluate the spectrum resolution abilities using two intervals, two alternatives forced-choice approach. The signal contrast level was decreased after three straight correct responses and increased after one incorrect answer. After three reversals in the adaptive track, the contrast was modified with a step size of 2 dB, which was then decreased to 0.5 dB (Levitt, 1971). The modulation detection thresholds were determined using this approach for the modulation frequency of 0.25 and 0.5 cycles/octave, and the spectral resolution indicator was the average of the thresholds for the two modulation frequencies. In other words, identifying ripples was accomplished by determining the minimal spectral modulation depth (in dB) that may be detected, adaptively varying the spectral modulation depth, and keeping a consistent ripple density throughout each run.

In the spectral ripple detection test, on the other hand, the listener was required to say which of the stimuli was distinct. A discriminating task was conducted between a target and a reference stimulus with a constant ripple density (Supin et al., 1998). Each noise burst, lasting 4 seconds, was spaced 0.5 seconds apart. The first and third bursts had phase reversals, but neither the second or just the second burst. These two interval types were randomly switched. The listener was responsible for reporting whether the adjustments appeared in the first, third, or second bursts.

Won et al. (2007) measured spectral discrimination abilities using speech perception in noise in 29 CI users. The stimulus utilized to produce the rippling noise stimuli consisted of 200 pure-tone frequency components. The component amplitudes were calculated using full-wave rectified sinusoidal 18 envelopes with evenly spaced ripple peaks on a logarithmic amplitude scale. The stimuli were produced with a peak-to-valley ratio of 30 dB and a 100-5,000 Hz bandwidth. For each participant, a different beginning phase of 65 dBA was used. The ripple stimuli included 14 distinct densities (in RPO). The ripple phase-reversed test stimulus phase was adjusted to π / 2, while the full-wave rectified sinusoidal spectral envelope for the reference stimuli was set to zero radians. The 150 ms rise/fall timings were scaled into the 500 ms long stimulus. A two-up, one-down adaptive approach with a three-interval forced choice was used to obtain the ripple resolution threshold. The participants had to determine the difference between the test and reference stimuli. Speech perception in noisy abilities was compared with the ripple resolution thresholds. To evaluate participants' ability to interpret speech, a spondee word list and two types of background noise—two-speaker babbling and steady-state noise were utilized. The strong association between spectral-ripple thresholds (RPO) and speech reception thresholds (dB SNR) in noise established evidence for the link between spectral resolution skills and speech perception in noise. The researchers concluded that spectral ripple discrimination would be a faster, non-linguistic method for assessing someone's understanding of speech in quiet and loud situations.

Anderson et al. (2011) compared the spectral ripple detection task in individuals with normal hearing and CI listeners. They noted that spectral ripple was seen at stimulation rates greater than predicted, suggesting that temporal-envelope cues may have been involved at higher rates and given rise to spectral cues. The research showed a significant correlation between speech recognition and ripple detection.

Spectral ripple discrimination is the ability for spectral ripple detection or discrimination utilizing a wide-band noise carrier modified with a sinusoidal function to produce spectral ripples (Resnick et al., 2020). Ripple density or spectral modulation rate is the sum of the number of ripples for linearly spaced and the number of ripples per octave for logarithmically spaced ripples. The highest ripple density at which the ripples can be differentiated or identified helps assess spectral resolution capabilities (Henry et al., 2005; Supin et al., 1994; Won et al., 2007). The Spectral Ripple Test (SRt), which includes a discriminating task, measures the target's maximum ripple density at which the tasks may be accomplished at a spectral modulation depth.

Azadpour and McKay (2012) measured spectral resolution abilities in eight post-linguistically deafened CI listeners. Spectrally flat and spectrally peaked pulse train stimuli were created by linking pulses on 11 electrodes. The psychometric functions between peaks and flat stimuli (in percent accurate discrimination) and the separation between peaks and valleys were measured on eight subjects. Strong correlations were seen between the peak electrode measurements of current level differential limens and spectral resolution capabilities. Spectral resolution capability, however, was not associated with the capacity to recognize sentences or phonemes in quiet background noise. Additional confusing cues with higher thresholds may include spectral centroid (the weighted mean frequency), loudness, and altering energy at the spectral boundaries of the stimulus.

Aronoff and Landsberger (2013) laid out a method using a modified version of the Spectral Ripple threshold (SRt) called the spectro-temporal modulated ripple test (SMRt). They used a method where the phase of the spectral modulation altered with time. SRt and SMRt used a wide band carrier to analyze the data over a wide range of frequencies (Drennan et al., 2014; Henry et al., 2005; Won et al., 2007). The SMRT adjusted the target stimulus's ripple density through an adaptive mechanism, rendering the listener unable to tell the difference between the target and reference stimuli. Each stimulus onset and offset were 500 ms-long linear ramps with a 44.1 kHz sampling rate. A nonharmonic tone complex of 202 equal-amplitude pure-tone frequency components spaced every 1/33.334 octave between 100 and 6400 Hz served as the stimulus. The SMRT stimulus was generated using the following formula:

$$S\,(t) = \sum_{i=1}^{i=202} P(\mathrm{i}) \times \left(\left| D \times sin\left[\frac{i \times RD \times \pi}{33.333} + (RR \times \pi \times t) + \varphi \right] \right| + D \right)$$

where, S is the SMRT stimulus, P is the intensity of the pure tone associated with index i (e.g., 100 Hz for i = 1, 102.1 Hz for i = 2, etc.), t is the duration, RD is the ripple density determined by the number of ripples per octave (RPO), and *φ determines the phase of the ripple at the onset of the stimulus, RR is the ripple repetition rate, indicating the number of times the ripple pattern repeats each second, and D scales the modulation depth of each ripple as it is feasible to utilize this equation to produce* *stimuli that test temporal resolution by altering RR instead of RD, as only RD and φ are altered across stimuli to test spectral resolution for the SMRT.*

The SMRT consists of a three-interval forced-choice task and a reference stimulus containing 20 RPO in two periods. With a starting RPO of 0.5 and a step size of 0.2 RPO, A one-up/one-down adaptive technique is used to change the target stimuli. For each target and reference stimulus, φ is randomly chosen from one of four values: 0, p/2, p, and 3p/2. Ten reversals later, the exam was over. The average of the past six reversals is used to define thresholds. RR is set at 5 Hz, and D is 20. At a distance of one meter from the listener's head and ear level, the speaker delivers the stimuli at a loudness of 65 dB(A).

The SMRT was used to evaluate participants with normal hearing (NH), while a vocoder was used to alter the number of available spectral channels systematically. It was done to show how sensitive the SMRT is to changes in spectral resolution. The stimuli were vocoded. To create pre-emphasis, the stimuli were first high-pass filtered at 1200 Hz with a 6 dB per octave roll-off. The number of spectral channels for each ear was then decided using one, four, eight, or sixteen bandpass filters. Every time, the bandpass filters, which employed fourth-order Butterworth filters with forward filtering, covered the same frequency range, 200 Hz to 7 kHz. Greenwood's (1990) equation was used to develop filters to sample uniformly spaced frequency ranges along the cochlea, and the output of all channels was then added. Arnoff and Landsberger concluded that the spectral ripple tests are quick and sensitive to assess the spectral resolution in listeners with normal hearing and hearing loss.

Henry et al. (2005) stated that spectral ripple thresholds correlate well with vowel, consonant, and word recognition, and speech recognition in noise (Ho Won et al., 2010; Won et al., 2007) found superior ripple discrimination abilities positively associated with music perception. (Moore, 1985) stated that the deterioration in spectral resolution may lead to a reduced ability to discriminate the frequency-related changes in a complex signal and, in turn, reduce speech understanding. These deficits are more likely to happen in individuals with sensorineural hearing loss, which affects the cochlea (Florentine et al., 1980; Moore, 1985; Pick et al., 1977; Zwicker et al., 1982).

Narne et al. (2016) used smeared and unsmeared STRt stimuli. The ripples are smeared when the modulation is applied over a wide range of frequencies over a longer time. In unsmeared ripples, modulation is over a narrow frequency range for a short time. Their investigation showed that individuals with normal hearing gave contradictory information about the amplitude modulation with rate R that appeared at the outputs of auditory filters for unsmeared stimuli. According to this theory, they were situated above the upper edge frequency and below the lower edge frequency of the stimulus. In order to reduce the STRn stimuli, they also advised introducing notched noise above the higher edge frequency and below the lower edge frequency. However, further studies by (Narne et al., 2018) proved that the addition of notched noise to remove the confounding cue would limit the utility of the stimulus to assess individuals with poor frequency resolution, such as those with cochlear hearing loss and cochlear implantees, as the added noise may limit their performance on the test and might provide undesired masking.

