COMPARISON OF SPECTRAL PROFILE ANALYSIS THRESHOLD BETWEEN CHILDREN WITH NORMAL HEARING AND WITH COCHLEAR IMPLANTS

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This Dissertation is submitted as part of fulfilment
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SEPTEMBER 2023

CERTIFICATE

This is to certify that this dissertation entitled “**Comparison of Spectral Profile Analysis Threshold between Children with Normal Hearing and with Cochlear Implants**” is a bonafide work submitted as part of fulfilment for the degree of Master of Science (Audiology) of the student with Registration number: P01II21S0081. This has been carried out under the guidance of the faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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This is to certify that this dissertation entitled "**Comparison of Spectral Profile Analysis Threshold between Children with Normal Hearing and with Cochlear Implants** " is a bonafide work submitted as part of fulfilment for the degree of Master of Science (Audiology) of the student with registration number P01II21S0081. This has been carried out under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any other University for the award of any Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled “**Comparison of Spectral Profile Analysis Threshold between Children with Normal Hearing and with Cochlear Implants** ” is the result of my own study under the guidance of Dr.N Devi, Associate Professor in Audiology, Department of Audiology, All India Institute of Speech and Hearing, Mysore and has not been submitted earlier to any other University for the award of any Diploma or Degree.

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ABSTRACT

The ability of the individuals to segregate incoming sounds into separate perceptual streams is called auditory stream segregation. Spectral profiling is an important spectral cue for auditory streaming. Spectral profile analysis test is for assessing the ability of an individual to detect change in spectral profile when amplitude of one of the component of complex tone is changed. In inividuals with hearing impairement the spectral profiling ability will be affected because of the alterations in the mechanism of the basilar membrane and due to increase in the region of excitation along the membrane. Therefore, cochlear implants (CI) which are devices to restore hearing for individuals with hearing loss are expected to re-establish the spectral profiling ability of the individuals. In the present study two groups of participants were included. Group I consist of 15 children with normal hearing and group II consist of 21 children with cochlear implant. The spectral profile analysis test was assessed in two groups using the 'mlp' toolbox, which implements the maximum likelihood procedure in the MATLAB software. The testing was done in four different frequencies (250 Hz, 500 Hz, 750 Hz and 1000 Hz). The result of the study indicates that profile analysis threshold at all four frequencies were significantly poorer in children with cochlear implant than children with normal hearing. The poorer performance in children with CI is suspected to be the result of reduced spectral resolution with cochlear implant.

Keywords: Auditory stream segregation, Spectral profile analysis threshold, Cochlear implants

CHAPTER 1

INTRODUCTION

A natural auditory process of dividing and categorizing the incoming sounds into separate perception streams that takes place every day is called as "auditory stream segregation," "auditory streaming," or "auditory perceptual organisation." (Bregman & Campbell, 1971). An individual with normal hearing, when following the tune played by an orchestral instrument or listening to a party talker, interprets this combination of sounds from several sources as independent sound producers. Sounds that are acoustically similar to one another are regarded by people with normal hearing as coming from a single source. In contrast, sounds that are acoustically dissimilar to one another are perceptually separated and are seen as emanating from different sources. This perceptional grouping may be simultaneous or sequential. The auditory system sequentially groups sounds that happen close together in time. Simultaneous frequency components from the same source are grouped together in simultaneous grouping (Hong & Turner, 2006).

Different stages of processing involved in auditory stream segregation has been examined through various behavioural experiments. According to the peripheral channelling hypothesis, early processing in the auditory periphery is where streaming is mostly centred (Beauvois & Meddis, 1996). Stream segregation may result from acoustic cues based on peripheral coding, such as frequency range and ear of stimulation. Amplification modulation rate (Grimault et al., 2002), timbre (Cusack & Roberts, 2000), pitch, and bandwidth contribute to central coding-based cues that have been found to also contribute to stream segregation.

According to Paredes-Gallardo et al. (2018), auditory scene analysis has been broken down into two main processes: auditory stream integration (the perceptual grouping of different sound events into a single stream) and auditory stream segregation (the perceptual grouping of different sound events into separate streams). Numerous spectral and temporal cues can be used to interpret an auditory scene. Spectral separation and spectral profiling are spectral indicators that aid in analyzing an auditory scene. Temporal separation, ordering, and regularity are some of the temporal cues.

Spectral profiling can be one of the major cues that help in separating auditory streams. It is the ability to detect changes in spectral profile as the intensity of one of a complex tone's components changes. Detecting and perceiving the changes is important for auditory streaming since the pattern of intensity change as a function of frequency, distinguishes the spectra of sound sources. Despite fluctuations in the source output's level, these spectral patterns frequently remain rather stable. Therefore, to do spectral profile analysis, it is essential to analyze the spectral pattern or profile of the source output independently of the overall level (Green, 1983).

Spectral profile analysis experiments typically involve the presentation of two complex sounds, a reference multi-tonal complex with equal amplitude logarithmic frequency-shaped sinusoidal components, and the signal with one component of the same multi-tonal complex that has an increase in intensity (Green & Nguyen, 1988). The spectral shape changes as one of the components is increased, and the task-related psychophysical detection of this spectral shape shift is measured.

Compared to individuals with normal hearing, people with hearing impairment have difficulty comprehending speech in background noise, which involves stream segregation. The possible reason for this is diminished stream segregation abilities (Hong & Turner, 2006). Hong and Turner (2006) investigated auditory stream segregation and the capacity to comprehend speech under conflicting noise in eight individuals with cochlear implants (39–78 years) and found statistically significant connections between these two abilities. Better stream segregation ability enhances speech in noise comprehension. These findings imply that auditory stream segmentation affects speech comprehension in noisy environments. In addition to reduced frequency resolution, which can lead to difficulties in pure-tone auditory streaming and understanding speech in noisy environments, central processes like selective attention also influence auditory stream segregation. These central processes are crucial factors that contribute to one's ability to perceive and comprehend speech in noisy conditions.

Banerjee and Prabhu (2021) conducted a study to assess the ability of individuals with cochlear pathology and auditory neuropathy spectrum disorder (ANSD) to segregate auditory streams. Spectral profile analysis threshold was used for the evaluation. The study revealed that individuals with ANSD and cochlear pathology exhibited lower spectral profile analysis thresholds, indicating poorer performance in auditory stream segregation. Also, the group with cochlear pathology performed better than the ANSD group. The diminished performance in the ANSD group may be attributed to the demyelination of auditory neurons, while in the cochlear pathology group, the loss of outer hair cells at the basilar membrane level could contribute to impaired spectral and temporal processing. Hearing loss also impacts how timbre is perceived, which depends on the spectral and temporal components of sounds. Changes in a sound's temporal envelope or long-term spectral structure may alter the perception of timbre. The frequency selectivity of the ear, which is reduced in those with cochlear damage, is necessary for the spectral shape-related components of timbre perception. This difficulty typically persists even after the sound is amplified to restore audibility.

