Acoustic Change Complex Responses to Tone Frequency Changes and its Relationship with Speech Perception Outcomes in Paediatric Cochlear implant users

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CERTIFICATE

This is to certify that this dissertation entitled **"Acoustic Change Complex Responses to Tone Frequency Changes and It's Relationship with Speech Perception Outcomes in Pediatric Cochlear Implant Users"** is a Bonafide work submitted as part of fulfilment of the degree of Master of Science **Audiology** of the student with Registration Number **P01II24S023039**. 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.

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CERTIFICATE

This is to certify that this dissertation entitled " Acoustic Change Complex Responses to Tone Frequency Changes and It's Relationship with Speech Perception Outcomes in Pediatric Cochlear Implant Users " has been prepared 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 other Diploma or Degree.

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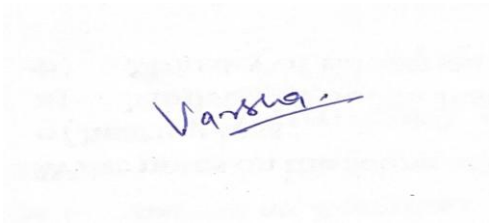
DECLARATION

This is to certify that this dissertation entitled " Acoustic Change Complex Responses to Tone Frequency Changes And It's Relationship with Speech Perception Outcomes in Paediatric Cochlear Implant Users " is the result of my own study under the guidance of Mr. Saravanan P ., Assistant Professor of Audiology, All India Institute of Speech and Hearing, Mysuru and has not been submitted earlier to any other university for the award of any other Diploma or Degree**.**



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List of Frequently Used Abbreviations

CI- Cochlear Implant

ACC- Acoustic Change Complex

AEP- Auditory Evoked Potentials

CAEP- Cortical Auditory Evoked Potential

eACC- Electrically Evoked Acoustic Change Complex

EEG- Electroencephalography

ERP- Event Related Potential

ABSTRACT

Background: Cochlear implants (CIs) provide effective auditory rehabilitation for children with severe-to-profound sensorineural hearing loss; however, speech perception outcomes vary considerably among users. Electrode discrimination ability is a key factor influencing these outcomes. The Acoustic Change Complex (ACC), a cortical auditory evoked potential elicited by changes within an ongoing stimulus, offers an objective measure of auditory discrimination that does not require active behavioural participation. Limited evidence is available regarding ACC responses across different cochlear regions in paediatric CI users.

Aim: This study aimed to compare ACC responses elicited by tone frequency changes at apical and basal electrode locations and to examine their relationship with speech perception performance in paediatric cochlear implant users.

Method: Nineteen paediatric unilateral CI users (12 males, 7 females; mean age = 6.98 years) with congenital bilateral severe-to-profound sensorineural hearing loss participated in the study. ACC responses were recorded using a two-channel cortical auditory evoked potential system. Pure-tone stimuli (810 ms duration) containing a frequency change at 410 ms were presented at 70 dB SPL. Apical stimulation involved a 500 Hz base frequency corresponding to electrode 20, while basal stimulation involved a 4000 Hz base frequency corresponding to electrode 06. Frequency changes were represented within-electrode, +1 adjacent electrode, and +3 adjacent electrode conditions. Open-set speech perception was assessed using 25 bisyllabic words. Data were analysed using Friedman tests with Bonferroni-corrected post hoc comparisons and Spearman's rank-order correlations.

Results: ACC responses were successfully recorded in all participants. Larger frequency changes produced clearer waveforms and larger ACC amplitudes. Compared to basal stimulation, apical stimulation elicited shorter P1′ and N1′ latencies and larger P1′, N1′, and P1′–N1′ amplitudes. Significant differences were observed across electrode conditions for P1′ latency and P1′–N1′ amplitude ($p < .001$), with the apical +3 adjacent electrode condition demonstrating the shortest latencies and largest amplitudes. Significant correlations with speech perception were identified for P1′ latency, N1′ latency, N1′ amplitude, and P1′–N1′ amplitude under specific stimulation conditions. Better speech perception performance was associated with shorter cortical response latencies and larger ACC amplitudes. Long latency response measures did not differ significantly across stimulation conditions.

Conclusion: ACC responses can be reliably recorded in paediatric CI users and are sensitive to changes in electrode location and the magnitude of frequency change. The observed associations between ACC measures and speech perception performance support the clinical utility of ACC as an objective biomarker of auditory discrimination and speech perception abilities, with potential applications in cochlear implant assessment and rehabilitation.

Keywords: *Acoustic Change Complex, Cochlear Implant, Paediatric, Electrode Discrimination, Speech Perception, Cortical Auditory Evoked Potentials, Apical Electrode, Basal Electrode*

Chapter 1

Introduction

A cochlear implant (CI) is an implantable hearing device and the most commonly used treatment option for individuals with severe to profound hearing loss. A CI greatly enhances speech perception skills for individuals who receive limited benefit from hearing aids (Bazon et al., 2015). The CI stimulates the auditory nerve directly by bypassing the damaged or injured sensory receptors, the hair cells. It is implanted directly into the inner ear. It is an electronic device found to be highly beneficial for patients with sensorineural hearing loss. Sahai et al. (2022). Regular CI use and extensive auditory rehabilitation, emphasising oral language, are also crucial determinants of successful speech outcomes. Children with other disabilities, inner ear malformations (usually preventing complete insertion of the electrode array), delayed diagnosis or implantation, and/or inconsistent use of the device and speech therapy typically have less successful speech outcomes.

Even with the improvements in CI technology, various elements such as the age at implantation, the cause of hearing loss, inner ear anomalies, and aetiology can affect the development of speech recognition and auditory skills in children with implants (Black et al., 2014). The way the central auditory system processes auditory signals is crucial to speech perception in individuals using CI. Factors such as age at implantation can significantly disrupt the normal development of the auditory cortex, which, in turn, can have a major effect on the success of cochlear implantation (Gilley et al., 2008; Kral & Sharma, 2012).

1.1. Electrode Discrimination

Electrode discrimination in CI is primarily viewed as the ability of users to differentiate between various spatial positions of electrical stimulation within the cochlea (Zwolan et al.,

1997). Dawson et al. (2000) investigated electrode discrimination abilities in paediatric CI users and their relationship with speech perception performance. The results revealed that approximately 65% of participants discriminated between adjacent electrodes in the mid and apical regions of the cochlea. In contrast, the remaining children required a wider electrode separation, ranging from 2 to 9 electrodes, for successful discrimination. Auditory discrimination abilities in paediatric CI users improve with age and stimulus intensity, and spatial separation alone may not determine electrode discriminability (Kopelovich et al., 2010)

1.2 Acoustic Change Complex

Acoustic Change Complex (ACC), a cortical auditory evoked potential elicited by a change in sound, may offer valuable objective indicators for evaluating hearing ability and could enhance our understanding of cortical auditory processing (Van Heteren et al., 2022). According to Kim. (2015) and Martin et al. (2008) the ACC offers an objective evaluation of sound discrimination ability because the testing process does not require a behavioural response from the participant. In recent years, researchers have shown great interest in the ACC as an impartial instrument for evaluating auditory discrimination skills. A detectable shift in auditory characteristics, such as frequency, intensity, and duration, might trigger the ACC in response to continuous stimuli (McGuire et al., 2021).

1.3. Need for the study

Several studies have shown the importance of electrode discrimination abilities in speech perception performance in adult CI users. Electrode discrimination is a measure of spectral resolution important for speech understanding and refers to the ability of CI users to discriminate between different sites of electrical stimulation along the cochlear electrode array. Zwolan et al. (1997) showed that adult CI users with better electrode discrimination abilities had better speech

recognition performance. Henry et al. (2000) found a significant association between electrode discrimination and speech perception outcomes, suggesting that enhanced spatial discrimination supports improved auditory processing of speech signals. Furthermore, a study by Dawson et al. (2000) further highlighted that the electrode's ability to discriminate is one of the strongest predictors of speech perception performance in CI users. The findings suggest that the brain's ability to discriminate electrical stimulation correctly is an important factor in successful cochlear implantation and further support the importance of objective measures of auditory discrimination.

Electrode discrimination is important for speech perception in CI users, as different electrodes can accurately transmit spectral speech cues. Mathew et al. (2017) showed that behavioural electrode discrimination, especially in the apical region of the CI electrode array, is a potent predictor of performance on vowel and sentence perception tasks. Their results showed that apical electrode discrimination explained 46% of the variance in vowel recognition and 53% of the variance in sentence perception, independent of demographics, including age of deafness onset and hearing loss duration. The study also highlighted the clinical importance of combining behavioural and objective measures, such as the ACC, to guide targeted auditory training or electrode deactivation strategies to improve speech clarity and overall CI outcomes.

For adult CI users, electrode discrimination is crucial for successful speech perception because it enables the accurate transmission of spectral speech cues via tonotopically organised electrodes. Debruyne et al. (2017) reported that poor discrimination between adjacent electrodes leads to channel interactions and reduced spectral resolution, negatively affecting the perception of vowels, consonants, and speech in noisy environments. Since speech understanding in noise relies heavily on fine spectral analysis, a reduction in spatial selectivity can severely degrade

communication performance. The study also highlighted the clinical utility of evaluating electrode discrimination to determine whether poor speech outcomes are due to peripheral limitations at the electrode-neural interface or to limitations in central auditory processing, thereby assisting clinicians in optimising auditory training and channel deactivation strategies.

Cochlear implantation is very beneficial for children with severe to profound sensorineural hearing loss, especially when devices are placed early at crucial times of development of the brain. However, the capacity of paediatric CI users to recognise and comprehend changes in sound frequency significantly influences heterogeneity in speech perception outcomes. A useful method for assessing auditory discrimination in young infants who are unable to participate in behavioural testing consistently is the ACC, an objective brain response to acoustic or electrical alterations (Gabr et al., 2024). According to research, children with hearing loss can predict speech perception outcomes based on the ACC responses (Meehan et al., 2024).