Narne et al. (2018) suggested the use of spectral ripples with the same ripple density, D (in ripples per octave or RPO), that varied in their direction of ripple glide, i.e., forward glides and backward glides can also avoid confounding cues that affected spectral ripple discrimination thresholds. This test was termed STRtdir, where 'dir' referred to the direction discrimination. Although the stimuli had amplitude fluctuations, the authors claimed that the same would not be a confounding cue since both upward and downward glides had similar fluctuations. They thus suggested using STRtdir stimulus would be applicable in assessing individuals with cochlear hearing loss and cochlear implant users.

Narne et al. (2019) studied the impact of the temporal repetition rate R on the internal processing and detection of spectro-temporal ripple stimuli. The highest ripple density, D, was determined at which it was possible to distinguish between upward and downward gliding ripples. The stimulus was created precisely as (Narne et al., 2016) specified. The findings demonstrated that thresholds for R from 2 to 8 Hz varied considerably, with a median threshold of just over five ripples/oct. When R was raised to 16 and 32 Hz, it was discovered that the thresholds were worse. Therefore, they proposed that lower values of R could be responsible for the auditory system's poor temporal resolution. Identifying a brief tone at a peak or a valley in the stimulus spectrum enables researchers to study how the brain processes inputs with static and downward-gliding spectral ripples. Thresholds were often more significant during a signal peak than during a signal trough. It was found that when D increased, the peak-valley disparities were reduced. They also found that D varied more for small R values than for large R. Based on these observations, the authors proposed that temporal resolution significantly affects the ability to distinguish between spectro-temporal ripples at lower ripple rates, up to 4–8 Hz, and at higher rates.

Narne et al. (2020) measured the spectro-temporal direction discrimination thresholds using narrowband and broad-band noise carriers. The stimuli were developed as proposed by (Narne et al., 2016), with the value of R kept constant at 5Hz (Narne et al., 2018). The stimuli for narrow band spectro-temporal direction discrimination (NB-STRn) were shown with pink noise that had been bandpass filtered between 125 Hz and the lower edge frequency of NB-STRn at a level 30dB over the threshold of the corresponding frequency of the pure tone. The center frequencies of NB-STRn included 500, 1000, 2000, and 4000 Hz. The procedure to obtain the spectro-temporal direction discrimination thresholds was identical to that of (Narne et al., 2018). Thus, the thresholds were correlated with Q10 values obtained at 500, 1000, 2000 and 4000Hz. The findings showed a strong correlation between the Q10 values at a given signal frequency and the thresholds achieved using narrowband stimuli (NB-STRn), demonstrating the usefulness of NB-STRn stimuli as a measure of frequency resolution. This provides a frequency-specific method for obtaining spectral resolution measures using a spectro-temporal direction discrimination test.

However, while reviewing these studies, we found that the stimulus generated in all of these studies had logarithmically spaced ripples. The log-spaced ripples need not necessarily represent the non-linear functioning of the basilar membrane. As these ripples measure the spectral resolution of the cochlea, a better representation might be by using ripples spaced on an equivalent rectangular bandwidth (ERB) scale. ERB-spaced ripple better represents an auditory filter shape than a logarithmic scale. Thus, in the present study, the spectral resolution was measured using the STRt-NBN test, where the ripples were placed as per ERB spacing, and the results were compared with the STRt-NBN test with logarithmically spaced ripples and correlated with that of PTCs.

ERB-spaced and log-spaced filters are two common approaches for defining the center frequencies of these filters. ERB-spaced filters were designed to replicate the frequency analysis similarly to the human auditory system. The ERB scale approximates the auditory filter bandwidth in psychoacoustics at multiple frequencies. The non-linearity of the human ear is taken into account in ERB-spaced filters. Auditory filters in a non-linear filter have an increasing bandwidth with frequency, meaning that they are broader at higher frequencies and smaller at lower frequencies. Various auditory processing tasks use this filter, e.g., in cochlear implant signal processing, coding audio signals, and another psychoacoustic research. It provides a reasonable representation for modelling auditory perception and explaining how our ears perceive different frequencies.

Log-spaced auditory filters are another way of describing the same concept. The auditory system does not linearly perceive frequency; instead, it perceives ratios of frequencies. By equally spacing filters throughout a logarithmic frequency spectrum, log-spaced filters consider this. This reflects the fact that, regardless of the beginning frequency, doubling a frequency corresponds to a constant interval of perceived pitch. The use of log-spaced filters is essential for accurately representing auditory perception. It aligns with how we perceive musical pitch and distinguish between different frequencies in a way that matches our subjective experience.

The non-linear spacing in the ERB filtering corresponds more closely to how the human ear perceives frequency differences, giving more resolution in lower frequencies and broader resolution in higher frequencies. Log-spaced filters are spaced evenly on a logarithmic scale. This spacing aligns with our perception of pitch based on frequency ratios, not absolute differences. Log filters are more evenly spaced in terms of perceived pitch, but they do not account for the varying bandwidths of auditory filters in the same way as ERB filters. Thus, ERB filters provide a more accurate representation of how the human auditory system processes sound. They capture the varying sensitivity of the ear to different frequencies and are particularly useful for tasks that involve detecting and discriminating between frequency components in complex sounds. On the other hand, log-spaced filters reflect the logarithmic nature of pitch perception; they might need to adequately depict the auditory system's non-uniform frequency resolution. As a result, their use is less common than that of ERB filters.

CHAPTER 3

METHODS

3.1 Research Design: Standard Group Comparison.

3.2 Subjects:

Thirty subjects within the age range of 25-45 years were randomly selected for the study. The participants were divided into two groups: Group 1 with normal hearing sensitivity (n = 15) and Group 2 with mild-moderate cochlear hearing loss (n= 15). Table 1 shows the demographic details of the subjects of both groups.

3.2.1 The subjects were selected based on the following criteria:

- All the subjects were native speakers of the Kannada language and could read and write Kannada.
- The pure tone hearing thresholds of all the subjects of group 1 were less than or equal to 15 dB HL in octave frequencies between 250-8000 Hz, in both ears. Group 2 subjects had pure tone thresholds within 26-55 dB HL, with air-bone gap ≤ 10 dB at 0.5, 1, 2 and 4 kHz frequencies in both ears. The pure tone audiometry was done using a modified Hughson-Westlake method for threshold estimation per ANSI S3.21 (2009) guidelines. Table 1 shows the pure tone average (PTA; average of thresholds at 0.5, 1, 2 and 4 kHz frequencies) of the subjects of both groups. Figure 3.1 shows the mean audiogram of subjects of group 1 and group 2.
- Speech recognition thresholds (SRT) were within ± 6 dB of PTA, and speech identification scores (SIS) of greater than 90% were noted for all subjects. The SRT and SIS were measured using standardized material following the procedure described by the American Speech-Language-Hearing Association (1988),

separately for each ear. Table 1 shows the SRT and SIS scores of subjects of both groups.

- Transient evoked (TE) OAEs were measured using a calibrated OAE meter **(**ILOv6 Echoport, Otodynamics Ltd, UK) for frequencies ranging from 0.5 to 4 kHz. The amplitude of the TEOAE was 6 dB above the noise floor at a minimum of three consecutive frequencies in both ears for the subjects of group 1. Group 2 subjects had absent/elevated TEOAE amplitude.
- All the subjects had an 'A' type of tympanogram. The presence of acoustic reflex in 0.5, 1, and 2 kHz frequencies for subjects of group 1, elevated/absent for subjects of group 2. Tympanogram was classified based on the standard criterion (Feldman, 1976; Jerger, 1970; Lidén et al., 1974). Immittance testing was carried out using a calibrated immittance meter (Titan, Interacoustics Inc., Denmark).
- None of the subjects was at risk of any auditory nerve pathology, measured using the supra threshold adaptation test (J. Jerger & Jerger, 1975) at 0.5, 1, and 2 kHz frequencies.
- The subjects with a recent history of middle ear pathology (last six months), history or present complaint of any related neurological, psychological, behavioral, or systemic illness, history or present complaint of tinnitus, vertigo, or other auditory-vestibular problem, progressive/ degenerative neurological conditions, history or present complaint of sudden sensorineural hearing loss, or with uncomfortable loudness levels less than 90 dB HL, were initially excluded from the testing.

All subjects were randomly selected from the audiology outpatient department of AIISH using a purposive sampling method. The subjects willing to volunteer for the study without any condition and signed an informed consent in compliance with the study protocol, were selected.