There are no studies that investigated the effect of amplification using a hearing aid in auditory stream segregation. Hearing aids amplify the signal, but more sophisticated technology, such as multichannel amplification, can improve their stream segregation ability. Cochlear implants (CI) can restore hearing for individuals with severe to profound hearing loss. Cochlear implants convert an acoustic signal into an electrical signal by directly stimulating auditory nerve. The ultimate objective is to re-establish the capacity to perceive speech's frequency (auditory spectral) and timing/amplitude (temporal) components. In most cases, individuals with cochlear implants show better speech understanding and satisfaction with their devices (Holden et al., 2013). However, individuals with CIs are known to have relatively poor spectral resolution (i.e., the spatial spread of cochlear activity) due to limitations in the device's signal processing, the limited number of electrodes placed in the cochlea, and the spread of neural excitation associated with electrical hearing (Boëx et al., 2003).

Also, the challenges in the acoustic environment will be more for children with hearing impairment when compared to adults. To determine if infants could distinguish between different sound sources, McAdams and Bertoncini (1997) studied different acoustic signals, such as timbre, spatial location, and frequency proximity of pure tone and found that infants require significantly larger differences between these acoustic dimensions compared to adults in order for auditory segregation to take place. In contrast, Sussman et al., (2001) suggested that when frequency proximity serves as the cue for segregation, the mechanisms for auditory stream segregation operate similarly in school-going children and adults.

Children spend much of their lives functioning in environments much noisier than those in adult lives. Therefore, children require better stream segregation abilities than adults for adequate speech perception in noise. Only limited studies examine the auditory stream segregation in CI listeners, especially in children. Also, the results of the existing studies show contradictory findings.

Therefore, current study aimed to compare spectral profile analysis thresholds between two groups: children with normal hearing and children with cochlear implants.

1.1 Need for the Study

Appropriate amplification devices play a vital role in speech recognition for individuals with hearing impairment. Amplification devices make sounds audible for them, but their major concern of trouble interpreting speech in noisy environments, continued. Better stream segregation enhances speech in noise comprehension (Hong & Turner, 2006). Therefore, some cochlear implant users may struggle in noisy environments because they cannot execute stream segregation. This challenge in the acoustic environment will be more for children with hearing impairment than adults. Therefore, children require stream segregation abilities than adults for adequate speech perception. Therefore, it’s important to know whether children as CI listeners can stream segregation. Spectral profiling is one of the major cues for stream segregation. Therefore, spectral profile analysis threshold can be used to estimate streaming ability. Limited studies that examine the auditory stream segregation in children with CI and the contradictory findings of existing studies highlight the importance of the current study.

1.2 Aim of the Study

To assess and compare spectral profile analysis thresholds in children with normal hearing and children with cochlear implants.

1.3 Objectives of the Study

The specific objectives of the study are:

1. To assess spectral profile analysis thresholds across 250 Hz, 500 Hz, 750 Hz and 1000 Hz in children with normal hearing.
2. To compare spectral profile analysis thresholds across 250 Hz, 500 Hz, 750 Hz and 1000 Hz in children with normal hearing.
3. To assess spectral profile analysis thresholds across 250 Hz, 500 Hz, 750 Hz and 1000 Hz in children with cochlear implants.
4. To compare spectral profile analysis thresholds across 250 Hz, 500 Hz, 750 Hz and 1000 Hz in children with cochlear implants.
5. To compare the spectral profile analysis threshold between children with normal hearing and children with cochlear implants at the four frequencies.

1.4 Null Hypotheses

1. There is no statistically significant difference in spectral profile analysis threshold across 250 Hz, 500 Hz, 750 Hz and 1000 Hz in children with normal hearing.

2. There is no statistically significant difference in spectral profile analysis threshold across 250 Hz, 500 Hz, 750 Hz and 1000 Hz in children with cochlear implants.

3. There is no statistically significant difference in spectral profile analysis threshold between children with normal hearing and with cochlear implants at the four frequencies.

CHAPTER 2

REVIEW OF LITERATURE

In our day-to-day environment, there are several noises playing simultaneously in the surroundings, coming from several sound sources. Although these noises can blend together, our auditory system can distinguish each sound clearly. This is referred to as the "cocktail party effect". According to van Noorden (1975), the auditory system groups together successive sounds into a single auditory stream when they contain similar acoustic features. The term "auditory integration," " fusion" or "coherence" was used to describe this process. Additionally, multiple auditory streams can be attributed to subsequent sounds when they are dissimilar. Auditory stream segregation, streaming, or fission were terms used to describe this process. Bregman (1990) first used "Auditory scene analysis" to describe how the auditory system separates complicated sound mixtures.

2.1 Auditory Stream Segregation in Individuals with Normal Hearing Abilities

Auditory scene analysis (ASA), the basis for hearing, refers to the ability to segregate sounds from different sources into different perceptual streams and combine sounds from the same source in a single stream. Numerous factors have been discovered influencing auditory stream segregation in people with normal hearing. According to Bregman and Campbell (1971), when the frequencies of two pure tones were closer together, they were interpreted as a single stream and as different auditory streams if they were of very different frequencies. This is because the two auditory stimuli would stimulate two distinct neuronal populations, resulting in two distinct auditory streams. For the perception of two streams with complex tones, the effect of bandwidth and center frequency of noise burst was important (Bregman, 1990). The F0 in complex signals was significantly involved in stream segregation in people with normal hearing (Moore & Glasberg, 2001). Additionally, complex stimuli with resolved harmonics are reported to result in higher stream segregation than complex stimuli with unresolved harmonics (Grimault et al., 2002).

The part of the auditory pathway involved in the auditory streaming mechanism is still unclear. However, certain evidence suggests central cortical (Carlyon, 2004) and peripheral cochlear components (Hartmann & Johnson, 1991) for this streaming ability. According to the "Peripheral Channelling" theory, the degree of overlap between the two stimuli's excitation patterns on the basilar membrane determines how likely the two excitation patterns will be interpreted as a single stream. Hearing impairment can affect the functioning of the basilar membrane, potentially leading to an increased region of excitation along the membrane.Studies have also revealed that in the absence of peripheral cues, centrally encoded cues such as amplitude modulation rate (Grimault et al., 2002), timbre (Cusack & Roberts, 2000), pitch, and bandwidth can also aid in stream segregation.