Previous studies show that the ACC can capture neural responses to changes in speech stimuli and reveal preliminary correlations with behavioural speech measures (Kim, 2015; Meehan et al., 2024; Sanju et al., 2023). Additionally, research indicates that the ACC can assess how well infants and children with hearing aids or varying degrees of hearing loss perceive speech, enabling prompt intervention (Martinez et al., 2013). Meehan et al. (2024) conducted a systematic review demonstrating the feasibility of obtaining ACC measurements in infants younger than 3 months and emphasising their diagnostic value in paediatric populations with CI, hearing aids, auditory brainstem implants, central auditory processing disorder, auditory neuropathy spectrum disorder, and hearing loss. To validate ACC results against behavioural speech perception tests, establish standardised age-specific methods, and assess their predictive

usefulness for long-term auditory and language outcomes in newborns and children, further study is necessary. Martinez et al. (2013) showed that children as young as two years and three months, including those with mild to moderately severe sensorineural hearing, may reliably elicit the ACC responses, as evaluated by cortical auditory evoked potentials. Ching et al. (2023) examined newborns between the ages of three and twelve months, including those with normal hearing and those with hearing aids. Seven of the infants were able to correctly record ACC responses as early as three to six months of age. The study supported the ACC as a trustworthy and impartial indicator of auditory discrimination in newborns and young children by finding strong relationships between ACC responses and parent-reported functional auditory ability.

The ability to recognise frequency differences is crucial for phoneme recognition, word identification, and prosody comprehension in effective speech perception. Brain responses, such as those in the ACC, can be used to assess spectral resolution, which is often compromised in children with CIs. These answers are predictive of speech outcomes and have been connected to a child's ability to discriminate between frequencies (Xie et al., 2022). Nonetheless, gaps remain in the literature regarding the ACC's role in young CI users, particularly its relationship to speech perception abilities. Relatively few studies have examined its use in paediatric CI populations, despite extensive research in adults and children with normal hearing. Because electrode discrimination represents channel independence along the electrode array, it is crucial for maximising CI speech perception. High channel independence improves spectral resolution by allowing electrodes to stimulate various brain populations. However, overlapping stimulation areas obscure spectral clues, which decreases intelligibility. Electrode discrimination testing enables clinicians to improve signal clarity and disable underperforming electrodes by identifying overlapping electrodes (Lien et al., 2025).

According to Warren & Atcherson (2023), spectral resolution is compromised by excessive channel interactions, as evidenced by poor electrode discrimination. Clinicians can deactivate underperforming electrodes while keeping working ones by using behavioural pitch-ranking 8 exercises. Both in quiet and noisy settings, this customised approach has resulted in quantifiable improvements in speech perception, with participants typically favouring the modified stimulation maps. Significantly, results improved over time, highlighting that long-term effects are enhanced by brain adaptation to updated stimulation. The spatial ACC, a cortical response to changes in stimulation site, has been used to measure electrode discrimination in adults objectively.

As early as one week after implantation, the spatial ACC can be measured. It has a good correlation with behavioural discrimination scores and occasionally provides predictive information beyond behavioural testing (Mathew et al., 2017). This demonstrates its usefulness as a reliable neurophysiological indication of the electrode-neural interface, which may be used to direct rehabilitation and improve long-term auditory outcomes in both adults and children. While much research has been conducted on adult CI users, comparatively few studies have used electrophysiological measures such as the ACC to investigate cortical auditory discrimination abilities in paediatric CI users. The present study, therefore, aimed to evaluate ACC responses to frequency changes across different electrode stimulation conditions in paediatric CI users and to investigate the relationship between these responses and speech perception performance.

1.4. Aim of the study

The present study aimed to compare acoustic change complex (ACC) responses to changes in tone frequency, measured at apical and basal electrode locations, and to assess the relationship between speech perception and ACC responses among paediatric cochlear implant users.

1.2. Objectives

1. To compare the latency and amplitude measures of acoustic change complex responses to tone frequency changes measured across the apical and basal electrode stimulation.
2. To compare the latency and amplitude measures of acoustic change complex response to tone frequency changes across stimulating the same electrode, +1 adjacent electrode and +3 adjacent electrode in the apical region.
3. To compare the latency and amplitude measures of acoustic change complex response to tonal frequency changes across stimulating the same electrode, +1 adjacent electrode and +3 adjacent electrode in the basal region.
4. To evaluate the relationship between latency and amplitude measures of acoustic change complex responses to tone frequency changes measured at apical and basal electrodes with speech perception outcomes.

1.3. Hypotheses of the Study

The null hypotheses for the objectives are given below:

1a. There are no significant differences in latency measures of acoustic change complex responses to tone frequency changes measured across the apical and basal electrode stimulation.

1b. There are no significant differences in amplitude measures of acoustic change complex responses to tone frequency changes measured across the apical and basal electrode stimulation.

2a. There are no significant differences in the latency measures of acoustic change complex response to tone frequency changes across stimulating the same electrode, +1 adjacent electrode and +3 adjacent electrode in the apical region.

2b. There are no significant differences in the amplitude measures of acoustic change complex response to tone frequency changes across stimulating the same electrode, +1 adjacent electrode and +3 adjacent electrode in the apical region.

3a. There are no significant differences in the latency measures of acoustic change complex response to tone frequency changes across stimulating the same electrode, +1 adjacent electrode and +3 adjacent electrode in the basal region.

3b. There are no significant differences in the amplitude measures of acoustic change complex response to tone frequency changes across stimulating the same electrode, +1 adjacent electrode and +3 adjacent electrode in the basal region.

4b. There is no significant relationship between latency and amplitude measures of acoustic change complex responses to tone frequency changes measured at apical and basal electrodes with speech perception outcomes.

Chapter II

Review of Literature

A Cochlear Implant (CI), the most advanced treatment for people with severe to profound sensorineural hearing loss (SNHL), is a modern, surgically implantable electronic medical device (Holden et al., 2013; Sahai et al., 2022). The CI, a form of neuroprosthesis, is intended to treat SNHL, which is mainly caused by injury or malfunction of the sensory hair cells in the cochlea, the inner ear's organ of hearing (Sahai et al., 2022).

The main purpose of the CI is to directly stimulate the remaining functional fibres of the auditory nerve, avoiding the damaged cochlear hair cells, whereas traditional hearing aids amplify acoustic signals (Bazon et al., 2015b; Sahai et al., 2022). Restoring auditory detection thresholds is a key and crucial indicator of CI success. In particular, studies show that most CI recipients can detect speech sounds well within the normal hearing threshold range, which is below 25 dB Hearing Level (HL), after post-activation and optimisation (Vermeire et al., 2003). According to Skinner et al. (1997), the ideal audiometric objective is to achieve an aided detection threshold between 20- and 35-dB HL, as this range provides sufficient audibility to make even the quietest speech acoustic cues accessible. The basis for later development in speech perception and spoken language acquisition, particularly in the paediatric population, is established by this basic restoration of audibility. In children with bilateral severe-to-profound sensorineural hearing loss, CI provides access to sound, which, in many cases, is sufficient to support the development of normal or near-normal speech perception. The most successful outcomes occur when children have normal inner ear anatomy, early diagnosis and hearing aid fitting, no other developmental disabilities, and early implantation (≤12 months of age). Regular CI use and extensive auditory rehabilitation, emphasising oral language, are also crucial

determinants of successful speech outcomes. Children with other disabilities, inner ear malformations (usually preventing complete insertion of the electrode array), delayed diagnosis or implantation, and/or inconsistent use of the device and speech therapy typically have less successful speech outcomes**.**

Despite advances in CI technology, a variety of factors, including implantation age, aetiology, inner ear abnormalities, and meningitis, may be associated with gains in speech recognition and auditory competence in these implanted children (Black et al., 2014). Delayed implantation and congenital hearing loss can significantly influence the normal maturation of the auditory cortex, which, in turn, can significantly impact the outcome of CI (Gilley et al., 2008; Kral & Sharma, 2012).

Frequency information in CI is mainly encoded by the location of electrical stimulation along the electrode array. Low-frequency sounds are presented to electrodes in the apical region, and high-frequency sounds to electrodes in the basal region, according to the cochlea's tonotopic organisation. The speech processor analyses the incoming acoustic signals into several frequency bands. Each frequency band is mapped into a corresponding electrode or group of electrodes. The success of frequency coding depends on the quality of the interface between the electrode and the neuron, channel interactions, and the accuracy of frequency-to-electrode allocation, which affect pitch perception and speech understanding in CI users.

2.1. Electrode discrimination- Principles

Electrode discrimination in CI is mainly considered a measure of how well users can distinguish between different spatial locations of electrical stimulation within the cochlea (Zwolan et al., 1997). A fixed-level verification task and a two-interval forced-choice adaptive procedure were used to assess each electrode's discriminability. These tasks determined which

electrodes were perceptually equivalent to one another, or in-discriminable (Gilley et al., 2008). Zwolan et al. (1997) study questioned the assumption that each channel of a multichannel implant offers distinct spatial pitch cues by examining the effect of perceptual electrode discrimination on speech recognition in post-lingually deaf adults. The researchers discovered significant variation in the subjects' spatial discrimination abilities when they used psychophysical tasks to distinguish between electrodes that were in-discriminable from their neighbours. Importantly, seven out of nine subjects demonstrated notable gains in speech recognition when fitted with an Experimental Map that only included the subset of electrodes considered perceptually distinct (fewer active channels overall), especially on tasks involving contextual cues like CID Everyday Sentences and NU6 Monosyllabic Words. On the other hand, there was no discernible improvement in performance on straightforward closed-set vowel and consonant recognition tasks. Zwolan et al. (1997) study questioned the notion that activating more electrodes always results in better performance and found that electrode discrimination tasks can enhance speech recognition for a subset of CI users. Reducing redundant or confusing spatial information optimises the signal sent to the central auditory system, according to the counterintuitive finding that fewer but perceptually distinct electrodes may be preferable to a full array with in-discriminable channels. The findings highlight a crucial functional bottleneck in multichannel CI design: the processor map must account for the listener's psychophysical limitations to optimise stimulation.