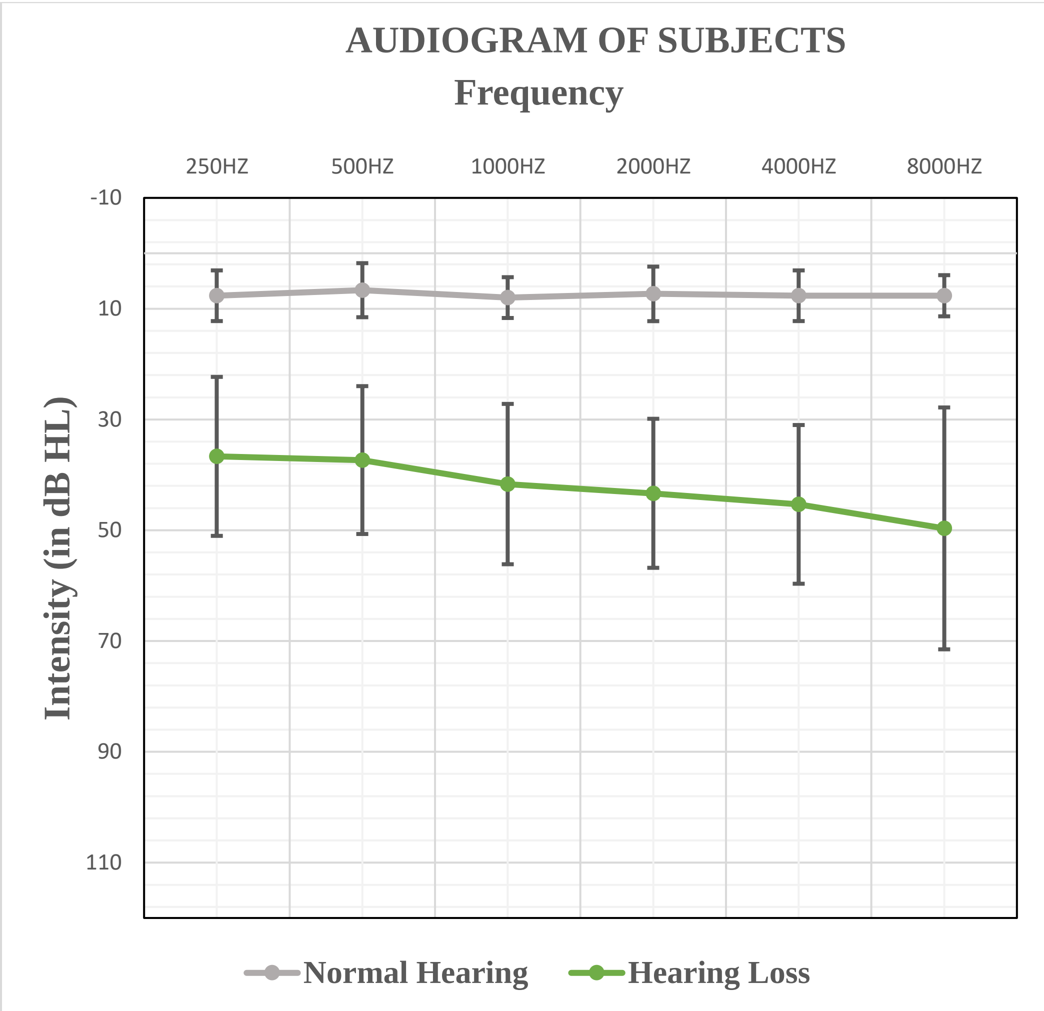
Table 3.1

The demographic details and the hearing thresholds of the subjects of both groups.

No. of participants	Group 1		Group 2	
	Right Ear	Left Ear	Right Ear	Left Ear
Number of Subjects (Males + Females)	15 (9 females + 6 males)		15 (8 females + 7 males)	
Age (in years)				
Mean	31.00		38.4	
SD	3.38		6.56	
Range	25-36		25-45	
PTA (in dB HL)				
Mean	7.5	7.33	44.30	43.92
SD	3.6	2.67	11.651	12.71
Range	2.5-13.75	2.5-11.25	26.25-58.75	22.5-57.5
SRT (in dB HL)				
Mean	9.33	8.73	46.00	46.33
SD	3.71	2.89	12.71	12.32
Range	05-15	05-15	25-65	25-60
SIS (in %)				
Mean	97.60	97.33	93.87	94.40
SD	2.52	2.47	6.74	7.53
Range	90-100	90-100	80 – 100	80 – 100
MCL (in dB HL)				
Mean	46	45	77.67	78.67
SD	4.71	4.63	9.68	10.08
Range	40-55	35-55	60-90	60-90
UCL (in dB HL)	>100	>100	>90	>90

Figure 3.1

Mean pure tone audiometry thresholds across frequencies for subjects with normal and hearing loss, and Error bars showing the Standard Deviation ear taken for testing of 30 participants.



3.3 Estimation of STRt thresholds:

3.3.1 Stimulus:

3.3.1.1 STRt-NBN-ERB Spaced: The STRt-NBN-ERB spaced stimuli were generated by following the procedure described by (Narne et al., 2016):

- A narrowband carrier of 500, 1000, 2000, and 4000 Hz center frequency was generated at a sampling frequency of 22050 Hz.

- The bandwidth of the carrier was calculated using the formula

$$ERB(f) = 24.7\ (4.37\ f + 1)$$

where f is in kHz and ERB is in Hz.

- 201 equal amplitude sinusoidal frequency components were superimposed on the carrier.
- The duration of the stimulus was 750 ms with 100 ms cosine squared onset and offset ramps.
- The STRt stimuli, as a function of time, is defined as:

$$STRt\ (t) = \sum_{i=1}^{i=201} (P(i)/201) * 10^{d(|\sin \pi Rt + 0.03 i \pi D + \theta 2| - 1)/20}$$

where,

$$P(i) = Sin 2\pi fc\ (i) t +\ \theta 1$$

fc = carrier frequency

P(i) = i^{th} component of carrier frequency

Θ_1 = starting phase and Θ_2 = ending phase of ripple

R = ripple rate in ripples per sec

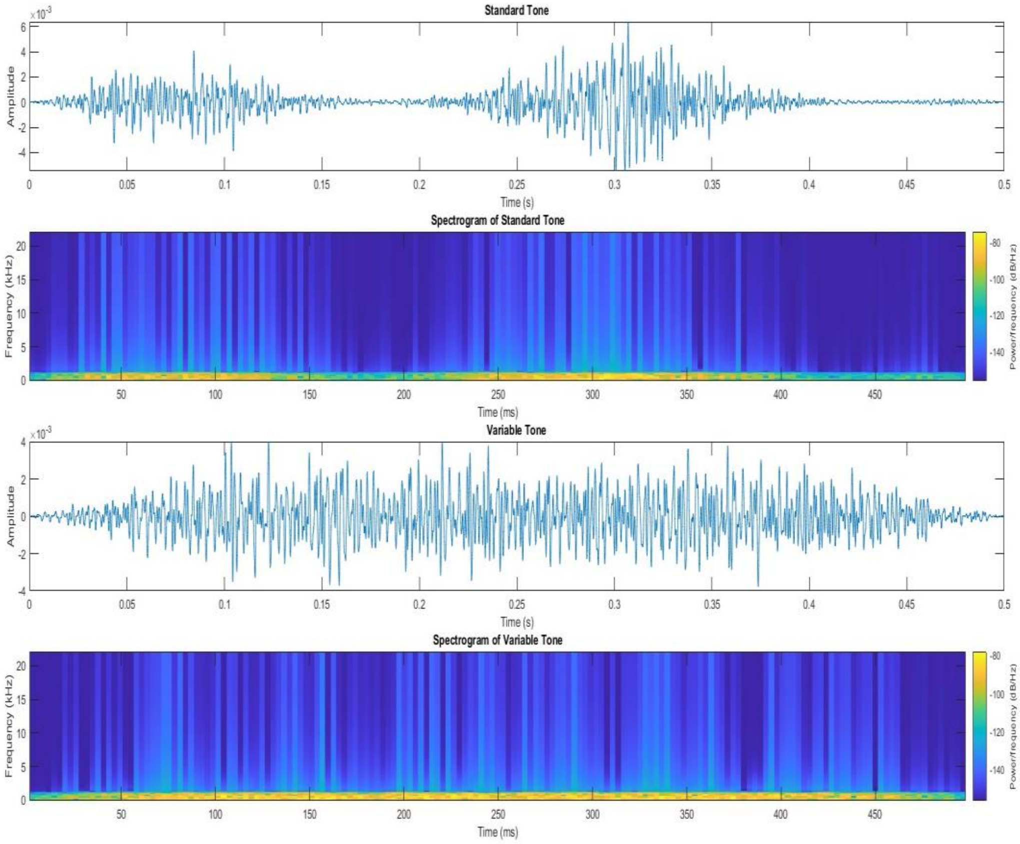
D = ripple density (in ripples per octave)

d = ripple depth

- The stimuli were presented at a repetition rate, R=5 Hz (Narne et al., 2018). and at a level of 25-30 dB above the threshold of all center frequencies (Narne et al., 2018). Fig 3.2 represents the waveform and spectrogram of STRt-NBN ERB spaced ripple stimuli.