Furthermore, it is generally accepted that the processing and perception of auditory objects involves the ventral auditory pathway, a network of brain regions that comprises the core auditory cortex, the anterolateral belt region of the auditory cortex, and the ventrolateral prefrontal cortex (Rauschecker & Tian, 2000). The top-down effects can be guided by processes such as memory, expectation, or attention. This effect of central cortical regions for streaming is further determined by studying variances brought on by musical training (Marozeau et al., 2010). Marozeau et al., (2010) developed a novel method to determine the perceptual distance to distinguish a simple four note melody from a background of interleaved distractor notes. The study's findings indicated that participants with musical training relied most on sound intensity as the primary cue for melody segregation. Even a small difference in intensity proved to be effective in achieving melody separation, in contrast to the spectral and temporal envelopes, which had less of an impact. However, both spectral envelope and intensity were equally effective streaming cues for non-musicians. CI users' capacity to stream content is still unknown in relation to auditory cues and their perceptual correlates.

2.2 Auditory Stream Segregation in Individuals with Hearing Impairment

People with hearing loss frequently complain of their inability to distinguish speech in noisy environments. This problem frequently persists even when sounds are enhanced to restore audibility. Reduced frequency selectivity may be a contributing factor, and the inability to assign rapid sequences to the correct sources to create perceptual streams can also be a reason for it (Rose & Moore, 2005).

It is well established that sensorineural hearing loss (SNHL) results in impaired spectro-temporal processing and negatively affects speech comprehension in difficult listening situations. Although loss of audibility is a major factor in the perceptual abnormalities that SNHL patients have, this defect is not the only one that these patients encounter. It has been demonstrated that the challenge typically persists even when sounds are enhanced (amplification devices) to restore audibility (Rose & Moore, 2005).

Antony and Barman (2021) investigated auditory stream segregation in individuals with sensorineural hearing loss (SNHL) using sinusoidally amplitude-modulated signals (SAM). The finding of the study revealed that the SNHL group had impaired stream perception because they were better at distinguishing irregularities compared to the normal hearing group. This discrepancy was likely due to the SNHL group's poorer frequency resolution, causing the A and B stimuli in the AB sequence to overlap in cochlear excitation patterns, hindering proper stream segregation. As a result, individuals with SNHL tended to perceive the AB sequence as a single stream, which made them more effective at detecting irregularities in it than those with normal hearing. Literature also suggests that people with SNHL are unaffected by temporal resolution (Mackersie et al., 2001; Moore, 2007). These results are consistent with the idea that spectral cues play a more crucial role in stream segregation.

The influence of frequency and tone duration on stream segregation in people with normal hearing (control group) and hearing impairment (experimental group) was also examined by Bayat et al., (2013). The Fission Boundary (FB) and Temporal Coherence Boundary (TCB) were assessed to better evaluate stream segregation. The researchers discovered that the experimental group stream segregation was worse than the control group when the frequency changed. It was determined that because of the weak frequency selectivity, reduced streaming ability is obtained in individuals with sensorineural hearing loss.

2.3 Auditory Stream Segregation in Individuals with the Cochlear Implants

When the listener hears naturally or via electrical stimulation, the auditory system's capacity to classify sounds according to their origins is significant and essential. Speech has spectral and temporal properties, which are necessary for an individual to decode for effective communication. While individuals with cochlear implants (CI) typically comprehend speech effectively in quiet settings, non-speech sounds like music require further improvement (McDermott, 2011). There are certain instances of CI users with strong musical aptitudes frequently related to in-depth musical training. Pitch discrimination, timbre discrimination, and auditory streaming ability are three basic abilities that are degraded in unsatisfactory music perception with CIs. Unfortunately, using a CI reduces the acoustic cues that create perceptual distinctions between different sound sources, making it harder for CI users to distinguish between them. As a result, it becomes harder to distinguish between distinct melodic lines, instruments, and voices within a crowd (Marozeau et al., 2013). Also, as the background noise levels rise, speech recognition quickly deteriorates for CI users. The lack of spectro-temporal cues can lead to decreased performance in noisy environments (Fu & Nogaki, 2005). In cases where hearing-impaired (HI) individuals listen to amplified speech, their broader auditory tuning curves may result in reduced spectral resolution, further impacting their ability to discern sounds in complex auditory settings. A number of factors constrain the possible spectral resolution for CI users: (1) the total number of electrodes implanted; (2) the uniformity, health, and proximity of the intact neurons to the implanted electrodes; and (3) the amount of current spreading from stimulating electrodes. The first factor demonstrates the reduced spectral resolution transmitted by the implant device, and the other two describe the amount of spectral information users receive. The effective spectral resolution of CI users may be further decreased when these spectral details are smeared because of electrode interactions (Nejime & Moore, 1997; Nelson et al., 2003).

Fu et al. (2005) conducted a study comparing sentence recognition between cochlear implant (CI) users and individuals with normal hearing, while both groups listened to acoustic simulations of CI in the presence of steady and square wave modulated speech-shaped noise. Regardless of the type of noise, whether it was steady or modulated, CI users experienced a decline in speech recognition in noisy conditions. This decline was attributed to the limited number of electrodes and spectral channels in the speech processing strategy of the CI, which resulted in the loss of spectro-temporal fine structure necessary for effective speech perception in noise. Speech recognition threshold (SRT) was better in individuals with normal hearing than CI users. Only when the shallow filter slopes smeared the spectral cues did NH listeners’ performance become comparable to that of CI users. The results of this study imply that the low spectral resolution and significant spectral smearing brought on by channel interaction may be the primary cause of implant users' reduced performance in the presence of noise (Fu et al., 1998; Friesen et al., 2001).

Cochlear implant recipients must deal with similar listening challenges as people with normal hearing thresholds. The majority of individuals with cochlear implants typically have only one implant and listen monaural. Consequently, they do not have access to binaural cues that could help them perceptually separate concurrent or sequential sounds. Additionally, the depth to which electrodes may be introduced into the cochlea is constrained, which causes an upward shift in frequency energy and additional spectral envelope distortions, including spectral compression (Dorman et al., 1997). Fu and colleagues (1998) investigated vowel and consonant identification in noise using three CI listeners and four simulation listeners with varying numbers of channels. The results reveal that, for a given SNR, the performance of both simulation listeners and actual users declined as the number of channels decreased. More channels were required in noisy situations than in quiet ones to get the best performance out of the subjects. Based on all these factors, reduced streaming capacities in CI listeners are hypothesized. Fusion is more likely to occur due to the wide area of stimulation around each electrode, leading to an overlap in sound sequences. (Marozeau et al., 2013).