In both adult and paediatric CI populations, electrode discrimination ability has been linked to speech perception (Dawson et al., 2000; Mathew et al., 2017). Dawson et al. (2000) assessed the effectiveness of a kid-friendly method for measuring electrode discrimination and to examine its relationship to young children's (ages 4 to 10) speech-perception abilities. According

to Dawson et al. (2000), the most reliable indicator of speech perception and auditory competence in young children with CI is electrode discrimination ability, which can be measured using a kid-friendly method. This finding implies that, regardless of typical demographic or experience factors in a young cohort, a child's speech recognition abilities are strongly bound by their auditory capacity to resolve spectral information (i.e., their psychophysical limits). To apply focused training or mapping techniques during the crucial years of language development, it is necessary to identify discrimination issues early.

Mathew et al. (2017) examined the feasibility of evaluating electrode discrimination in adult CI users, including those who had recently received an implant and those with devices from different manufacturers (Advanced Bionics and MED-EL), using an objective electrophysiological measure, the spatial Auditory Change Complex (ACC). A continuous 800 ms pulse train that moved the stimulation site to the halfway point (the "Suprathreshold Change" condition) was used to directly stimulate the intracochlear electrodes, avoiding the speech processor. To ensure reliable artifact control, responses were compared to a silent "Subthreshold Change" condition using advanced spatial filtering techniques. The objective ACC results were then compared to functional speech perception scores (BKB sentences and CAPT vowels) and behavioural electrode discrimination (a three-interval, two-alternative forced-choice task). The spatial Auditory Change Complex (ACC), which can be recorded as early as 1 week after switch-on and is feasible across 2 CI manufacturers (AB and MED-EL), was successfully validated as a strong objective biomarker of functional performance. The results demonstrated a high degree of agreement between the behavioural electrode discrimination results and the objective ACC response, which indicates cortical encoding of spectral shift, especially in post-lingually deaf adults. The ACC, however, was occasionally observed in pre-lingually deaf individuals even in

the absence of accurate behavioural discrimination. Neural encoding was evident despite the participant not being able to consciously perceive or make use of the stimulus variation. The findings indicate that the ACC is a useful indicator for evaluating the performance of CI programming and auditory rehabilitation strategies.

Debruyne et al. (2017) demonstrated that prelingually deafened adults' electrode-discrimination capacity strongly relates to speech-perception performance, affirming the value of high spectral resolution for optimal CI function. Their work emphasises the high heterogeneity in perceptual encoding across users and the potential of quantitative measures to inform clinical mapping approaches. Applying this method to paediatric groups, cortical responses, such as ACC responses to changes in tone frequency, could serve as an early, attention-independent biomarker of auditory discrimination abilities. Neural coding of changes in the stimulus seemed to occur regardless of whether the individual was capable of being aware of and making use of the auditory stimulus. Another important point made was that there could be some value in using ACC as an objective tool in CI programming and therapy.

2.2. Electrode discrimination- Methods

Electrode discrimination can be measured behaviourally and objectively, providing complementary information about auditory processing in CI users. Psychoacoustic procedures, including two-alternative forced-choice tests or pitch-ranking paradigms, quantify one's perception of differences between stimulation locations, but behavioural measures are highly attention-, cognition-, and language-dependent, limiting their utility in older children and adults (Dawson et al., 2000). Conversely, ACC provides an objective electrophysiological measure by recording cortical responses to changes in continuing stimulation and thus indexes discrimination capacity without active engagement (Chen & Small, 2015; Mathew et al., 2017). Chen & Small,

(2015) study overcame earlier methodological constraints by effectively using the ACC to objectively evaluate speech-sound discrimination in 4-month-old infants. To achieve robust ACC elicitation with distinct P1 and N1 morphology, the researchers demonstrated that long-duration stimuli were essential. This technique was thought to accommodate the longer neuronal refractory periods of the immature central auditory pathways. The main conclusion was that the degree of acoustic distinction was directly reflected in the magnitude of the P1 amplitude; in particular, P1 amplitudes elicited by significant changes (such as /daba/ and /dada/) were statistically larger than those elicited by minimal changes (the /dada/ control). This amplitude differential validates the ACC P1 amplitude as a valid index of the earliest stages of phonetic discrimination, objectively demonstrating that the infant brain recognises and processes acoustic distinctions based on magnitude.

According to Martinez et al. (2013) the ACC is a promising instrument for objectively evaluating auditory resolution—the capacity to distinguish between the acoustic components of speech—at the level of the auditory cortex and can be successfully measured in the majority of young children. For children too young for conventional behavioural speech tests, this objective measure provides information beyond simple stimulus detection and may help clinicians assess the effectiveness of auditory aids and intervention techniques.

2.3. Acoustic Change Complex (ACC)

A cortical evoked potential, with particular focus on the ACC and its relevance in assessing the auditory discrimination abilities among paediatric cochlear implant users. An event-related potential (ERP) that represents cortical neural processing of changes within an ongoing auditory stimulus is called the ACC. After an acoustic change, such as a shift in

frequency, intensity, or spectral range, it usually appears as a negative-positive waveform (N1–P2 complex) (Alain & Tremblay, 2007; Martin & Boothroyd, 2000).

According to Alain & Tremblay, (2007) the ACC is physiologically produced in the auditory cortex, primarily in the superior temporal gyrus and Heschl's gyrus. This suggests that it is not brainstem activity but rather higher-level cortical processing of auditory contrasts. Although the ACC happens after an intra-stimulus change, indicating neural detection of an acoustic transition rather than sound onset, it is believed to share neural generators with the onset cortical auditory evoked potentials (CAEPs), specifically the N1–P2 components (Martin & Boothroyd, 2000). According to research, a variety of acoustic variations within a continuous sound stimulus can trigger the ACC, a flexible cortical response. ACC responses are reliably triggered by changes in intensity and duration, in addition to frequency-specific shifts (Alain & Tremblay., 2007; Martin & Boothroyd., 2000).

2.3.1. ACC as a measure of electrode discrimination ability

The potential of ACC responses as an objective indicator of auditory discrimination and cortical processing efficiency in cochlear implant (CI) users has been highlighted by several studies examining the relationship between ACC responses and speech perception outcomes. The effectiveness of the spatial ACC as an objective measure of auditory discrimination ability in children with auditory neuropathy spectrum disorder (ANSD) who wore CIs was examined by He et al. (2014). For comparison, the study included age-matched normally hearing (NH) children and paediatric CI users. To create a spatial ACC, electrical stimuli were delivered via the CI, switching between two electrodes along the implant array to mimic a change in stimulation location. Electroencephalography (EEG) was used to record cortical responses, and the amplitude and latency of the ACC's distinctive N1–P2 waveform were examined. This

suggests that robust ACC responses are indicative of improved speech perception abilities. The extent to which cortical encoding of spatial change reflected perceptual discrimination was assessed by comparing electrophysiological responses with behavioural measures of electrode discrimination, which quantified the smallest electrode separation the child could detect. This can be reliably elicited by electrode changes in CI users, as demonstrated by the successful recording of the spatial ACC in both groups. As the distance between stimulating electrodes increased, ACC amplitudes rose, and latencies decreased, indicating sensitivity to the extent of spectral change. Compared to CI users, children who were normally hearing displayed larger and earlier ACC responses, indicating more developed cortical processing.

Better behavioural electrode discrimination was associated with stronger, more consistent ACC responses in the CI group, whereas poorer discrimination was associated with fewer or no responses. Children with more robust ACCs typically scored higher on speech perception tests, and statistical analysis showed a strong positive correlation between ACC amplitude and behavioural electrode discrimination performance. Even very young or non-verbal children can provide ACC responses, demonstrating the viability of applying this measure in populations where trustworthy behavioural feedback is unavailable. According to He et al. (2014) the spatial ACC, is a valid and impartial indicator of auditory discrimination in children who use cochlear implants. According to the study, ACC presence and amplitude predict speech perception outcomes and closely match behavioural electrode discrimination. These findings support the inclusion of ACC in routine paediatric CI evaluation and rehabilitation planning, highlighting its clinical utility for assessing cortical auditory development and implant performance in children with ANSD, particularly when behavioural testing is challenging.

Using multichannel CI, Dawson et al. (2000) examined electrode discrimination and its connection to speech perception in 17 children ages 4 to 10. Children were asked to indicate when stimulation changed between electrodes along the cochlear array during a play-based change-detection task. Level jitter up to 40% was incorporated into the stimuli to avoid dependence on loudness cues. In addition, participants finished a nonverbal intelligence test (K-ABC), a speech feature test (SFT), and a closed-set word recognition task. Each child's smallest discriminable electrode separation (SDES) was calculated after electrode discrimination was evaluated in the apical and mid-array regions. Around 65% of the children in Dawson et al. (2000) study were able to distinguish between adjacent electrodes in at least one cochlear region, whereas others required separations of up to 9 electrodes. The average smallest discriminable electrode separation (SDES) was less than two electrodes. With mean scores of 77.6% on the Speech Feature Test and 85.4% on the word recognition test, children demonstrated superior speech perception skills for vowel contrasts compared to consonant contrasts. Better electrode discrimination was associated with higher speech perception performance, as evidenced by a significant negative correlation between SDES and speech perception scores. While variables such as age at implantation or length of deafness did not significantly affect results, electrode discrimination accounted for 37% of the variance in word recognition scores and 66% of the variance in speech-feature discrimination.

The reliability of recording the electrically evoked eACC in adult CI users was first demonstrated by Brown et al. (2008). To replicate spectral changes and measure cortical responses via EEG, they alternated activation between two electrodes along the cochlear array using direct electrical stimulation via the Nucleus CI system. According to the study, eACC waveforms showed a distinct N1–P2 complex following the electrode change and closely

matched conventional onset CAEPs. Additionally, as electrode separation increased, eACC amplitude rose, and latency fell, demonstrating that the cortical response is sensitive to spectral and spatial variations in electrical stimulation.

2.3.2. Fundamentals of ACC testing

The ACC provides objective, neurophysiological insight into a paediatric CI user's spectral resolution, that is, their ability to discriminate between electrical channels or acoustic frequencies. The ACC verifies whether the brain detects a spectral difference because young children are unable to accurately report what they hear.