Figure 3.2

Waveform and spectrogram of a sample standard tone and a variable tone used in STRt-NBN-ERB spaced ripples.



3.3.1.2 STRt-NBN-Log spaced: The stimuli were generated the same as described above, but the carrier frequency was logarithmically spaced using the formula:

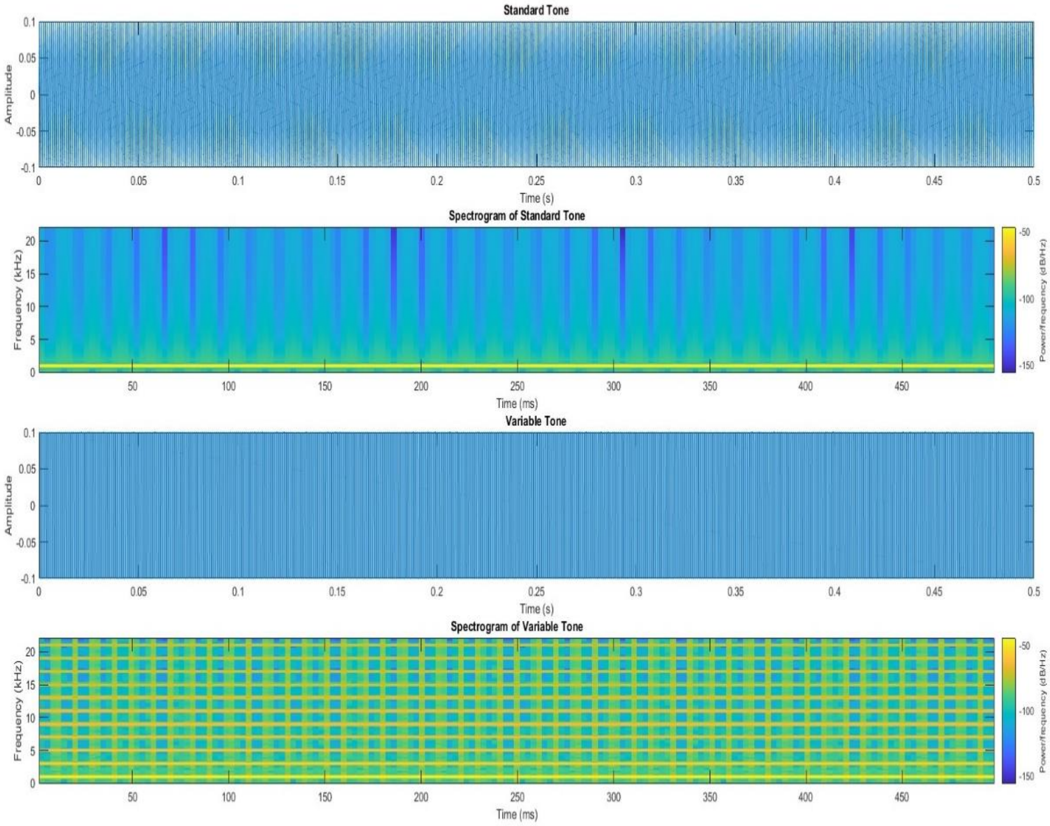
$$CB = 25 + 75\,(1 + 1.4f^2)^{0.69}$$

Where CB is the bandwidth in Hz, and *f* is the frequency of the carrier signal in kHz.

The entire stimuli were generated using a signal processing toolbox in Matlab.

Figure 3.3.

Waveform and spectrogram of a sample standard tone and a variable tone used in STRt-NBN-Log spaced ripples.



3.3.2 Procedure:

- STRt-NBN thresholds were estimated using a three-alternative forced-choice (3-AFC) procedure.
- Two intervals contained standard stimulus with a ripple density of 20 RPO.
- The ripple density in the target interval was initially at 0.5 RPO and was modified using a two-down, one-up staircase procedure.
- The step size was initially 0.5 RPO and was decreased to 0.1 RPO after two reversals.

- A customized platform was developed in Matlab to present the stimuli and record the responses.

3.3.3 Responses: The participants were instructed to listen to the stimuli carefully and identify which of the three alternatives differs from the other two. They were asked to press the buttons labelled 1, 2, or 3 on the numerical pad of the keyboard if they found alternative 1, 2, or 3 was different from the other two, respectively.

3.3.4 Scoring: With each correct response, the RPO in the subsequent trial was reduced, and with each incorrect response, the RPO in the subsequent trial was increased, following the two-down, one-up staircase procedure. The arithmetic mean of the last six reversals was taken as the threshold.

3.3.5 Practice Trials: Five practice trials were given at the beginning of the test.

3.4 Measurement of PTCs:

3.4.1 Stimulus:

- Signal: The pulsed sinusoidal tone of 200 ms duration (20-ms rise-fall time) with an interval of 200 ms between pulses was presented 10 dB above the absolute threshold. The signal frequencies were 500, 1000, 2000, and 4000 Hz.
- Masker: The masker of narrowband noise with a bandwidth that reduces the salience of beats as a cue while limiting the masker bandwidth to be close to the value of ERBn at that center frequency (Kluk & Moore, 2004, 2005) was used.

3.4.2 Procedure:

- PTCs were measured using a "fast" method that employs a slowly swept masker in center frequency from a low to a high value or vice versa (Sęk et al., 2005; Sęk & Moore, 2011).

- The noise level required to mask the signal was determined as a function of the masker center frequency, *fc*, using a procedure similar to that used in Bekesy audiometry. The masker's starting level was 50 dB SPL for the normal hearing participants and 70 dB SPL for the participants with cochlear hearing loss.

3.4.3 Responses:

- The subjects were instructed to press the spacebar on the keyboard when the signal was audible and release the spacebar when the signal was inaudible.
- The level of the noise was varied at a rate of 2 dB/s. Practice trials were provided.
- Two PTCs were measured for each signal frequency: one with an upward and one with a downward masker sweep.

3.4.4 Scoring:

- The sharpness of the PTCs was quantified by estimating Q10, which is the signal frequency divided by the bandwidth 10 dB above the level at the tip.
- For each signal frequency, the Q10 value was estimated separately for the upward and downward sweep, and the two estimates were averaged.

3.5 Test Environment and Equipment:

The entire experiment was conducted in a sound-treated room designed per ANSI specifications (ANSI, 2013). The entire stimuli were generated using “Matlab” and presented using the AFC procedure in “Matlab”. PTCs were measured using Fast PTC software (Sęk & Moore, 2011). The testing was carried out using Seinheiser-HD-206 headphones connected to a laptop. The output of the headphones was calibrated using the sound level meter.

3.6 Statistical Analysis:

Statistical analysis was carried out to compare the STRt-NBN-ERB, STRt-NBN-Log, and PTCs between individuals with normal hearing and cochlear hearing loss and then STRt-NBN-ERB and STRt-NBN-Log test thresholds were correlated with the PTCs.

The normalcy distribution of data was done using Shapiro-Wilk’s test. for normally distributed data the between-group comparison was done using an independent sample t-test. For non nor distributed data the between-group comparison was done using the Mann-Whitney U test and within within-group comparison was done with Wilcoxon signed rank. The PTC was correlated with STRt-NBN thresholds using Pearson’s product-moment correlation.

CHAPTER 4

RESULTS

The present study aimed to measure the spectral resolution using the STRt-NBN test with ERB and Log-spaced ripples in individuals with normal hearing and cochlear hearing loss. The psychophysical tuning curves, which are considered as a standard test for assessing spectral resolution, were measured, each at 500, 1000, 2000, and 4000 Hz center frequencies, and were correlated with spectral resolution. The responses of all participants were tabulated and analyzed using SPSS software (IBM SPSS ver. 26).

The results obtained are discussed under the following headings:

1. Comparing the spectral resolution abilities using STRt-NBN stimuli with ERB-spaced ripples in individuals with normal hearing and hearing loss.
2. Comparing the spectral resolution abilities using STRt-NBN stimuli with logarithmically spaced ripples in individuals with normal hearing and hearing loss.
3. Comparing the psychoacoustic tuning curves in individuals with normal hearing and hearing loss.
4. Comparing the spectral resolution thresholds obtained for STRt-NBN-ERB spaced with that of STRt-NBN-Log spaced stimuli in individuals with normal hearing and hearing loss.
5. Finding the relationship of spectral resolution thresholds obtained for STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with PTCs.