Cochlear implant users often exhibit relatively good speech comprehension in quiet environments but encounter challenges when it comes to understanding music and coping with background noise. This difficulty can be attributed to increased spectral smearing and diminished spectral resolution caused by the spread of excitation across channels (Cooper & Roberts, 2009). Additionally, modern cochlear implant speech-processing strategies employ input filters for individual channels that are generally too broad to effectively distinguish specific harmonics. The further spreading of current across the cochlea exacerbates the blending or "mixing" of harmonics, making it harder for users to separate speech from background noise (Oxenham, 2008).

There are limited shreds of evidence that explain auditory stream segregation in CI users. Among them, few studies show that individuals with CI could perform auditory streaming. Marozeau et al., (2013) conducted a study to examine how cochlear implants affect different auditory and perceptual cues related to auditory streaming and their connection to melody segregation. The study's main findings revealed that as the physical difference between the target and the distractor increased, listeners, including cochlear implant users, reported a reduced level of difficulty in segregating the melody from the distractor notes. This suggests that cochlear implant users can effectively separate auditory streams, similar to individuals with normal hearing, when the difference between the target and distractor is sufficiently substantial.

Bockmann-Barthel et al.,(2014) evaluated the build-up of streaming by contrasting listeners with and without cochlear implants. The stimulus consists of 30-s long sequences of alternately occurring A and B harmonic complexes, with four fundamental frequency separations ranging from 2 to 14 semitones. The participants must indicate whether they perceived it as a single stream or as two streams. Also, the amount of time required to distinguish between the experience of one stream and two streams, as well as the amount of time required to reach that first perceptual decision, were measured. According to the current study, the majority of CI users show stream segregation that is comparable to that of listeners with normal hearing. A two-stream percept predominates when the A and B tones vary significantly. The results of CI users and listeners with normal hearing were comparable, proving that using a CI does not affect the stream generation ability. This argues against a strong relation between stream segregation and frequency discrimination since the latter is affected by the limitations of the CI.

According to Chatterjee et al.,(2006) a study was conducted to investigate stream segregation in cochlear implant (CI) listeners using a subjective "Yes-No" paradigm. In this paradigm, participants were required to indicate whether or not they perceived a sequence of sounds as two distinct streams. The stimuli used in the study were brief, 50-ms pulse trains labeled as A and B, which were different in cochlear location. These pulse trains were presented in a specific sequence, where the pattern was A-B-A-A-B-A..., with each stimulus separated by a 50-ms interval. The sequences' duration was varied to measure the build-up of streaming. The stimulus was presented through a research interface, and prior to the experiments, all the stimuli were precisely loudness balanced. The objective of the study was to understand how CI listeners perceive and segregate auditory streams. The result of the study showed that CI listeners can perceptually segregate stimuli sequences using the loudness difference between stimuli, as in normal hearing listeners. Significant intersubject variability was noted. A second set of tests that one of the participants took part in revealed that he could perceptually separate stimuli with various cochlear electrode locations and stimuli with different temporal envelopes. These preliminary findings imply that some cochlear implant users may be able to perceptually distinguish between different stimuli based on variations in cochlear location and temporal envelope.

Using a temporal discrimination test, Hong and Turner(2006)comprehensively evaluated stream segregation in CI users. This test was chosen for its inherent ability to measure the perceptual characteristics of auditory events within streams rather than across them. The pioneering experiment by Hong and Turner was based on the task developed by Robert et al.,(2002), wherein the subjects were exposed to two successive rapid alternation pure tone sequences (A and B) on each trial. One sequence maintained an isochronous rhythm throughout, while the other began as isochronous but gradually transitioned into a progressive rhythm. The listener's task was to recognize the inconsistent interval as the amount of the delay applied to tone B was changed using an adaptive staircase method. The investigation results showed a strong relationship between the frequency gap between tones A and B and an increase in temporal discrimination thresholds. These findings strongly support the hypothesis that stream segregation indeed occurs in individuals with cochlear implants.

In the experiment by Hong and turner, (2006) employed an adaptive rhythmic discrimination task to assess the ability to perceive auditory streaming based on the frequency separation between tones. The study's results indicated a significant diversity in streaming abilities both among different cochlear implant users and within individual cochlear implant recipients, particularly when considering various cochlear regions. As the gap in frequency between two alternating tones increased, some cochlear implant users exhibited streaming performance comparable to individuals with normal hearing, while others showed substantially diminished streaming capabilities compared to those with normal hearing. Additionally, the study found a moderate correlation between the variation in pure-tone streaming skills across cochlear implant users across a wide frequency range and their capacity to comprehend speech when exposed to steady-state noise and multi-talker babble. Better stream segregation is related to improved speech in noise understanding. The study comes to the conclusion that reduced frequency resolution probably affects speech perception in noise as well as pure-tone auditory streaming. Additionally, common central processes like selective attention have been demonstrated to alter how the auditory stream is perceived.

Although some studies have shown that cochlear implant users can perform stream segregation, others have suggested that CI users do not exhibit these abilities. According to Cooper and Robert (2007), cochlear implant users must rely on schema-based processing to segregate auditory perceptual streams and this places them at a significant disadvantage, especially in challenging listening situations where attentional resources are limited. On the other hand, Chatterjee et al., (2006), who indicated that cochlear implant users may possess primitive stream segregation abilities. Cooper and Robert (2007) concluded that individuals with cochlear implants may not exhibit significant indications of automatic stream segregation due to the limited perceptual space for distinguishing between sounds. It was observed that self-reported stream segregation in cochlear implant users primarily reflects their capacity to discern variations in pitch among electrodes rather than the automatic streaming phenomenon experienced by individuals with normal hearing when exposed to rapidly alternating tones with vastly different frequencies.

Nie and Nelson (2015), explored how spectral overlap and amplitude modulation (AM) rate affect stream segregation in noise signals and the build-up effect based on these two cues. They used an objective paradigm with listeners' attention directed towards stream segregation. The study found that cochlear implant

(CI) users can effectively separate streams, but only when there are significant spectral separations and variations in AM rate. In other words, CI users may require substantial differences in these cues to perceive distinct auditory streams.