2.3.3 Uses of ACC testing

In particular, the ACC evoked by temporal gaps (electrically or acoustically) is an objective indicator of the neural ability in children to detect brief periods of silence, a critical temporal cue for speech perception, in a continuous auditory input. Gap-evoked ACCs have been shown to be a promising tool for assessing temporal resolution in paediatric CI users (He et al., 2014) successfully recorded eACC responses to temporal gaps in children with cochlear implants and ABI, thus confirming the feasibility of this method as an objective assessment tool of temporal processing capabilities.

Similarly, Xie et al. (2022) found significant relationships between speech perception outcomes and ACC responses to temporal gaps, suggesting that temporal ACC measures may serve as useful predictors of speech recognition performance in CI users. These findings emphasise the potential utility of gap-evoked ACC testing as a non-behavioural tool for assessing auditory temporal resolution in paediatric implant populations. The eACC can serve as an objective measure of electrode or place discrimination in paediatric CI users. Interchanging stimulation between different electrodes of the CI alters waveform amplitude and latency,

yielding eACC responses that indicate the auditory system's ability to discriminate stimulation from different electrode sites. This information would be helpful for optimising the mapping of the CI, especially when behavioural feedback is limited.

He et al. (2014) reported that eACC responses showed high sensitivity to changes in electrode position and a significant relationship with behavioural electrode discrimination and speech perception in children with ANSD, supporting its use as an objective tool for assessing spatial auditory resolution in paediatric CI users. ACC measures, especially those elicited by temporal-gap stimuli, have shown significant correlations with speech perception skills in CI users. Studies indicate that ACC amplitude and latency may function as neural predictors of functional listening performance.

Xie et al. (2022) reported that ACC amplitudes evoked by temporal gaps significantly predicted both disyllabic word recognition scores in quiet and SRTs in noise. Similarly, He et al. (2014) demonstrated a clear relationship between ACC gap-detection thresholds and behavioural speech-perception measures in paediatric CI users. These findings suggest that ACC metrics may serve as reliable objective indicators of speech perception outcomes in children with cochlear implants.

The ACC and its electrically evoked counterpart, eACC, have demonstrated feasibility in young or difficult-to-test paediatric populations, allowing for an objective assessment of auditory discrimination when behavioural testing is unreliable. Studies have demonstrated the clinical use of ACC/eACC in children with ANSD and CND, including for evaluating CI candidacy and setting realistic expectations post-implantation. He et al. (2014) demonstrated that ACC responses could indicate cortical detection of auditory change in children with ANSD, and He et al. (2018) showed the feasibility of recording eACC responses in children receiving ABI or with

CND. Meehan et al. (2024), in a systematic review of ACC measurements in children, highlighted the potential of the ACC as an objective measure of the neural capacity for sound and speech discrimination. ACC is described as a cortical auditory evoked potential caused by the perception of a change in an already perceived acoustic signal. In contrast to previous measures of cortical auditory evoked potentials, which have mostly been used to assess sound-onset-related events, ACC can be considered a method for assessing the auditory system's ability to process changes in acoustic stimuli, such as frequency, amplitude, duration, and speech sounds. According to the study, ACC was considered a potential objective measure of auditory discrimination because it does not depend on listeners' active behaviour. The review demonstrated that ACC responses can be reliably recorded in infants and children, including paediatric cochlear implant users, and may provide clinically useful information regarding auditory discrimination abilities. The authors further suggested that ACC measures could help guide hearing intervention and rehabilitation strategies, particularly in difficult-to-test paediatric populations. However, they emphasised the need for additional research to establish stronger relationships between objective ACC responses and behavioural measures of speech perception for effective clinical implementation.

Children and adults show similar ACC waveform morphology during development; however, younger listeners exhibit longer latencies and smaller amplitudes, reflecting maturational effects in cortical processing (Small & Werker, 2012; Strahm et al., 2022). The ACC has been successfully recorded in CI users with both electric and acoustic stimuli, demonstrating that it represents central cortical encoding of change rather than peripheral or device-related responses (He et al., 2014; Mathew et al., 2017). Converging evidence suggests that the ACC provides an objective measure of auditory discrimination ability in both normal-

hearing and hearing-impaired populations, and that it functions as a neural marker of cortical discrimination of acoustic changes, particularly tone frequency shifts.

2.4. ACC responses and relationship with speech perception among CI users

Effective speech perception relies heavily on the ability to distinguish frequency variations for phoneme recognition, word identification, and prosody comprehension. Spectral resolution, often impaired in children with CIs, can be evaluated by measuring brain responses such as the ACC. These responses have been linked to a child's capacity for frequency discrimination and are predictive of speech outcomes Xie et al. (2022). However, gaps in the literature persist regarding the role of the ACC in paediatric CI users, especially its connection to real-world speech perception. Although widely explored in adults and children with normal hearing, relatively few studies have focused on its application in paediatric CI populations. Electrode discrimination is essential to optimising CI speech perception, as it reflects channel independence along the electrode array. High channel independence improves spectral resolution by allowing electrodes to stimulate distinct neural populations. Conversely, overlapping stimulation fields blur spectral cues, reducing intelligibility.

Electrode discrimination testing can identify overlapping electrodes, allowing clinicians to deactivate underperforming ones and enhance signal clarity (Lien et al., 2025). Warren and Atcherson (2023) highlighted that poor electrode discrimination signals excessive channel interaction, compromising spectral resolution. Through behavioural pitch-ranking tasks, clinicians can deactivate poorly performing electrodes while retaining functional ones. This individualised strategy has produced measurable gains in speech perception, both in quiet and noisy environments, with participants generally preferring the adjusted stimulation maps. Importantly, outcomes improved over time, emphasising that neural adaptation to revised

stimulation enhances long-term benefits. In adults, electrode discrimination has been objectively assessed using the spatial ACC, a cortical response to changes in stimulation site. The spatial ACC can be recorded as early as one-week post-implantation and correlates strongly with behavioural discrimination scores, sometimes offering predictive insights beyond behavioural tests (Mathew et al., 2017). This highlights its value as a robust neurophysiological indicator of the electrode–neural interface with potential applications for guiding rehabilitation and improving long-term auditory outcomes in both adults and children.

The relationship between electrode discrimination ability and speech perception performance in paediatric cochlear implant users has been well documented using both behavioural and electrophysiological measures. A strong, significant inverse correlation was found between electrode-discrimination thresholds and PBK word scores: $r = -0.96$; $p < 0.01$, which indicated that children who have poorer electrode discrimination-i.e., requiring larger changes in stimulation to detect a difference-tend to have lower speech-perception performance. In fact, according to Dawson et al. (2000), there is a clear link between behavioural electrode discrimination and word recognition performance in paediatric patients with CI, with poor spectral resolution correlating with poor word recognition.

He et al. (2014) found eACC sensitivity to changes in stimulating electrode position and reported associations between eACC, behavioural electrode discrimination and speech perception in paediatric CI users (incl. ANSD). When comparing performance groups, children classified as good performers (PBK score ≥ 70% correct) showed better electrode discrimination, requiring only a one-electrode separation to detect behavioural and cortical response changes, as measured by the electrically evoked Acoustic Change Complex (eACC). Children who were

poor performers (PBK score < 70% correct) typically needed at least 2 electrodes apart to reliably hear the change, indicating coarser spectral resolution within the implant array.

Electrophysiological data further supported these behavioural findings: good performers demonstrated significantly larger eACC root-mean-square (RMS) amplitudes, reflecting more robust cortical encoding of spectral changes. Larger RMS amplitudes are suggestive of more effective neural representation of electrode place differences, consistent with better speech understanding. Together, these findings highlight the importance of the eACC as an objective and predictive tool for measuring electrode-discrimination capacity in children who receive cochlear implants. By offering an electrophysiological correlate of spectral resolution, the eACC provides a clinically useful, non-behavioural indicator of a child's potential speech-perception performance.

Meehan et al. (2024) emphasised that speech perception is fundamental and inherently linked to the auditory system's capacity to discriminate dynamically variable sounds, which is why the ACC is a promising objective tool in this area. A number of included studies have examined this relationship by contrasting objective measures of ACC with behavioural tests of speech discrimination. In three studies, significant correlations were observed between ACC measures and open-set speech perception, using a variety of speech materials (e.g., words and sentences) in quiet and noise. More specifically, among children with ANSD who used either CIs or hearing aids, there was a significant association between improved ACC gap-detection thresholds and improved scores on the PBK words. Moreover, results showed that the amplitude of the ACC evoked by a temporal gap significantly predicted recognition of disyllabic words in quiet and in SRTs in noise for CI users. For infants, ACC responses to vowel-contrast detection were more sensitive and robust than behavioural measures, such as the VRISD paradigm; the

former showed sensitivity over 90%, whereas VRISD showed approximately 70%. The VRISD (Visual Reinforcement Infant Speech Discrimination) task is a behavioural method designed to assess the ability of babies, who are still too young to provide verbal responses, to discriminate between speech sounds. The test relies on the conditioned orientation response, in which babies learn to orient towards the direction of a stimulus as they detect a difference between two sounds, such as the distinction between /ba/ and /da/, or even the contrast between vowels. Once the baby learns to discriminate and detect differences in sounds, visual reinforcement, such as a lit-up toy or other visual stimuli, is rewarded. Overall, the review supports the use of ACC measurements as an assessment tool for neural discrimination of speech and potentially for guiding early hearing intervention choices for children, including those being considered for CIs.

Ching et al. (2023) shows that the ACC is a valid and reliable electrophysiological index of the brain's capacity to process acoustic changes in speech that can be used as an objective measure of speech discrimination capacity in awake infants with and without hearing loss, from 3 to 12 months of age. Key findings were that ACC responses to stimuli targeting low-frequency (voicing via [szs], mid-frequency [uiu], and high-frequency (Spectral Ripple Noise) spectral changes could be recorded in most infants, while response rates decreased with increased hearing loss, particularly for the high-frequency stimulus. Importantly, the objective measure of ACC was significantly and positively related to subjective, parent-reported functional auditory performance in real life, as measured by the PEACH scale ($r=0.37$, $p<0.001$). The authors concluded that the ACC indicates physiological evidence of the potential capacity to discriminate sounds by children as young as 3-6 months of age, so the use of ACC as a clinical tool might be an important adjunct to the evaluation of hearing aid fitting and early intervention decisions,

such as referral for cochlear implantation, especially for infants with severe-profound hearing loss.