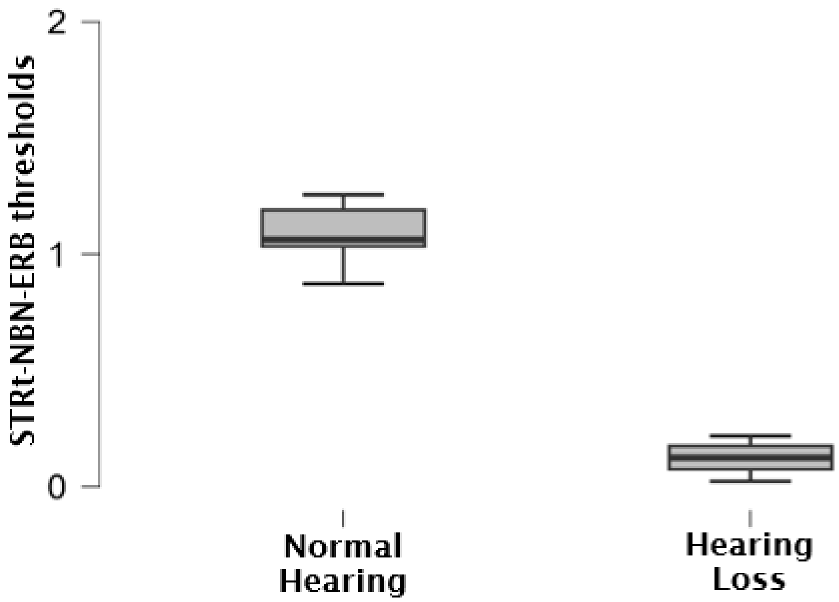
The data was analyzed for normality using Shapira-Wilk's test. The STRt-NBN-ERB and STRt-NBN-Log spaced thresholds did not follow the normal distribution ($p < 0.05$). Hence, the data were subjected to non-parametric tests. The result of the scores the Q10 values obtained for PTC measurement followed the normal distribution ($p > 0.05$). Hence, the data were subjected to parametric tests. The scores for the spectral resolution thresholds obtained for STRt-NBN-ERB spaced with that of STRt-NBN-Log spaced stimuli were compared within the group using the Wilcoxon Sign Ranked test, and between group using the Mann Whitney test. The results of the STRt-NBN-ERB spaced and STRt-NBN-Log spaced test were correlated with PTCs using Pearson's correlation.

4.1. Comparing the spectral resolution abilities using STRt-NBN stimuli with ERB-spaced ripples in individuals with normal hearing and hearing loss.

The mean threshold for individuals with normal hearing was 1.584 (SD = 0.844), whereas that of the individuals with hearing loss was 0.124 (SD = 0.230). The descriptive statistics values are plotted in Figure 4.1. Mann-Whitney U test showed a significant difference between normal and hearing loss individuals for the STRt-NBN-ERB test ($Z = 4.587$; $p < 0.001$; $\eta^2 = 0.668$). The individuals with cochlear hearing loss had poorer thresholds, compared to normal hearing individuals. Hence, the hypothesis stating that there is no effect of hearing measured using STRt-NBN-ERB test was rejected.

Figure 4.1.

The box-and-whisker plot shows the median and quartile range of the STRt-NBN with ERB-spaced ripple thresholds.

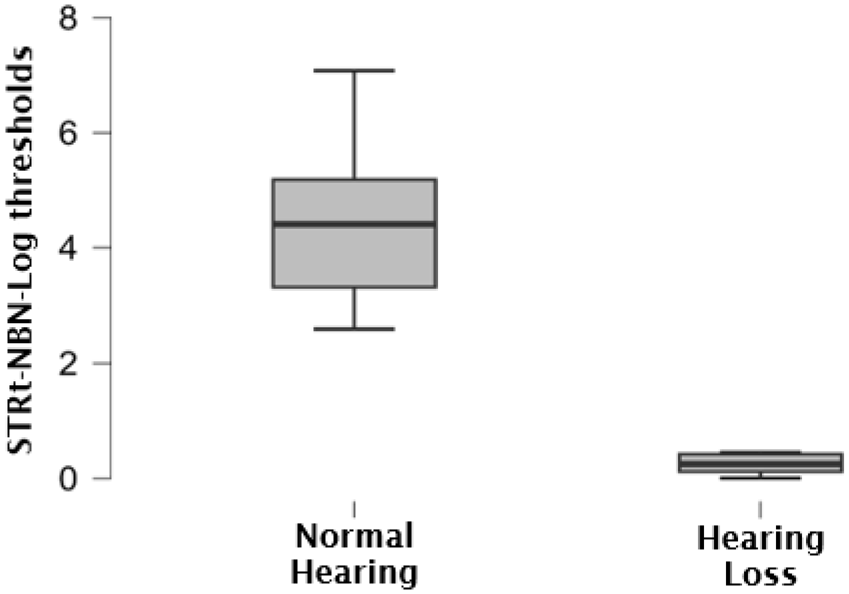


4.2. Comparing the spectral resolution abilities using STRt-NBN stimuli with Log-spaced ripples in individuals with normal hearing and hearing loss.

The mean threshold for individuals with normal hearing was 7.374 (SD = 4.835), whereas that of those with hearing loss was 0.590 (SD = 0.921). The descriptive statistics values are plotted in Figure 4.2. Mann-Whitney U test showed a significant difference between normal and hearing loss individuals for the **S**TRt-NBN-Log test ($Z = 4.543$; $p < 0.001$; $\eta^2 = 0.668$). The individuals with cochlear hearing loss had poorer spectral resolution thresholds, compared to normal hearing individuals. Therefore, with respect to the above findings. Hence, hypothesis stating that there is no effect of hearing loss on spectral resolution measured using STRt-NBN-Log test was rejected.

Figure 4.2.

The box-and-whisker plot shows the median and quartile range of the STRt-NBN with LOG-spaced ripple thresholds.

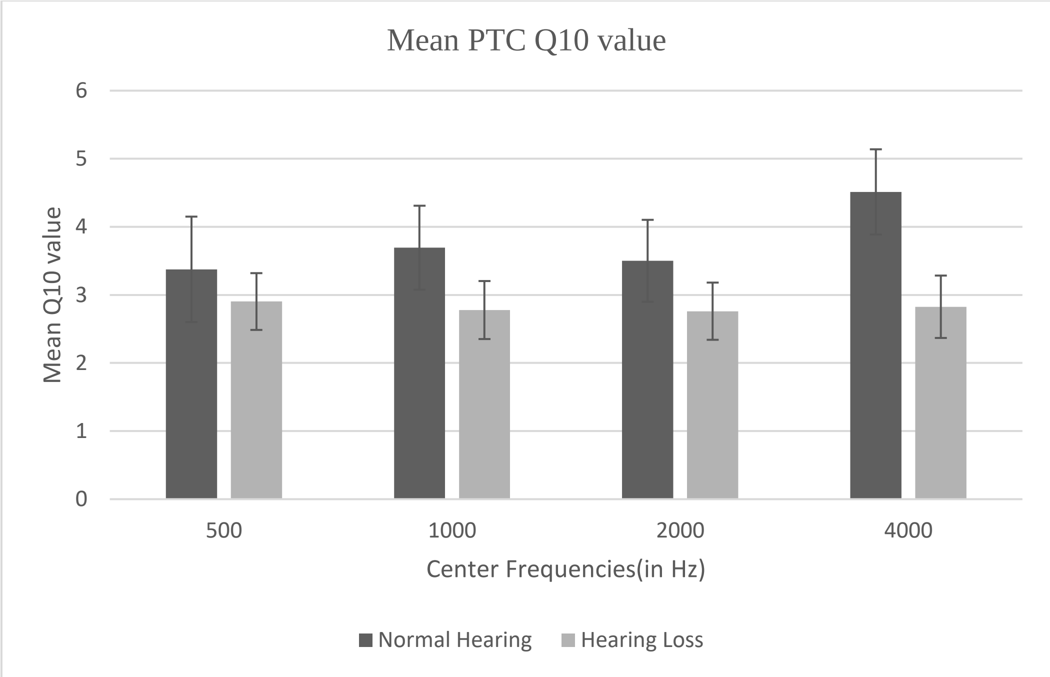


4.3. Comparing the psychoacoustic tuning in individuals with normal hearing and hearing loss.

The mean Q10 values of psychoacoustic tuning curves measured at 500, 10000, 2000, and 4000 Hz frequencies for individuals with normal hearing and hearing loss are plotted in Figure 4.3. The error bars show the standard deviation. As seen from the Figure, the mean Q10 values for individuals with normal hearing were higher than those with hearing loss across all test frequencies. Higher Q10 values indicate sharper tuning curves and better spectral resolution.

Figure 4.3.

Mean Q10 values and standard deviation measured from PTCs across four test frequencies.



The independent sample t-test results showed a significant difference in the Q10 values between individuals with normal hearing and hearing loss for 500 [$t(28) = 2.083$, $p = 0.047$, Cohen's $d = 0.762$], 1000 [$t(28) = 4.728$, $p \leq 0.001$, Cohen's $d = 1.727$], 2000 [$t(28) = 3.906$, $p \leq 0.001$, Cohen's $d = 1.428$] and 4000 Hz [$t(28) = 8.425$, $p \leq 0.001$, Cohen's $d = 3.078$] test frequencies. Consistent with the results of the descriptive statistics, the individuals with hearing loss had poorer spectral resolution abilities than those with normal hearing, as measured using psychoacoustic tuning curves. Thus, the hypothesis there will be no effect of hearing loss on spectral resolution thresholds using PTCs was rejected.