Tejani et al.,(2017) used an irregular rhythm detection task to compare the auditory stream segregation of listeners with CI (mean age of 55.66 years), older normal hearing listeners (mean age of 68.25 years), and adult normal hearing individuals (mean age of 19 years). Cochlear Implants (CI) users receive auditory stimulation through two different methods: pure tones delivered through loudspeakers and direct electrical stimulation. Recent studies show that when CI listeners are subjected to direct electrical stimulation, they experience stronger stream segregation. The mean normalized pattern of CI listeners was found to be comparable to that of individuals with normal hearing. However, CI users displayed poorer stream segregation when the stimulus was delivered through their speech processors. Features in the speech processor algorithms bring about the distinction. Multiple electrodes might get stimulated when the pure tone is processed through speech processor filters, as observed in studies conducted on individuals with cochlear implants (CI). Additionally, the Automatic Gain Control (AGC) mechanism may contribute to temporal distortion of the auditory stimulus. Furthermore, the research findings suggest that the challenges experienced by CI users in perceiving speech streams during routine listening may not solely be attributed to the reduced spectral and temporal resolution of the impaired auditory system. Instead, the signal processing algorithms employed by the CI device further modify the spectral and temporal cues of the incoming auditory signal before it reaches the auditory periphery.

2.4 Spectral Profiling

The arrangement of the spectral elements that make up complex sounds is referred to as the spectral profile. Spectral Profile analysis tasks can be used to measure the auditory system's sensitivity to variations in spectral shapes (Green, 1983). The detectability of this spectral shape change is tested psychophysically in studies involving profile analysis. These investigations often include adding an increment to one or more components, which results in a change in the spectral shape or profile of the stimulus.

A set of components characterized by a consistent spectral pattern, for example consist of frequencies at 650 Hz, 850 Hz, 1050 Hz, 1250 Hz, and 1,450 Hz were perceived as fused together, creating a unified perceptual stream for the listeners. However, a distinctive component within this complex tone was observed to "pop out" and be perceived as a separate entity when one of its constituent frequencies was altered in a way that disrupted the regular spectral pattern of the complex tone. (Johnson et al., 2021). This change in the spectral shape produces a qualitative difference in the sound, which can be stated as timber perception. The ability to process differences in timber is crucial to distinguish one sound source from another.

Johnson et al., (2021) conducted a study to examine the contrast in spectral profile thresholds between individuals with musical backgrounds and those without. The findings of the study reveals that musicians displayed considerably better profile analysis thresholds compared with non-musicians. Therefore they concluded that auditory stream segregation tends to be more proficient among musicians than non-musicians. Furthermore, the study also revealed that the performance in spectral profile analysis improved in musicians with more years of training. Authors proposed that improved attention and enhanced spectral processing can be the reason for better spectral profile threshold in musicians.

Using a spectral profiling task, Goyal et al., (2010) studied the effect of age and gender on auditory stream segregation abilities in individuals with normal hearing. Three groups were included: Group A 21-30 years, Group B 31-40 years, Group C 41-50 years. The spectral profiling task was measured using the maximum likelihood procedure in MATLAB at four frequencies: 250 Hz, 500 Hz, 750 Hz, and 1000 Hz. The results demonstrate that Group A did better than the other two groups; changes in neural structures explain the younger group's better performance. Ageing causes changes in the neuronal structures and physiology and reduces attention span and working memory. Reduced neuronal function also results in decreased ability to separate streams. Age-related declines in tonic inhibition lead to an increase in neural noise, which also impacts the central auditory process. Males did somewhat better than females in the study, but the authors did not detect any significant gender differences.

Using profile analysis tests, Banerjee and Prabhu (2021) assessed auditory stream segregation comprehensively in different populations, including those with normal hearing, cochlear pathology, and auditory neuropathy spectrum disorder (ANSD). The tests were administered at four different frequencies - 250 Hz, 500 Hz, 750 Hz, and 1000 Hz - utilizing the ‘mlp’ toolbox. Upon analyzing the results, it was evident that the profile analysis thresholds varied among the different groups. The control group exhibited the best thresholds, followed by the cochlear pathology group, and finally the ANSD group. This discrepancy in the thresholds indicated that the profile analysis threshold was most significantly affected in individuals with ANSD, indicating a distinct auditory processing deficit within this population. When cochlear hearing loss leads to changes in the mechanics of the basilar membrane due to loss of outer hair cells, auditory neuropathy spectrum disorder negatively affects the synchronous firing of auditory neurons. This cochlear and neural damage affects the spectral and temporal processing. Since normal spectral and temporal processing is pre-requisites for efficient spectral profiling, it can be the reason for getting reduced auditory stream segregation abilities in individuals with cochlear hearing loss and ANSD.

CHAPTER 3

METHODS

3.1 Research Design

The study implemented a standard-group comparison. A purposive sampling technique was used to choose the participants.

3.2 Participants

For the study, two participant groups were taken into consideration. 15 children between the ages of 6 and 12 (mean age 9.6, SD 1.4 years) with normal hearing belong to Group I. 21 children between the ages of 6 and 12 (mean age 9.5, SD 1.8 year) who have cochlear implants in one ear formed Group II.

3.2.1 Inclusion criteria of the participants of group I (control group)

- In order to ensure unbiased results, all the participants for the study were randomly selected, and along with that, pure tone audiometric evaluation was done and ensured that none of the selected participants had pure tone average (PTA) of more than 25 dBHL.

3.2.2 Exclusion criteria of the participants of group I (control group)

- The subjects who reported any middle ear pathology, academic challenges, intellectual issues, or auditory processing deficits (as determined by passing the Screening checklist for processing disorder) were excluded from the study.

3.2.3 Inclusion criteria of the participants of group II (Experimental group)

- 21 children, aged between 6 and 12 years, who had been diagnosed with bilateral severe to profound hearing loss and had received a cochlear implant in one ear.

- Every participant had received a cochlear implant before reaching the age of 6, and the aided threshold of the implanted ear is well within the upper range of the speech spectrum.
- Participants with a stable map of the CI, at least six months of implant usage, and actively participated in listening training.
- Participants were all using the same speech processor and company.

3.2.4 Exclusion criteria of the participants of group II (Experimental group)

- Children with additional issues like intellectual disability, autism, hyperactivity, and children who were not cooperative for testing or showed inconsistent responses were excluded from the study.

3.3 Test Environment

The testing was carried out in a space that met with ANSI S3.1-1999 (R2013) requirements for anechoic rooms. The test room was also distraction free and had the ideal temperature and lighting. Informed consent was obtained from each participant, and tests were conducted using non-invasive techniques after informing them study's goals and methods.

3.4 Procedure

3.4.1 Participant Selection

- Participants were chosen according to the specified inclusion and exclusion criteria.
- Comprehensive case history was obtained to rule out the presence of ear pain, ear discharge and other general health conditions.
- An otoscopic examination was conducted to visually inspect the ear canal and the tympanic membrane.