McGuire et al. (2021) explored indices of cortical processing and found that they were associated with speech perception outcomes in adult CI users. The specific focus was to determine objective and behavioural factors predicting variability in speech perception performance, with a particular emphasis on frequency discrimination performance as a critical factor in the cortical-level change processing of auditory stimuli. FCDT (Frequency Change Detection Threshold) refers to the smallest percentage change in frequency within a continuous tone that a listener can reliably detect. It is a behavioural measure of sensitivity to within-stimulus spectral changes. Lower FCDT values indicate better frequency-change detection ability and superior spectral resolution, whereas higher FCDT values indicate poorer sensitivity to frequency changes. The authors reported that the mean FCDT strongly predicted speech perception performance and suggested a cutoff value of 10%, with individuals showing FCDTs ≥ 10% demonstrating poorer speech recognition outcomes across speech measures. Behaviourally, FCDT was found to be an essential predictor of speech perception performance. Subjects with lower (better) mean FCDT scores showed higher scores on several standardised tests of speech perception performance, such as CNC word recognition, CNC phoneme identification, AzBio sentence recognition in quiet and in noise, and Digit in Noise (DIN) speech reception threshold. By contrast, subjects with increased FCDT (≥10%) showed poor performance across all speech perception measures, suggesting that reduced sensitivity to spectral differences was highly predictive of impaired speech recognition in both quiet and noisy environments.

Electrophysiologically, auditory change response latencies (cortical ACC latencies), specifically N1′ and P2′ latencies, also showed significant correlations with speech perception

results. Increased ACC N1′ latency was significantly associated with poorer speech perception performance, showing negative correlations with CNC word recognition ($r = -0.40$, $p < .05$) and CNC phoneme recognition scores ($r = -0.40$, $p < .05$). Additionally, N1′ latency was positively correlated with mean FCDT ($r = 0.46$, $p < .05$), suggesting that delayed cortical processing was associated with poorer frequency-change detection ability. Similarly, ACC P2′ latency demonstrated positive correlations with DIN thresholds ($r = 0.47$, $p < .05$) and mean FCDT ($r = 0.47$, $p < .05$), indicating that delayed cortical responses were associated with reduced speech-in-noise perception and poorer spectral discrimination. All these results indicate that the delay in the cortical analysis of spectral changes is associated with inefficiency in auditory discrimination processes, which are crucial for speech perception. Even though morphologically the ACC amplitudes demonstrated some difference between good and poor listeners, peak-to-peak ACC amplitudes (N1′–P2′) did not reveal any significant correlation with speech perception abilities. In contrast, there was no significant difference between poor and good speech perceivers on demographic measures such as duration of hearing loss, years with CI, and age at CI surgery, even though a pattern emerged in which poor performers had more years of deafness. In general, McGuire et al. (2021) demonstrated that frequency discrimination and auditory processing measures, especially ACC latency measurements, show stronger correlations with speech perception outcomes than biographical variables.

Van Heteren et al. (2022) investigated the relationship between speech perception performance and both psychophysical frequency discrimination and electrophysiological indices of cortical auditory processing in cochlear implant (CI) users, including bilaterally deaf (BD-CI) and single-sided deaf (SSD-CI) individuals. The study aimed to identify objective, non-linguistic predictors of speech perception outcomes by integrating behavioural, cognitive, and

neurophysiological measures. At the behavioural level, the frequency discrimination threshold (FDT) showed a strong correlation with speech perception: poor spectral resolution was associated with worse performance in recognising CVCs in noise and lower DIN speech reception thresholds. The relationships persisted in CI ears only, indicating the significance of FDT in predicting performance on speech perception tasks in quiet and noisy conditions. Regarding electrophysiology, there was a clear complementarity between ACC parameters: short N1 latency ($r = -0.69$, $p = .002$) and large N1-P2 amplitude correlated with good speech perception performance ($r = 0.53$, $p = .020$), especially in noise. In contrast, P2 latency did not correlate with speech perception performance ($r = -0.52$, $p = .033$). Neither the estimated IQ nor prior musical experience had any effect on speech perception or psychophysical test results, and there were no predictions for speech perception in SSD-CI participants from their contralateral, normally hearing ear results, indicating a low impact of general cognition or cross-ear effects. All the findings indicate significant prediction of speech perception in CI users by behavioural frequency discrimination and cortical timing and amplitude metrics derived from ACC responses.

Liang et al. (2018) explored electrophysiological and psychoacoustic predictors of speech perception outcomes among adult cochlear implant users by evaluating Acoustic Change Complex (ACC) in response to within-stimulus frequency changes and behavioural frequency change detection threshold (FCDT). The results of their research revealed that lower ACC N1′ latency was significantly correlated with better speech perception, especially for CNC words ($R^2 = .36$, $p < 0.05$). The researchers concluded that rapid cortical spectral encoding of the stimulus enhances speech comprehension. In turn, ACC peak-to-peak amplitude was not a significant predictor of participants' success. At the behavioural level, high FCDT was significantly

correlated with ACC N1′ latency, confirming the strong relationship between the speed of cortical processing and psychoacoustic frequency discrimination performance. Moreover, the duration of deafness contributed to the poor frequency discrimination skills. In this respect, the AzBio score did not demonstrate any significant correlations with the ACC latency measure. The combination of cortical processing measures assessed using the ACC, along with psychoacoustic frequency discrimination, is an important predictor of participants' speech perception performance.

According to Mathew et al. (2018), an investigation was conducted into the relationship between behavioural discrimination abilities for apical electrodes and electrophysiological measures generated from the spatial Acoustic Change Complex (ACC) to determine whether either predicted speech perception outcomes in adults after activation of their cochlear implants during the first six months. The behavioural measures revealed that behavioural discrimination ability for the apical electrodes strongly predicted good performance on open-set sentences (BKB sentences) and closed-set vowel identification. This implied that better spatial resolution ability at apical electrodes was associated with improved speech comprehension. On the other hand, electrophysiological ACC measures such as peak-to-peak amplitudes and the number of objectively discriminable electrode channels were not significant predictors of speech perception.

Han & Dimitrijevic. (2020) studied the association between responses to acoustic change complex (ACC) elicited by an amplitude modulation (AM) frequency change and speech perception ability in CI recipients. Results showed that ACC N1 latency induced by 40 Hz AM change was significantly correlated with speech perception scores. In particular, shorter N1 latency in ACC response to 40 Hz AM change predicted better perception of vowels, consonants,

words, and sentences during silent conditions. Moreover, individuals with shorter 40 Hz N1 latency showed enhanced vowel perception and word recognition scores when exposed to environmental noise. Group analysis of speech-in-noise performance showed that poor performers had greater N1 latency than better performers, suggesting inefficient cortical processing of sound in the time domain. However, there were no significant associations between ACC N1 amplitude and responses to other AM changes (4 Hz, 100 Hz, and 300 Hz). These results indicate that the latency of cortical encoding, especially the latency of the N1 elicited by changes in 40 Hz modulation amplitude, could serve as an objective physiological marker of speech perception in CI users.

Zhang et al. (2019) highlighted the importance of the ACC as a neural marker of auditory processing that is closely related to speech perception in cochlear implant users. It was noted that, due to the resemblance between the within-interval frequency change method employed for generating ACC and the dynamics in frequency that characterise natural speech (e.g., formant changes or alterations in fundamental frequency), this process differs from traditional pitch discrimination tasks that compare two separate stimuli. More specifically, unlike classic pitch discrimination tasks that focus on comparisons between stimuli, the ACC can be regarded as the result of an instantaneous frequency change within the presented stimuli. Given the significance of detecting dynamic acoustic parameters for speech comprehension, this implies that the mechanisms underlying ACC generation must be directly linked to speech perception. Specifically, the study indicates that the ACC reflects cortical processing of complex frequency changes in electrodes, as reflected in changes in frequency.

Chapter III

Method

The present study aimed to investigate how the cochlea's apical and basal regions' acoustic change complex (ACC) responses to tone frequency changes and their relationship to speech perception outcomes in paediatric cochlear implant (CI) users.

3.1. Participants

The study involved 19 paediatric unilateral CI recipients, consisting of 12 males and 7 females. The average age during testing was 6.98 years, with a range from 6 to 9 and a standard deviation of 1.14 years. All participants had received Cochlear Nucleus (Cochlear Ltd, Australia) implants and had been using the CI for at least 1 year. The average age at implantation was 4.74 years, with a standard deviation of 1.37 years. The children were diagnosed with bilateral severe to profound congenital hearing loss and underwent unilateral cochlear implantation. All the participants had a congenital onset of hearing loss. Sixteen children received implants in the right ear, and three in the left, based on pre-implant radiological evaluations.

All participants had a normal cochlear anatomy and auditory nerves in the implanted ear. A fully inserted electrode array confirmed by intraoperative neural response telemetry measures and post-operative X-ray reports. All participants wore the CI during waking hours and used a digital behind-the-ear hearing aid in the non-implanted ear. All participants had normal electrode impedance across all intracochlear electrodes. Their aided sound-field thresholds with the CI ranged from 20 to 30dB HL across frequencies of 250 to 8,000Hz. The children received standard care, including CI programming and auditory-verbal therapy, for 1 year. None of the participants had associated behavioural, cognitive, or neurological disorders. Table 3.1 presents the demographic information for the participants in the present study.

Table 3.1

Demographic information of the participants of the present study.