4.4. Comparing the spectral resolution thresholds obtained for STRt-NBN-ERB spaced with that of STRt-NBN-Log spaced stimuli in individuals with normal hearing and hearing loss.

Figures 4.4 and 4.5 show the mean STRt-NBN-ERB and STRt-NBN-Log thresholds for individuals with normal hearing and hearing loss. The mean STRt-NBN thresholds were higher for Log-spaced stimuli than for ERB-spaced stimuli. A higher threshold indicates poorer performance. Within-group comparison was done using the Wilcoxon Signed Ranks test.

Figure 4.4.

The box-and-whisker plot shows the median and quartile range of the STRt-NBN-ERB and STRt-NBN-Log thresholds in normal hearing individuals.

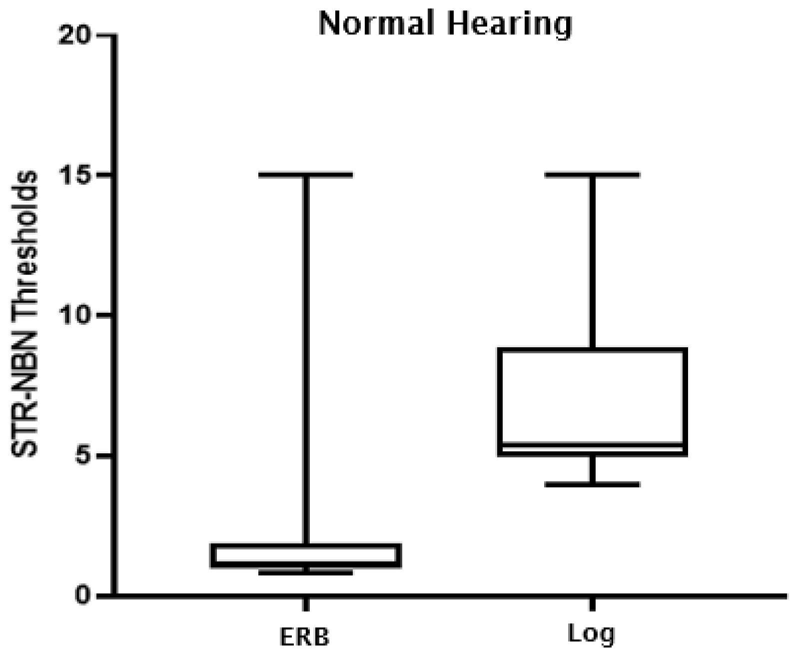
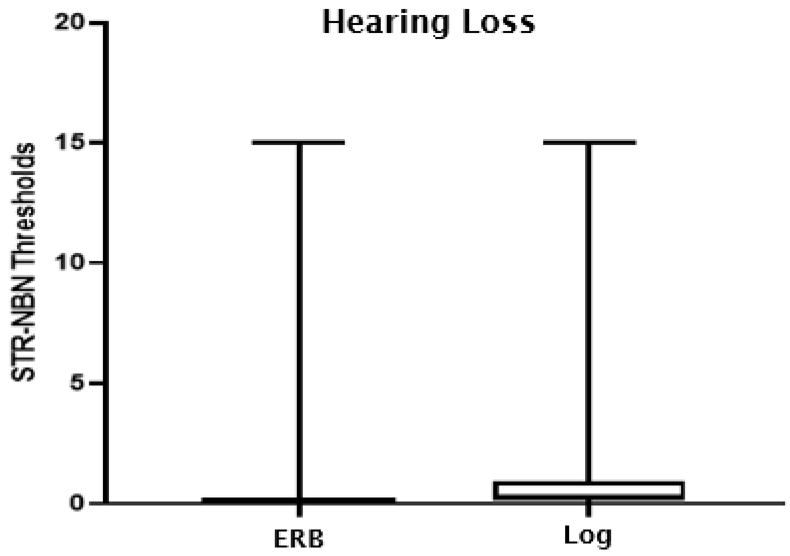


Figure 4.5.

The box-and-whisker plot shows the median and quartile range of the STRt-NBN-ERB and STRt-NBN-Log thresholds in individuals with hearing loss.



The result indicated that there was a significant difference between **S**TRt-NBN-ERB and STRt-NBN-Log thresholds for individuals with normal hearing (Z = 3.408; $p \leq 0.001$; $ŋ^2 = 0.682$) and hearing loss (Z = 3.011; $p \leq 0.001$; $ŋ^2 = 0.687$. The scores were significantly better for ERB-spaced than for Log-space ripples. Therefore, the hypothesis stating that there will be no difference in thresholds obtained in STRt-NBN-ERB spaced stimuli and STRt-NBN-Log spaced stimuli was rejected.

4.5. The relationship of spectral resolution thresholds obtained for STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with PTCs.

The correlation of STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with PTCs was done using Pearson's product-moment correlation. The results indicated that PTCs significantly correlated with the thresholds of STRt-NBN-ERB thresholds at 1000 (r = 0.460' p = 0.010), 2000 (r = 0.396' p = 0.030), and 4000 Hz (r = 0.682' p =

0.000). No significant correlation was seen between 500 Hz PTCs and STRt-NBN-ERB thresholds (r = 0.185’ p = 0.327). Conversely, the correlation of PTCs with STRt-NBN-Log thresholds was seen only for 4000 Hz (r = 0.575’ p = 0.001). These results indicate that the ERB spacing of the ripples in the STRt-NBN test better predicts the spectral resolution abilities than the Log spacing. Therefore, the hypothesis stating that there will be no correlation between STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli was rejected. Table 4.5 shows the correlation values.

Table 4.1

The correlation coefficient and the significance values showing the relationship between STRt-NBN-ERB thresholds with PTCs and STRt-NBN-Log thresholds with PTCs.

	STRt-NBN-ERB		STRt-NBN-Log	
	r-values	p-values	r-values	p-values
PTC 500	-0.185	0.327	-0.287	0.124
PTC 1000	-0.460	0.010	-0.257	0.170
PTC 2000	-0.396	0.030	-0.213	0.258
PTC 4000	-0.682	0.000	-0.575	0.001

CHAPTER 5

DISCUSSIONS

The present study aimed to measure the spectral resolution using the STRt-NBN test with ERB and Log-spaced ripples in two groups of individuals, i.e., those with normal hearing and cochlear hearing loss. The psychophysical tuning curves, considered a standard test for assessing spectral resolution, were plotted, each at 500, 1000, 2000, and 4000 Hz center frequencies. The PTCs were correlated with spectral resolution thresholds obtained for STRt-NBN-ERB spaced, and STRt-NBN-Log spaced ripple perception tests. The results of the study are discussed under the following headings:

5.1. Comparing the spectral resolution abilities using STRt-NBN stimuli with ERB-spaced ripples in individuals with normal hearing and hearing loss.

The study compared STRt-NBN with ERB-spaced ripple test thresholds between normal hearing and cochlear hearing loss groups. (Aronoff & Landsberger, 2013)) first programmed this test as spectro-temporal modulation ripple test (SMRT). They stated that SMRT is an alternative test to assess cochlea's spectral resolution ability. STRt is derived from SMRT. STRt precisely and objectively assesses the ability to resolve spectral and temporal features in auditory stimuli. (Davies-Venn et al., 2015) found that it is sensitive to minimal changes in spectral and temporal cues, thus, is useful for following enhancements or descents in auditory processing over time. Many researchers have gained insights into the mechanisms of auditory perception(Holden et al., 2016; Kirby et al., 2015; H. Zhou et al., 2017) (Holden et al., 2016; Kirby et al., 2015; Zhou, 2017) using this test. It helps in understanding how the cochlea processes complex auditory information (Lawlor, 2018).

Previous researchers have used broadband and narrowband stimuli to measure the spectral resolution in STRt test. Broadband stimuli cover a wide frequency range. (Overath et al., 2012) used the broadband stimuli and found that it measures the overall spectral and temporal modulations, but not specific to certain regions of the basilar membrane. Conversely, narrowband stimuli are of limited frequency range. They are specifically useful for investigating frequency selectivity and the discrimination of fine spectral details (Narne et al., 2020). Such stimuli examine the ability to detect and discriminate spectral ripples within a narrow frequency range. Thus, narrowband stimuli are preferred over broadband stimuli, and hence, used in the present study. The development of the stimuli strictly followed the recommended standard procedures (Narne et al., 2018, 2019, 2020). These test stimuli repeatedly showed consistent results (Isarangura et al., 2019; Jorgensen et al., 2020; Narne et al., 2018). (Narne et al., 2020) found that there is a strong correlation between the Q10 values at a given signal frequency and the thresholds achieved using narrow-band stimuli (NB-STRn), demonstrating the usefulness of NB-STRn stimuli as a measure of frequency resolution.