- To determine pure tone air conduction and bone conduction thresholds, the study utilized the modified Hughson Westlake technique (Carhart and Jerger, 1959). Thresholds were assessed at octave frequencies spanning the range of 250 to 8000 Hz for air conduction and 250 to 4000 Hz for bone conduction.
- Speech recognition threshold (SRT) and Speech identification scores (SIS) were measured using word lists in Kannada that were developed at the Department of Audiology, AIISH, Mysore.
- Tympanometry was performed with a 226 Hz probe frequency to evaluate middle ear function. Acoustic Reflex thresholds were measured ipsilaterally and contralaterally at 500 Hz, 1 kHz, 2 kHz, and 4 kHz.

3.4.2 Assessment of Spectral Profile Analysis Test

The study involved assessing the spectral profile analysis test in children with cochlear implants and those with normal hearing. The evaluation was conducted using the 'mlp' toolbox, which implements the maximum likelihood approach within the MATLAB software. This test aimed to assess the children's sensitivity to auditory stream segregation. To perform the spectral profile analysis, four fundamental frequencies (250 Hz, 500 Hz, 750 Hz, and 1000 Hz) were used. Complex tones with five harmonics corresponding to these fundamental frequencies were presented to each participant in a randomized fashion during the study. Three complex tones must be listened by participants, in two of them will be the same tones (standard tones). All tones have five harmonics, with the same amplitude (f0 = 330Hz,). The third tone has a similar harmonic structure, but since the third harmonic component's amplitude is larger than the standard, it produces a distinct timber. Therefore, here, the participant has to identify the odd timbre tone. On each trial, the overall level of the standard and variable tones was randomly adjusted within a 5 dB range. Two 10 ms raised cosine ramps were used to gate the onset and offset of the tones. Three alternative forced-choice procedures were used to conduct this experiment. The stimulus was delivered using a personal computer connected to an audiometer, and sound was presented at 60 dB through loudspeakers. The participant had to identify the exact number of stimuli that contained an odd timber. Thirty such stimulus trials were presented to the participants. The software then displays a number in decibels (dB). This value was subtracted from the standard value, and the resulting numerical value was taken as the spectral profile analysis threshold.

3.5 Statistical Analyses

The data collected in the study were analyzed using the Statistical Package for the Social Sciences (SPSS) Version 20.0. To determine whether the data followed a normal distribution, the Shapiro-Wilk test of normality was employed. Spectral profile analysis test results for those children with cochlear implants and with normal hearing were statistically examined.

CHAPTER 4

RESULTS

The current study aimed to assess and compare the auditory stream segregation ability through spectral profile analysis tests in children with normal hearing (group I) and children with cochlear implants (group II). Group I included 15 children (mean age 9.6, SD 1.4 years) with normal hearing, and group II included 21 children with cochlear implants (mean age 9.5, SD 1.8 year). The data obtained was analyzed using the statistical package of social science (SPSS) software version 20.0.

Shapiro-Wilk's test of normality was done to check whether the data is normally distributed, and this study's data for group I was found to be normally distributed ($p>0.05$). Therefore, parametric tests were used to perform inferential statistics. Also, the data for children in group II followed a non-normal distribution ($p < 0.05$), and non-parametric tests were used.

The results of the study are described under the following headings:

4.1, Descriptive statistics of spectral profile analysis thresholds across the frequencies in children with normal hearing (group I)

4.2, Descriptive statistics of spectral profile analysis threshold across the frequencies in children with cochlear implant (group II)

4.3, Comparison of spectral profile analysis threshold across the frequencies in both the groups (children with normal hearing and with cochlear implant)

4.4, Comparison of spectral profile analysis threshold between two groups (children with normal hearing and with cochlear implant) across the frequencies.

4.1 Descriptive Statistics of Spectral Profile Analysis Threshold across the Frequencies in Children with Normal hearing

The mean, median, standard deviation (SD) and interquartile range of spectral profile analysis threshold at different frequencies in children with normal hearing is shown in Table 4.1 and Figure 4.1.

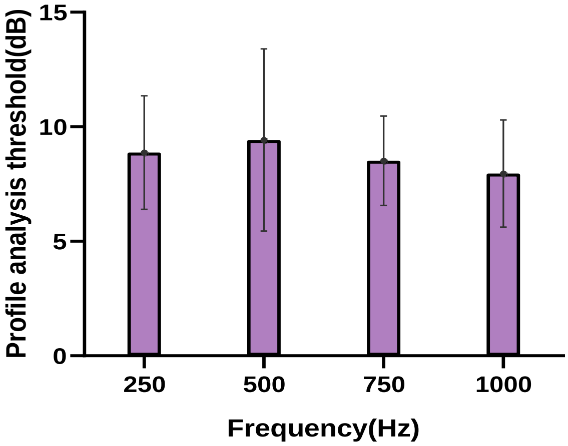
Table 4.1

Mean, Median, Standard deviation (SD) and Interquartile range (IQR) of Spectral Profile Analysis Threshold (dB) in Children with Normal Hearing

Frequency (Hz)	**Mean (dB)**	**SD**	**Median**	**IQR**
250	8.88	2.48	8.57	2.80
500	9.42	3.99	9.57	6.20
750	8.52	1.96	8.57	3.40
1000	7.96	2.35	8.17	3.80

Figure 4.1

Mean and SD of spectral Profile Analysis Threshold (dB) in Children with Normal Hearing (group I)



The results of descriptive statistics, as in Table 4.1 and Figure 4.1 showed similar scores (Spectral profile analysis threshold) across the frequencies in group I participants.

4.2 Descriptive Statistics of Spectral Profile Analysis Threshold across the Frequencies in Children with the Cochlear Implant

The mean, median, standard deviation (SD) and interquartile range of spectral profile analysis threshold in children with cochlear implants at various frequencies is shown in Table 4.2 and Figure 4.2.

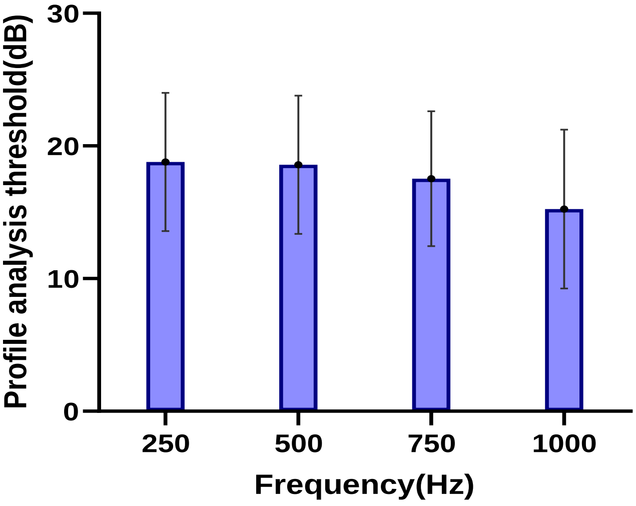
Table 4.2

Mean, Median, Standard deviation (SD), and Interquartile range (IQR) of Spectral Profile Analysis Threshold (dB) in Children with Cochlear Implants

Frequency (Hz)	Mean (dB)	SD	Median	IQR
250	18.0	5.22	21.37	2.43
500	18.59	5.22	21.37	3.20
750	17.54	5.09	19.77	5.20
1000	15.25	6.01	18.17	10.90

Figure 4.2

Mean and SD of Spectral Profile Analysis Threshold (dB) of Children with Cochlear Implant.