Participants	Sex	Ear	Implant model	Speech Processor	Age at Implantation (years)	Age at testing (years)	Time in use (years)
S1	M	Left	CI24RE	CP802	3.0	9.0	6.0
S2	F	Right	CI522	CP802	6.0	8.0	2.0
S3	F	Left	CI422	CP1002	8.0	9.0	1.0
S4	M	Right	CI422	CP802	5.0	8.0	3.0
S5	M	Left	CI422	CP802	5.0	8.0	3.0
S6	M	Right	CI422	CP802	5.0	8.0	3.0
S7	M	Right	CI422	CP802	5.0	6.8	1.8
S8	M	Right	CI422	CP802	4.0	6.0	2.0
S9	M	Right	CI422	CP802	5.0	6.0	1.0
S10	F	Right	CI24RE	CP802	3.9	6.0	2.1
S11	M	Right	CI422	CP802	4.0	7.0	3.0
S12	M	Right	CI422	CP802	4.0	7.0	3.0
S13	F	Right	CI422	CP802	4.2	6.0	1.8
S14	M	Right	CI422	CP802	5.0	6.0	1.0
S15	F	Right	CI422	CP802	4.0	6.0	2.0
S16	M	Right	CI422	CP802	4.0	6.0	2.0
S17	F	Right	CI422	CP802	3.0	6.0	3.0
S18	M	Right	CI422	CP802	8.0	9.0	1.0
S19	F	Right	CI522	CP1002	4.0	7.0	3.0

Note= M= male; F= Female

3.2. Ethical Consideration

Ethical approval for Bio-behavioural research was given by the AIISH Institute Review Board (IRB) on 06/01/2026 with Reference number SH/IRB/M.4/AUD.39/2025-26. All the testing procedures in the present study were performed using a non- invasive approach. Written informed consent was obtained from all the participants' parents or legal guardians before their inclusion in the study. The copy of the ethical approval is given in Appendix 1.

3.3. Test environment

The ACC testing and aided speech perception measurements were carried out in sound-treated audiometric rooms with noise levels within the maximum permissible noise levels (ANSI S3.1-1991) (R2013).

3.4. Instrumentation

- A calibrated dual-channel diagnostic audiometer with a sound field was used for the measurement of speech perception testing.
- A calibrated Intelligent Hearing System (IHS) Smart EP (IHS, Florida, USA) Auditory Evoked Potentials (AEP) system with an advanced research module was used for measurement of aided acoustic change complex (ACC) testing.

3.5. Stimuli for ACC Recording

The stimuli were generated using MATLAB with a sampling rate of 44.1 kHz. Each stimulus comprised three sequential segments:

(1) a 400 ms steady-state tone at the base frequency (f1),

(2) a 10 ms logarithmic frequency glide from f1 to the target frequency (f2), and

(3) a 400 ms steady-state tone at f2, yielding a total stimulus duration of 810 ms.

Logarithmic (exponential) frequency modulation was employed during the glide to generate a perceptually smooth pitch transition. Phase continuity was maintained across all segment boundaries to eliminate spectral discontinuities and audible clicks. All stimuli were enveloped with a cosine-squared amplitude gate applied exclusively at stimulus onset and offset (10 ms rise/fall time each), leaving the frequency transition segment unmodulated. Two base frequencies (500 Hz and 4000 Hz) were selected to span the speech frequency range, with frequency targets reflecting clinically relevant electrode spacing in cochlear implants: at 500 Hz,

targets were 525, 625, and 875 Hz; at 4000 Hz, targets were 4040, 4400, and 5600 Hz. Control stimuli (500→500 Hz and 4000→4000 Hz) with identical temporal and envelope characteristics, but with no frequency change, were included to confirm that any cortical response was specific to the acoustic change and not attributable to the stimulus structure itself. All audio files were normalised to 90% of full scale and saved as 16-bit PCM .wav files.

The Cochlear™ Nucleus implant contains 22 intracochlear electrodes, numbered E01 to E22, with the first electrode (E01) situated near the basal side of the cochlea and the last electrode (E22) on the apical side. Each electrode has been assigned a frequency range based on the participant's clinical MAP. In the present study, the stimuli have been developed to activate specific electrodes by varying the frequency of the acoustic stimulus within each electrode's respective frequency range.

For apical stimulation, a base frequency of 500 H**z** was selected, as this frequency falls within the frequency allocation range of electrode 20 (E20: 500–525 Hz). Thus, the 500 Hz stimulus primarily activated E20. Tone frequency changes were then introduced to progressively stimulate the adjacent electrodes. The stimulus conditions were as follows:

- 5% increase: Same electrode (Within electrode 20): 500-525 Hz.
- 25% increase: +1 adjacent electrode (stimulated E20 and E19): 500-625 Hz.
- 75% increase: +3 adjacent electrode (stimulated E20 and E17): 500-875 Hz.

For the apical stimulation conditions, a base frequency of 500 Hz was selected because it fell within the frequency allocation range of electrode 20 (frequency allocation of E20: 438-563 Hz). A 5% frequency increase remained within the frequency range assigned to E20, thereby stimulating the same electrode. A 25% increase extended the frequency range to 625 Hz, resulting in stimulation of E20 and the immediately adjacent electrode 19 (frequency allocation

of E19: 563-688 Hz). Similarly, a 75% increase extended the frequency range to 875 Hz, recruiting E20 along with electrode 17 (frequency allocation of E17: 813-938 Hz), thereby stimulating three adjacent electrodes from the target electrode.

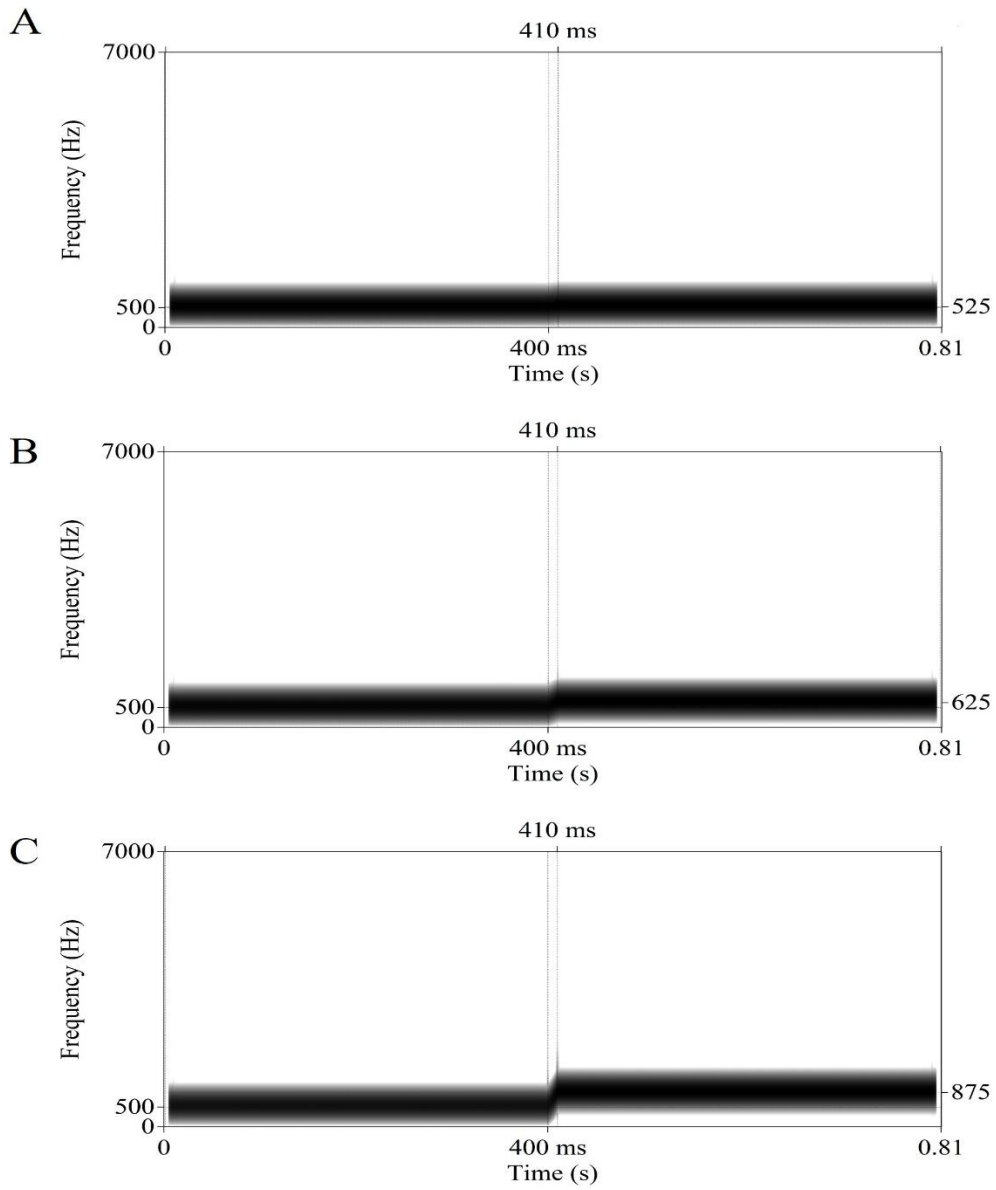
Similarly, for basal stimulation, a base frequency of 4000 Hz was selected because it fell within the frequency allocation range of electrode 06 (E06: 4000–4040 Hz). Therefore, the base stimulus primarily activated E06. Subsequent frequency increases were designed to stimulate neighbouring basal electrodes. The stimulus conditions were:

- 1% increase: Same electrode (within E06): 4000-4040.
- 10% increase: +1 adjacent electrode (stimulated E06 and E05): 4000-4440 Hz.
- 40% increase: +3 adjacent electrode (stimulated E06 and E03): 4000-5600Hz.

For the basal stimulation conditions, a base frequency of 4000 Hz was selected because it fell within the frequency allocation range of electrode 06 (E06: 4000–4040 Hz). A 1% frequency increase remained within the frequency range assigned to E06, thereby stimulating the same electrode (frequency allocation of E06: 3563–4063 Hz). A 10% increase extended the frequency range to 4440 Hz, resulting in stimulation of E06 and the immediately adjacent electrode 5 (frequency allocation of E05: 4063-4688 Hz). Similarly, a 40% increase extended the frequency range to 5600 Hz, recruiting E06 and electrode 3 (E03: 5313–6063 Hz), thereby stimulating three adjacent electrodes from the target electrode.