ERB-spaced and log-spaced filters are two common approaches for defining the center frequencies of these filters. ERB-spaced filters were designed to replicate the frequency analysis, similar to the human auditory system (B. C. J. Moore, 1986). The ERB scale approximates the auditory filter bandwidth in psychoacoustics at multiple frequencies. The Equivalent Rectangular Bandwidth (ERB) scale was used as it closely mimics the non-linear nature of the cochlea's frequency selectivity (B. C. J. Moore, 1986), making it physiologically relevant when modeling auditory perception (Sayles & Winter, 2010). It also accurately represents the processing of sounds in the human ears, especially at lower frequencies (Leschke et al., 2022). ERB-based modeling aligns well with psychoacoustic studies, showing that the auditory system's resolution varies with frequency (Herre & Dick, 2019; Soares et al., 2021; Tass et al., 2019).

The cochlear hearing loss group had significantly poorer thresholds when compared to the normal hearing group. The present study’s findings are consistent with the findings of (Bernstein et al., 2013), who reported that the spectrotemporal modulation gives information on the reduced frequency selectivity associated with hearing loss, negatively impacting modulation sensitivity. (Mehraei et al., 2014) reported that poor spectrotemporal modulation and speech recognition could be due to reduced frequency selectivity and temporal fine-structuring processing.

Sensorineural hearing loss reduces frequency selectivity (Halliday et al., 2019) negatively affecting modulation sensitivity. (Mehraei et al., 2014) stated that individuals with hearing loss have difficulty detecting and processing spectrotemporal modulations. (Leek & Summers, 1996) reported that in individuals with hearing loss, the ability to discern subtle changes in the spectral and temporal aspects of the sounds is the consequence of the reduced frequency selectivity, which hampers the perception of speech and other complex auditory stimuli. Several researchers have highlighted that impaired spectrotemporal modulation sensitivity can serve as a predictor of speech intelligibility in individuals with hearing loss (Bernstein et al., 2013; Casaponsa et al., 2019; Mehraei et al., 2014). This link is essential to understand so that effective intervention strategies and hearing aids can be developed based on the specific needs of individuals with hearing loss. It can be done by enhancing their modulation sensitivity and, consequently, their overall auditory perception.

5.2. Comparing the spectral resolution abilities using STRt-NBN stimuli with Log-spaced ripples in individuals with normal hearing and hearing loss.

The study compared STRt-NBN with Log-spaced ripple test thresholds between normal and cochlear hearing loss groups. Logarithmic scales mimic the human auditory system's sensitivity to sound frequency and intensity changes. Based on Fechner's law, it is often argued that the human perception of pitch and loudness is logarithmic (Urban, 1933). Spectrotemporal ripple stimuli using Log-spaced ripples allow researchers to create stimuli that more accurately represent how humans perceive sound (N. Zhou et al., 2020). Studies related to auditory perception, hearing disorders, and the neural processing of complex auditory signals have used logarithmic scales (Choi et al., 2018; Depireux et al., 2001; Schönwiesner & Zatorre, 2009).

When STRt-NBN-Log thresholds were compared, the cochlear hearing loss group had significantly poorer thresholds when compared to the normal hearing group. Their findings were consistent with those obtained for STRt-NBN-ERB scaled ripples. Log-spaced auditory filters are another way of describing the same concept. The auditory system does not linearly perceive frequency; instead, it perceives ratios of frequencies. By equally spacing filters throughout a logarithmic frequency spectrum, log-spaced filters consider this. It reflects that doubling a frequency corresponds to a constant interval of perceived pitch regardless of the beginning frequency.

5.3 Comparing the psychoacoustic tuning in individuals with normal hearing and hearing loss.

The study compared PTCs Q10 value between normal hearing and cochlear hearing loss groups. The cochlear hearing loss group had a lesser Q10 value when compared to the normal hearing group. The present study observed a significant difference between normal and cochlear hearing loss groups. Psychophysical tuning curves are considered a standard test for spectral resolution ability. When comparing PTCs between normal hearing and cochlear hearing loss individuals, we found that individuals with cochlear hearing loss had broader PTCs and lower Q10 values than the normal hearing group, suggesting that the cochlear hearing loss group had poorer spectral resolution ability.

The Fast PTC method was used in the present study. This technique involves exposing a listener to pure tones of different frequencies mixed with masking noise, either simultaneously or in a forward manner. The goal was to assess the detection or discrimination threshold at each frequency, as described by (Tyler et al., 1984). The determination of PTCs was achieved through a rapid method devised by (Sęk et al., 2005). (Kluk & Moore, 2005) stated that the PTCs yielded consistent results when employing standard and fast-PTC methods among those with normal hearing. The fast-tracking approach proved highly reproducible, particularly for participants with dead regions in their hearing. The resulting curve's shape can offer valuable insights into the cochlea's ability to differentiate between various frequencies, as elucidated by (Florentine, 1992). (B. C. J. Moore, 1978) conducted a study involving five normal listeners, comparing the fast-tracking approach with the conventional PTC method, employing simultaneous and forward masking at different levels and frequencies of test tones. The PTCs obtained through the forward masking paradigm exhibited sharper peaks and steeper slopes when contrasted with those from the simultaneous masking paradigm. Moore and his team concluded that PTCs derived from the simultaneous masking paradigm could be influenced by beats, lateral suppression, and combination tones. Conversely, PTCs acquired using the forward masking paradigm could be better predicter, and hence, used in the present study.

Individuals with cochlear damage show poorer spectral resolution abilities as their auditory filters will be broadened due to the insult in cochlear structures. Studies have shown that individuals with cochlear hearing loss and dead regions had broader, flat, irregular, or inverted PTCs. The present study's findings are consistent with those of (Carney & Nelson, 1983) who found that the tuning curves from the listeners with hearing loss were flat, irregular, broad, or inverted. Tuning curves from listeners with normal hearing were as precise as expected at low SPLs.

Mason et al. (1981) reported that hearing-impaired listeners' PTCs were broader than normal hearing individuals compared to the exact measurements. (Kimberley et al., 1989) found that sensorineural hearing loss listeners had abnormally flat PTCs. (Devi et al., 2022) reported that PTCs were significantly different in individuals with cochlear hearing loss with mild degree and normal hearing individuals, and the Q10 scores were poorer with the elevated tip frequency of PTC. Individuals with cochlear damage show poorer spectral resolution abilities as their auditory filters will be broadened due to the insult in cochlear structures. Studies have shown that individuals with cochlear hearing loss and dead regions had broader, flat, irregular, or inverted PTCs. All the above studies reported that individuals with cochlear hearing loss have poorer PTC, which results in poorer spectral resolution ability, consistent with the present study's findings. The Q10 values obtained in the present study were similar to that obtained by (Devi et al., 2022), indicating that our results are consistent and reliable.

5.4 Comparing the spectral resolution thresholds obtained for STRt-NBN-ERB spaced with that of STRt-NBN-Log spaced stimuli in individuals with normal hearing and hearing loss.

The study compared spectral resolution thresholds obtained for the STRt-NBN test with ERB-spaced ripple thresholds with that of the STRt-NBN test with Log-spaced ripple thresholds in individuals with normal hearing and hearing loss groups. There was a significant difference between the STRt-NBN test with ERB-spaced ripple thresholds and the STRt-NBN test with ERB-spaced ripple thresholds in individuals with normal hearing and cochlear hearing loss groups.

The ERB scale is often better than a logarithmic scale for representing spectral resolution (Biswas et al., 2014), especially in auditory or perceptual analysis. Manley and (Manley & van Dijk, 2016) found that the non-linear frequency resolution of the human ear is more than just logarithmic. If such is the case, the ERB scale better matches the human auditory system perception spectral information (Song et al., 2016). (Young & Smithson, 2014) stated that the ERBs align closely with the critical band, which is not evenly spaced as represented on a logarithmic scale. The ERB scale is often used to model the auditory system's response better while designing audio processing algorithms (Herre & Dick, 2019). It takes into account the speech coding in the auditory system (B. C. J. Moore, 2008), speech processing (Apoux & Healy, 2009), and audio synthesis (Necciari et al., 2018) by more accurately representing how we perceive different frequencies. (Oh & Chung, 2014) found that using the ERB scale can lead to better results in tasks such as speech recognition, sound source localization, and music analysis. It provides a more perceptually relevant representation of spectral content. Auditory masking is also closely related to the ERB scale (Balazs et al., 2012). They stated that the ERB scale could simplify the modeling of auditory masking effects. Sounds within the same critical band can mask each other more effectively than those in different bands. The results of the present study favor the earlier findings of the advantage of ERB-spaced ripples over Log-spaced ripples in the STRt-NBN test for measuring the spectral resolution in individuals with normal hearing and those with hearing loss.