The results of descriptive statistics, as in Table 4.1 and Figure 4.1 showed differences in scores (spectral profile analysis threshold) across the frequencies across in group II participants.

4.3 Comparison of Spectral Profile Analysis Threshold across the Frequencies in both the groups (Children with normal hearing and with Cochlear implants)

Shapiro-Wilk's test of normality was done for the data obtained in children with normal hearing, and the findings showed that the data was normally distributed ($p>0.05$). Hence, parametric inferential statistics were administered. One-way repeated measure ANOVA was done, and the results indicate no significant difference ($p> 0.05$) in the profile analysis threshold across the frequencies in children with normal hearing.

The Shapiro-Wilk's test of normality was conducted on the data from children with cochlear implants, and the results indicated that the data did not follow a normal distribution ($p\leq0.05$). Consequently, non-parametric inferential statistics were used. Friedman test was performed to assess and compare the profile analysis threshold across the different frequencies (250 Hz, 500 Hz, 750 Hz, and 1000 Hz) in children with cochlear implants. The result of Friedman's test showed a significant difference across frequencies, $\chi^2 = 18.536$ (3), $p < 0.05$.

Since there is a significant difference, a pairwise comparison was done for the spectral profile analysis threshold across the frequencies. The pairwise comparison results show no significant difference in profile analysis threshold across frequencies except at 1000 Hz and 250 Hz ($p\leq0.05$). The results indicate that the scores were poorer at 250 Hz, and better performance was obtained at 1000 Hz in children with cochlear implants.

4.4 Comparison of Spectral Profile Analysis Threshold between two Groups (Children with Normal Hearing and with Cochlear Implant) across the Frequencies

Mann-Whitney U test was done to compare spectral profile analysis threshold between two groups for each frequency separately. The results of Mann-Whitney U tests are shown in Table 4.3 and Figure 4.3.

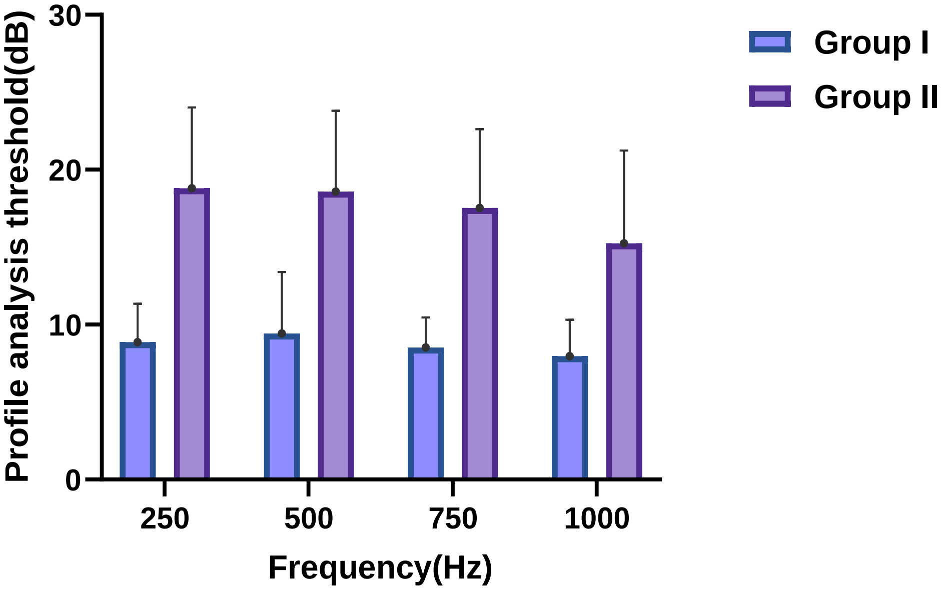
Table 4.3

Results of Mann-Whitney U test comparing Spectral Profile Analysis Threshold (dB) between the two groups across the Frequencies

Frequency (Hz)	**Z**	**P – value**
250	-4.21	0.000
500	-3.93	0.000
750	-4.05	0.000
1000	-3.44	0.001

Figure 4.3

Mean and SD of Spectral *Profile Analysis Threshold (dB)between the two groups across the Frequencies.*



As shown in the Table 4.3 and Figure 4.3, there was a significant difference between the two groups. The results indicate the scores are poorer or higher thresholds in children with cochlear implants, and better performance was observed for children with normal hearing sensitivity.

CHAPTER 5

DISCUSSION

The study aimed to compare the spectral profile analysis threshold between children with normal hearing and with cochlear implants. Spectral profile analysis, which is the ability to detect variations in the shape of complex acoustic spectra, is an important cue for auditory stream segregation (Green, 1983). Therefore, an increased spectral profile analysis threshold indicates a reduced ability of the listener to detect variations in the spectral shape of the complex multi-component waveform. The inability to analyze auditory scenes can result in inadequate communication or communication failure.

Hearing loss can impact the basilar membrane processes, increase the excitation region along the membrane, and affect spectral profiling ability. Cochlear hearing loss due to abnormal spectral processing of signal at the basilar membrane shows poor performance in spectral profiling. Reduced spectral profiling ability in auditory neuropathy spectrum disorder can be due to asynchronous and disrupted firing of auditory neurons, leading to difficulty in systematically processing spectral and temporal cues by the central auditory nervous system (Banerjee & Prabhu, 2021). Therefore, cochlear implants that restore hearing for individuals with hearing loss are expected to re-establish the capacity to perceive speech’s spectral and temporal components. Challenges in the acoustic environment will be more for children when compared to adults. Therefore, children require better stream segregation abilities than adults for adequate speech perception. In contrast to adults, infants require significantly larger differences between the acoustic characteristics of sounds in order to effectively perceive auditory segregation. (McAdams & Bertoncini, 1997).

Therefore, it’s important to address the spectral profiling ability of children with cochlear implants.