Figure 3.1

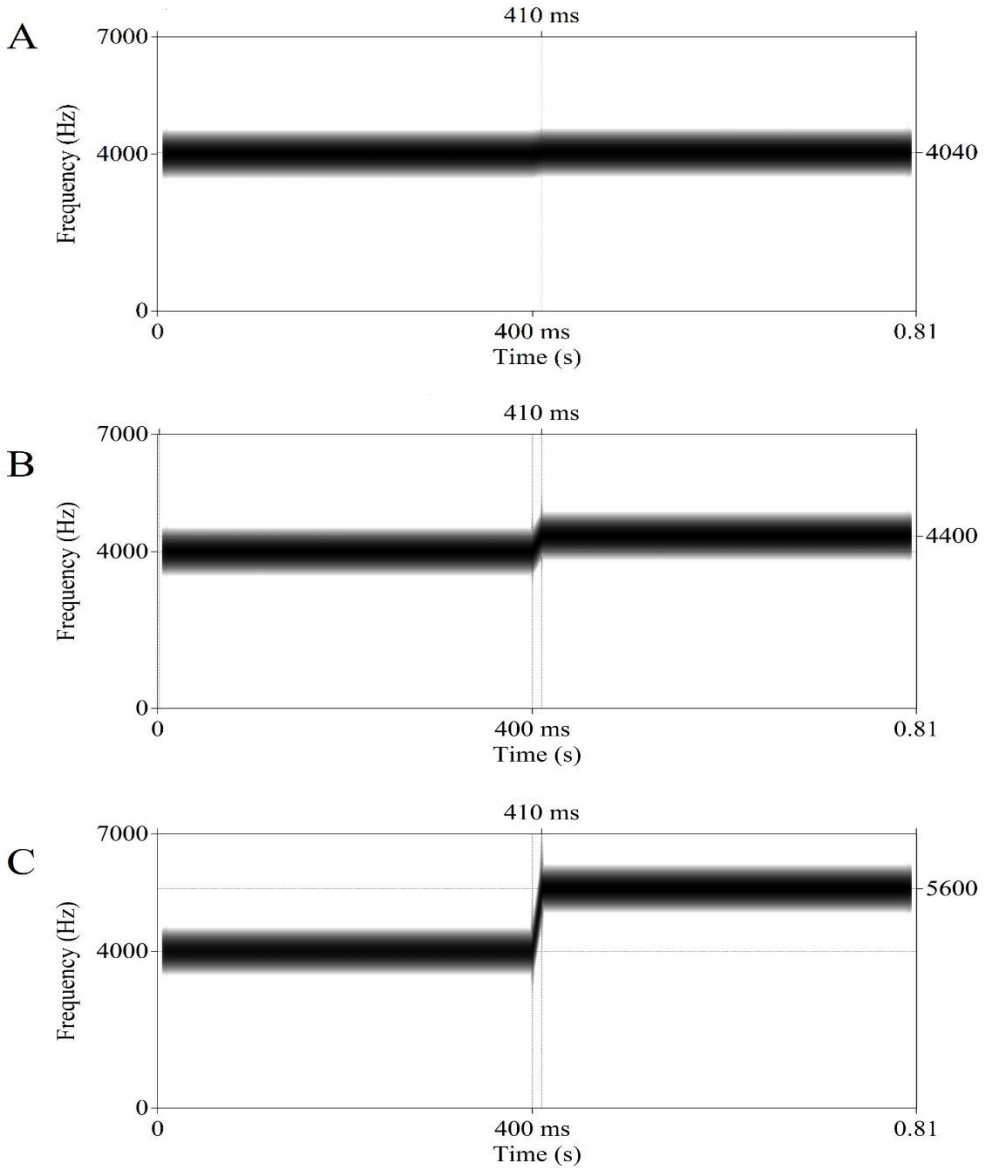
Spectrographic representation of the 500 Hz base frequency stimulus, along with tone frequency changes for ACC recording, A) 500-525 Hz, B) 500-625 Hz and C)500-875 Hz



Note. ACC- Acoustic Change complex*;* The stimuli had a base frequency of 500 Hz (electrode 20). Frequency changes occurred at 410 ms and corresponded to 5% (500–525 Hz; same electrode), 25% (500–625 Hz; +1 adjacent electrode), and 75% (500–875 Hz; +3 adjacent electrodes) increases.

Figure 3.2.

Spectrographic representation of the 4000Hz base frequency stimulus, along with tone frequency changes for ACC recording, A) 4000-4040 Hz, B) 4000-4440 Hz and C)4000-5600 Hz



Note. ACC- Acoustic Change complex*;* The stimuli had a base frequency of 4000 Hz (electrode 06). Frequency changes occurred at 410 ms and corresponded to 1% (4000–4040 Hz; same electrode), 10% (4000-4400Hz; +1 adjacent electrode), and 40% (4000-5600Hz; +3 adjacent electrodes) increases.

3.6. Procedure

The study procedure included ACC measurement and aided sound field speech perception testing in the implanted ear.

3.6.1 ACC Measurement

During the ACC recording sessions, all children were seated comfortably in a quiet testing environment. Each session lasted about 45 minutes and included electrode placement and the actual ACC recordings. The recordings were performed using two channels: one focused on the ACC recording. In contrast, the second channel was used to monitor and eliminate eye-blink artifacts, with electrodes placed on the upper and lower parts of the eye. The electrodes were arranged following the international 10–20 system. During testing, the hearing aid in the contralateral, non-implanted ear was removed or turned off to eliminate acoustic stimulation from the non-test ear. Participants were seated in a comfortable reclining chair and instructed to remain relaxed throughout the recording procedure. To minimise movement artifacts and facilitate cooperation during testing, a muted cartoon video was presented for visual engagement. The electrode application areas were treated with a mildly abrasive skin-preparation gel (Nu-Prep) to ensure optimal conductivity.

The absolute impedance at each electrode location was maintained below 5 kΩ, and the interelectrode impedance was kept at 2 kΩ. The non-inverting electrode was positioned at the vertex (Cz) and above the opposite eye, while the inverting electrodes were situated on the opposite mastoid and below the opposite eye. The ground electrode was placed on the lower forehead (Fpz). Data were captured at a sampling rate of 930 Hz, with online band-pass filtering applied to the 1-30 Hz range. At least two visually reproducible responses were collected for

each recording session, which included 100 sweeps. Table 3.2 shows the stimulus and acquisition parameters that were used in the ACC recording.

Table 3.2.

Stimulus and Acquisition parameters for ACC recording.

Parameter	Details
Stimulus parameters	
Transducer	Loudspeakers at 0° azimuth
Stimulus Type	Pure tone signal
Base Frequency 500Hz	5% increase: within (E20)- 500-525Hz, 25% increase: +1 adjacent electrode (E20&E19)-500-625Hz, 75% increase: +3 adjacent electrode (E20 &E17)- 500-875Hz.
Base Frequency 4000Hz	1% increase: within (E06)- 4000-4040Hz,10% increase: +1 adjacent electrode (E06&E05)-4000-4040Hz, 40% increase: +3 adjacent electrode (E06 &E03)- 4000-5600Hz.
Duration	810 ms (frequency change at 400 ms)
Intensity	70 dB SPL
Polarity	Alternating
Rate	0.9 per second
Rise/Fall Time	30 ms cosine ramp at onset and offset
Acquisition parameters	
Analysis Window	1000 ms
Pre-stimulus Interval	100 ms
Filter Setting	1–30 Hz
Number of Sweeps	100
Artifact Rejection	±100 µV
Amplification	50,000
Channel 1	Non-inverting: Vertex (Cz); Inverting: Contralateral mastoid (M1)
Channel 2	Non-inverting: Above contralateral eye; Inverting: Below contralateral eye.
Ground Electrode	Lower forehead (Fpz)

Note- ACC = Acoustic change complex

3.6.2. Speech perception measurement

Speech perception was assessed using the Picture Identification Test tailored for Kannada-speaking children (Vandana, 1998). The duration of the speech perception evaluation was roughly 20 minutes. Open-set speech perception was measured with 25 bisyllabic words. The recorded stimuli were presented at 60 dB SPL through a loudspeaker positioned 1 meter from the implanted ear at a 45-degree angle relative to the implanted ear, utilising a calibrated diagnostic audiometer. Only the implanted ear was evaluated for speech perception, with the contralateral hearing aid turned off. The child was guided to listen attentively and repeat the words. Initially, each child was familiarised with the task through trial items. The response was audio-recorded for the data analysis. During analysis of the recorded samples, articulation errors were taken into account in scoring speech identification.

3.7. Data Analysis

The grand average ACC responses were plotted using the plot function in the EEGLAB toolbox. The recorded electrophysiological data were exported and saved as ASCII files for offline waveform analysis. The baseline correction was applied to the pre-stimulus interval of −100 to 0 milliseconds using the custom-designed MATLAB code (Mathworks, USA). The study assessed various dependent variables, including the latency and absolute amplitude of positive peak P1, P2, and negative peak N1 in milliseconds (ms), and the peak-to-peak amplitudes between P1 and N1 (P1-N1) in microvolts (μV) of the LLR and the latency and absolute amplitude of positive peak P1', P2', and negative peak N1' in milliseconds (ms), and the peak-to-peak amplitudes between P1' and N1' (P1'-N1') in microvolts of the ACC. The independent variable was the electrode location (apical and basal). Most commonly, the biphasic responses were observed, and the ACC waveforms were visually inspected by two experienced

audiologists working with CI children. P1 and N1 peaks were identified as the first robust positivity followed by the largest negativity, and the P2 peak was identified as the second positive deflection after N1 of the LLR. Similarly, P1' and N1' peaks were identified as the first robust positivity followed by the largest negativity, and the P2' peak was identified as the second positive deflection after N1' for the ACC. The average waveforms were plotted using the EEGLAB toolbox (Delorme & Makeig, 2004) implemented in MATLAB (Mathworks, USA).