5.5. The relationship of spectral resolution thresholds obtained for STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with PTCs.

The correlation of STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with that of PTCs was done in the study to find the relationship of spectral resolution thresholds obtained for STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with PTCs. The present study observed a significant correlation between the thresholds of STRt-NBN-ERB thresholds with the PTCs at 1000, 2000, and 4000Hz signal frequencies and no significant correlation was seen between 500 Hz PTCs and STRt-NBN-ERB thresholds. Conversely, the correlation of PTCs with STRt-NBN-Log thresholds was seen only for 4000Hz signal frequency. However, the results suggested that the ERB spacing of the ripples in the STRt-NBN test better predicts the spectral resolution abilities, than the Log spacing.

The non-linear spacing in the ERB filtering corresponds more closely to how the human ear perceives frequency differences, giving more resolution in lower frequencies and broader resolution in higher frequencies (B. C. J. Moore, 2008). Log-spaced filters are spaced evenly on a logarithmic scale. This spacing aligns with our perception of pitch based on frequency ratios, not absolute differences. Log filters are more evenly spaced in terms of perceived pitch, but they do not account for the varying bandwidths of auditory filters in the same way as ERB filters. Thus, ERB filters provide a more accurate representation of how the human auditory system processes sound. They capture the varying sensitivity of the ear to different frequencies and are particularly useful for tasks that involve detecting and discriminating between frequency components in complex sounds.

Auditory filters in a non-linear filter have an increasing bandwidth with frequency, meaning that they are broader at higher frequencies and smaller at lower frequencies. Various auditory processing tasks use this filter, e.g., in cochlear implant signal processing, coding audio signals, and other psychoacoustic research. It provides a reasonable representation for modelling auditory perception and explaining how our ears perceive different frequencies.

CHAPTER 6

SUMMARY AND CONCLUSION

Spectral resolution is the ability of the auditory system to differentiate the frequencies of the incoming complex signal and speech. Spectral resolution plays a vital role in speech perception as it decomposes the incoming sound waves into constituent frequencies and analyses the information in those frequencies to perceive speech sounds. One can detect closely spaced frequencies with strong spectral resolution, assisting in picking up minute variations in the speech. The differentiation between frequencies of sound takes place in the cochlea. Travelling waves are produced along the basilar membrane's length as it vibrates. These waves peak at particular locations along the basilar membrane according to the frequency of the entering sound. The fundamental physiology of spectral resolution is as follows.

In recent days, the STRt- NBN test has been one of the promising tests in identifying the spectral resolution of individuals with high accuracy, and the impact of spectral resolution has been assessed in some of the studies. The literature review suggested that individuals with cochlear hearing loss have poor spectral resolution abilities. In a study by (Narne et al., 2020), they found a strong correlation between the STRt-NBN test and Psychometric Threshold Curves (PTCs). However, one potential limitation was their study's use of logarithmic spacing for ripples. To address this limitation, they propose arranging the ripples based on the Equivalent Rectangular Bandwidth (ERB) scale, which better represents the spectral resolution of the cochlea and auditory filters.

The ERB scale is advantageous because it aligns with how the human ear perceives differences in frequency. It offers higher resolution in lower frequencies and broader resolution in higher frequencies, reflecting the non-linear sensitivity of our auditory system. In contrast, logarithmically spaced filters, while suitable for representing perceived pitch based on frequency ratios, do not account for the varying bandwidths of auditory filters as effectively as ERB filters.

ERB filters are precious in tasks involving detecting and discriminating frequency components in complex sounds, such as cochlear implant signal processing, audio signal coding, and psychoacoustic research. They provide a more accurate representation of how the human auditory system processes sound due to their increasing bandwidth with frequency, mirroring the ear's sensitivity to different frequencies.

In the present study, the researchers plan to measure spectral resolution using the STRt-NBN test, where ripples were placed according to ERB spacing. They intend to compare the results with the STRt-NBN test using logarithmically spaced ripples and correlate these findings with PTCs to understand auditory perception and spectral resolution better.

The present study opted for a cross-sectional research study design with standard group comparison. Two groups in the age range of 25 to 45 years were considered in the study. Group I consisted of individuals with normal hearing, and Group II consisted of individuals with cochlear hearing loss. All the participants had undergone testing with STRt-NBN with ERB spaced ripples and Log spaced ripples and PTCs (500Hz, 1000Hz, 2000Hz, and 4000Hz).

The study compared the STRt-NBN with ERB-spaced ripple thresholds between the normal and cochlear hearing loss groups. The cochlear hearing loss group was found to have poorer thresholds when compared to the normal hearing group. It suggests that the cochlear hearing loss group had poorer spectral resolution abilities due to insult to structures in the cochlea.

The study compared the STRt-NBN with Log-spaced ripple thresholds between the normal and cochlear hearing loss groups. The cochlear hearing loss group was found to have poorer thresholds when compared to the normal hearing group. It suggests that the cochlear hearing loss group had poorer spectral resolution abilities due to insult to structures in the cochlea.

The study compared the PTCs with signal frequencies (500Hz, 1000Hz, 2000Hz, and 4000Hz) between the normal and cochlear hearing loss groups. The cochlear hearing loss group was found to have a lower Q10 value when compared to the normal hearing group. It suggests that the cochlear hearing loss group had poorer spectral resolution abilities due to insult to structures in the cochlea.

The within-group comparison was done to check for any significant difference between the groups for the **S**TRt-NBN stimuli with ERB-spaced ripples and **S**TRt-NBN stimuli with LOG-spaced ripples. The result indicated a significant difference for **S**TRt-NBN thresholds obtained with ERB-spaced and Log-spaced ripples for individuals with normal hearing and those with cochlear hearing loss. The STRt-NBN thresholds were higher for Log-spaced stimuli than for ERB-spaced stimuli. A higher threshold indicates poorer performance.

Correlation of STRt-NBN-ERB spaced and STRt-NBN-Log spaced stimuli with PTCs was done. The results found that the STRt-NBN with ERB-spaced ripple thresholds were significantly correlated with PTCs of 1000Hz, 2000Hz, and 4000Hz and did not correlate with 500Hz. Conversely, correlation was found with PTCs and STRt-NBN with Log-spaced ripples at 4000Hz. Therefore, the results suggested that the STRt-NBN test with ERB-spaced ripples predicts the spectral resolution better than the STRt-NBN test with Log-spaced ripples.

6.1 CONCLUSION:

The STRt-NBN test with ERB spaced ripples can better assess the spectral resolution of the cochlea in individuals with normal hearing and hearing loss when compared with the STRt-NBN test with Log spaced ripples. STRt-NBN test with ERB spaced ripple thresholds correlated well with the PTCs. The test can be used to assess the cochlear implant candidacy. It can help assess the patient's ability to perceive and discriminate complex auditory stimuli, essential for cochlear implant success. For individuals who have received cochlear implants, the test can aid in programming the implant. It helps clinicians fine-tune the implant settings to optimize the patient's ability to understand real-world speech and other auditory signals. The STRt-NBN-ERB test can provide insights into a person's auditory processing abilities, precisely their capacity to discriminate between different spectral and temporal features in sound. This information can help diagnose and manage auditory processing disorders. Beyond clinical applications, the test is a valuable research tool. Audiologists and researchers use it to investigate the underlying mechanisms of auditory perception, plasticity, and rehabilitation strategies. It helps advance our understanding of how the auditory system processes complex acoustic information.

6.2 IMPLICATIONS OF THE STUDY:

- Assessment of spectrotemporal resolution helps assess cochlear functioning. Using a wide range of frequencies, this test can help understand the functional implications of cochlear damage.

- Using frequency-specific stimuli, the functioning of the various regions of the cochlea can be specifically examined under ideal conditions. Such a measure has clinical applicability in cochlear implantation to provide tonotopic stimulation across different cochlear regions.
- An Equivalent Rectangular Bandwidth scale spacing better represents the spectral resolution of auditory filters than logarithmically spacing.
- The use of frequency-specific stimuli helps obtain the dead region of the cochlea.

6.3 STRENGTHS AND LIMITATIONS OF THE STUDY:

- The present study is one of the first to compare the spectral resolution using the STRt-NBN with ERB-spaced ripples and LOG-spaced ripples in normal hearing and cochlear hearing loss groups.
- The study proved the efficacy of the STRt-NBN test with ERB-spaced ripples in assessing spectral resolution.
- It is one of the studies that has correlated the STRt-NBN with ERB-spaced ripples and LOG-spaced ripples thresholds with PTCs.
- In the current study, the age range of the individuals could have been taken, and the sample size could have been more than 15 in each group to generalize the findings.

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