Various researchers have explored the auditory stream segregation abilities of individuals with cochlear implants, and their findings have produced conflicting results. While Chatterjee et al., (2006) suggested that cochlear implant users might have rudimentary stream segregation abilities, Cooper and Robert, (2007) concluded, individuals with cochlear implants may not demonstrate significant signs of automatic stream segregation, primarily because of the restricted perceptual capacity to differentiate between sounds. The large differences in sample size and methodologies can be the reason for these variations in findings.

Users of cochlear implants may interpret speech pretty well in a calm setting, but they frequently struggle to perceive music and to understand speech in background noise. Competing speech can have a detrimental impact on the performance of cochlear implant users, and this effect can occur even when there is a relatively high signal-to-noise ratio of +16 dB (Nelson et al., 2003). The variable spatial interaction between electrode channels may cause of poor performance. Due to constrained number of independent spectral channels and the interaction between the channels caused by current spread, users with cochlear implants (CIs) have low spectral resolution and it impairs some of the auditory cues crucial to speech perception (Feng & Oxenham, 2018).

While a healthy cochlea transmits frequency and temporal information through approximately 3000 inner hair cells, cochlear implants (CI) convey information that has been degraded due to signal processing, such as signal compression, band-pass filtering, and temporal envelope extraction. Additionally, CIs use only a limited number of electrodes. However, because of challenges like channel interactions and frequency-to-electrode mismatches, it is likely that the actual number of spectral channels effectively used by the majority of CI users is significantly less than 8.(Fu et al., 2004)**.** The temporal fine structure that allows listeners with normal hearing to detect pitch is also removed by signal processing. Also, CI users, neural degeneration associated with long-term deafness exacerbates their weakened capacity to recognize frequency distinctions of sounds (Moore, 2007). The limited frequency resolution provided by a cochlear implant (CI) speech processor explains why CI users often struggle in tasks that involve pitch perception, such as melody recognition, prosody perception, and separating sounds from multiple sources. This limitation makes it challenging for them to excel in tasks related to pitch discrimination and perception.

The present study shows a poorer profile analysis threshold in children with cochlear implants compared to children with normal hearing. Also, when the threshold was compared across frequencies (250 Hz, 500 Hz, 750 Hz and 1000 Hz), significant difference was observed between 1000 Hz and 250 Hz. Threshold was better at 1000 Hz (high frequency) when compared to 250 Hz (low frequency). Electrical stimulation patterns that match the enlarged excitation region along the basilar membrane in listeners with hearing loss are thought to cause the lower streaming capacity in CI listeners. Fusion is more likely to occur because of the wide area of stimulation around each electrode, which can lead to overlap in sound sequences ((Marozeau et al., 2013). The spread of excitation across channels might result in a higher degree of spectral "smearing" and reduced spectral resolution.(Cooper & Roberts, 2009). Furthermore, modern cochlear implant speech-processing strategies employ input filters for individual channels that are usually too wide to effectively distinguish individual harmonics in the incoming sound. Consequently, the spread of electrical current across the cochlea amplifies the blending or "mixing" of harmonics, making it even more challenging for cochlear implant users to perceive and separate different elements within complex sounds like speech and music (Oxenham, 2008).

The better performance at high frequency (1000 Hz) can be related to the cochlear tonotopical organization and characteristics of electrode array insertion. Wagner et al.,(2021) examined how the frequency differences relative to the electrode frequency bands affect the pure tone discrimination. Two sinusoidal tones with different frequency discrepancies were given. The center frequency of the basal or apical electrodes was used to get the reference tone frequency. In a three-interval, two-alternative, forced-choice (3I-2AFC) approach, discrimination skills were psychophysically assessed for several CI electrodes. Pure tone discrimination was assessed and compared between high and low frequencies, that is, between basal and apical CI electrode contacts. The results indicated that better frequency discrimination was observed at higher frequencies. This improved discrimination at higher frequencies may be attributed to the stimulation of cochlear regions that are closer to the natural frequency-coding sites in the cochlea, which allows for more precise perception of frequency differences.The basal regions' increased spiral ganglion neuron density may also have contributed to these findings.

CHAPTER 6

SUMMARY AND CONCLUSION

Auditory stream segregation is the process in which our auditory system divides and categorises incoming sounds into separate perception streams (Bregman & Campbell, 1971). Numerous spectral and temporal cues can be used to interpret an auditory scene. Spectral profiling is an important spectral cue for auditory streaming. There are limited studies on spectral profile analysis in hearing-impaired individuals. An individual can detect the change in spectral profile when the amplitude of one of the components of complex tone is changed. The study aimed to assess and compare spectral profile analysis threshold between children with normal hearing and with cochlear implants.

The participants were divided into two groups: Group I, comprising 15 children with normal hearing aged 6 to 12 years, and Group II, consisting of 21 children aged 6 to 12 years with cochlear implants. The spectral profile analysis test was conducted on both groups using the 'mlp' toolbox, which utilizes the maximum likelihood procedure within the MATLAB software.

Statistical Package for the Social Sciences (SPSS) Version 20.0 was used to analyze the data. One-way repeated measures ANOVA was done to assess spectral profile analysis thresholds across four frequencies in children with normal hearing. The outcomes revealed no significant differences among the frequencies. The Friedman test was employed to compare profile analysis thresholds across four frequencies in children with cochlear implants, and the findings indicated statistically significant differences among these frequencies. Since there is a significant difference, a pairwise comparison was done for the spectral profile analysis threshold across frequencies. The pairwise comparison results show no significant difference in profile analysis threshold across frequencies except at 1000 Hz and 250 Hz. Additionally, Mann-Whitney U test was performed to compare spectral profile analysis thresholds between the two groups for each frequency individually, and the results demonstrated a significant difference between the two groups.The results indicate the scores are poorer or higher thresholds in children with cochlear implants, and better performance was observed for children with normal hearing sensitivity.

The poorer performance in children with cochlear implants is suspected to result from reduced spectral resolution. When there is a broad region of stimulation encompassing each electrode, it leads to an overlap in sound sequences, increasing the likelihood of fusion in children with cochlear implants (CIs). This extended stimulation area can result in a greater degree of spectral "smearing" and reduced spectral resolution due to the spread of excitation across multiple channels.

6.1 Implication of the Study

- The study helps to understand the spectral profile analysis abilities in children with normal hearing and with cochlear implant.
- The result of the study would help in counseling the children with cochlear implant and their caregivers about auditory scene analysis abilities.

6.2 Future Directions

- To study the effect of other spectral and temporal cues on auditory stream segregation in children with normal hearing and with cochlear implants.
- To study the spectral profile analysis threshold in children with cochlear implants through direct stimulation.

- To study the spectral profile analysis threshold in adults with cochlear implants.
- To study the association between spectral profile analysis threshold in children with cochlear implants and their speech in noise ability.

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