Statistical analyses were performed using SPSS (Statistical Package for the Social Sciences) Version 26 for Windows. The Shapiro–Wilk test was used to assess the normality of the data distribution. Variables that met the assumptions of normality were analysed using parametric statistical tests, whereas non-normally distributed variables were analysed using non-parametric tests. The Friedman test was used to compare latency and amplitude measures of ACC responses across the different electrode stimulation conditions. Post hoc pairwise comparisons with the Bonferroni correction were conducted to identify significant differences between electrode conditions. Correlation analyses using Spearman's rank-order correlation coefficient, depending on the data distribution, were performed to examine the relationship between ACC measures and speech perception performance. A *p*-value of less than 0.05 was considered statistically significant for all analyses.

Chapter IV

Results

The aim of the current study was to compare Acoustic Change Complex (ACC) responses to changes in tone frequency across different electrode locations and to assess the relationships between speech perception and the ACC responses among paediatric cochlear implant (CI) users.

ACC responses to tone frequency changes were observed in all paediatric CI users at apical and basal electrode locations. Most participants showed distinct cortical responses that included P1-N1 and ACC components (P1'-N1'). The ACC P2' peak was not consistently identifiable across all study participants. Due to the inconsistent morphology and absence of a clearly defined P2 component in several recordings, reliable measurement of P2 and ACC P2' latency and amplitude could not be obtained for all conditions. Therefore, only the latency and amplitude measures of the P1 and N1 and ACC P1' and N1' peaks were included for statistical analysis. The ACC responses varied with respect to the tone frequency changes. Larger ACC amplitudes and clearer waveforms were observed with larger frequency changes, indicating better neural discrimination of the acoustic changes.

4.1. Effect of tone frequency changes on ACC latency measures: A within and between comparison of apical and basal electrode stimulations.

4.1.1. ACC P1' latency

Descriptive statistics of ACC P1' latency revealed that, across all stimulus conditions, it was shorter for apical electrodes than for basal electrodes. The same electrode stimulation showed a longer P1' latency than +1 or +3 electrode stimulation at both basal and apical electrodes. In basal electrode stimulation, the median latency was shorter for E06+E03

stimulation (542.9 ms), and a longer latency was observed in E06+E05 stimulation (561.1 ms). During apical electrode stimulations, the median ACC P1' latency decreased gradually from 539.6 ms (E20) to 522.4 ms (E20+E17). The median and interquartile range (IQR) values of ACC P1' latency for E20, E20+E19, E20+E17, E06, E06+E05, and E06+E03 are shown in Table 4.1.

Table 4.1

Median and IQR of the ACC P1' latency (ms) measured at apical and basal electrodes.

Electrode Location	Electrode Stimulation	n	Median	IQR
	E20	19	539.6	20.43
Apical	*E20 + E19*	19	528.9	18.82
	E20 + E17	19	522.4	10.75
	E06	19	555.8	21.50
Basal	*E06 + E05*	19	561.1	37.09
	E06 + E03	19	542.9	32.25

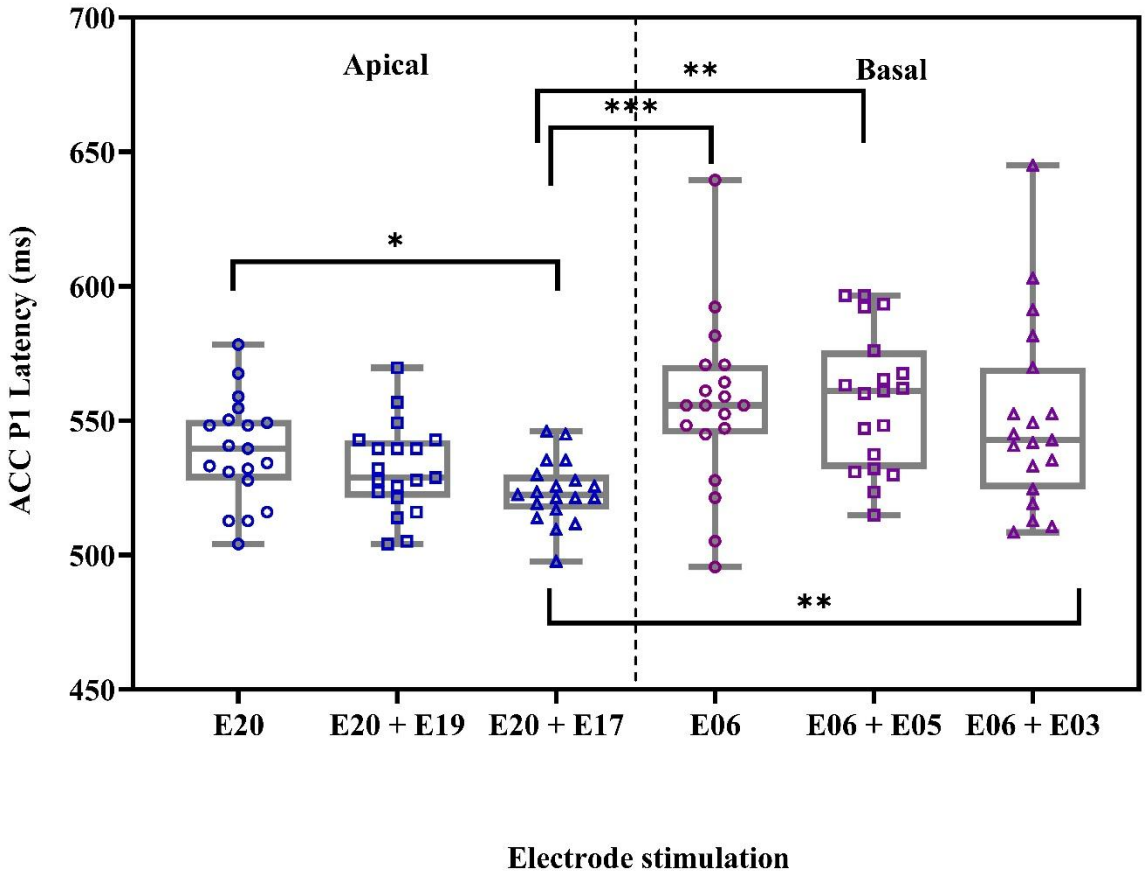
Note. ACC- Acoustic change complex; n – sample size; IQR- interquartile range

A Friedman test was conducted incorporating all six electrode stimulations (E20, E20+E19, E20 + E17, E06, E06 + E05, and E06 + E03). The results revealed that, overall, there was a significant difference in ACC P1' latency across 6 stimulation conditions, measured at basal and apical electrodes [χ^2 (5, N = 19) = 26.318, $p < .001$, Kendall's W = 0.277], with a medium effect size. Subsequent pairwise post hoc comparisons with Bonferroni corrections for multiple comparisons revealed that the significantly lower ACC P1' latency was observed for E20+E17 stimulation in the apical electrodes than compared to the E06 (Z = -4.032, p = .001, r = 0.92), E06+E05 (Z = -4.422, $p < .001$, r = 1.01) and the E06+E05 (Z = -3.338, p = .013, r = 0.77) in the basal electrodes with large effect size. These findings indicate that ACC P1 latency was significantly shorter in the +3 adjacent apical electrode condition (E20+E17) than in any of the basal electrode stimulation. No other pairwise comparisons reached statistical significance after

Bonferroni correction ($p > .05$). Collectively, these results suggest that ACC P1' latency was systematically shorter under apical (+3 adjacent electrode) stimulation than under basal region stimulation. The comparison of the ACC P1' latency is shown in Figure 4.1.

Figure 4.1

Comparison of ACC P1' latency (ms) measured at apical and basal electrodes.



Note. Apical electrodes: Base frequency = 500-525 Hz (E20), +1 = 500-625 Hz (E20 + E19), +3 = 500-875 Hz (E20 + E17); Basal electrodes: Base frequency = 4000-4040 Hz (E06), +1= 4000-4400 Hz (E06 + E05), +3 = 4000-5600 Hz (E06 + E03); ** $p < 0.01$, ***$p < 0.001$; * $p < 0.05$.

A separate Friedman's Two-Way Analysis of Variance by Ranks was conducted for apical and basal electrodes. In the apical electrode stimulations, results revealed that there were

significant differences observed for ACC P1' latency, [χ^2 (2, N = 19) = 11.541, p = .003, Kendall's W = 0.304] with a medium effect size indicating that latency varied as a function of electrode stimulation configuration within the apical region (E20, E20+E19 & E20+E17). Post-hoc pairwise comparisons with Bonferroni corrections for multiple comparisons revealed a significant difference only between E20+E17 and E20 for ACC P1' latency (Z= -4.032, p = .004, r= 0.92) (E20 + E17 < E20) with a large effect size. In contrast, the comparisons between E20+E17 and E20+E19, and between E20+E19 and E20, were not significantly different.

In basal electrodes, the results of the Friedman test showed no statistically significant differences in ACC P1' latency [χ^2 (2, N = 19) = 11.541, p = .368]. Mean ranks were broadly comparable across conditions (E06 = 2.13, E06+E05 = 2.13, E06+E03= 1.74), indicating no significant systematic ordering of ACC P1' latency as a function of electrode separation in the basal region. However, the ACC P1' latency was lower for E06+E03 stimulation than for the other two conditions.

Overall, the findings demonstrated that ACC P1' latency was shorter for apical than for basal electrode stimulations across all conditions. Among the six stimulation configurations, the apical +3 adjacent electrode condition (E20+E17) elicited the shortest ACC P1' latency and showed significantly lower latency than all basal stimulation conditions, indicating faster cortical processing for wider apical electrode separations. Within the apical region, ACC P1' latency decreased significantly as electrode separation increased, whereas no statistically significant differences were observed among the basal electrode conditions. Although the basal +3 adjacent electrode condition (E06+E03) demonstrated relatively shorter latency than the other basal conditions, the differences were not statistically significant. Collectively, these findings suggest

enhanced cortical sensitivity and more efficient neural processing for apical electrode stimulation, particularly with wider electrode separation.

4.1.2. ACC N1' latency across

Descriptive statistics of ACC N1' latency revealed that across all stimulus conditions, it was shorter for apical electrodes than for basal electrodes. Among the apical electrode stimulation, the median N1' latency demonstrated a gradual decrease from 632.1 ms in E20 to 612.7 ms in E20 + E17. In basal electrode stimulation, median latencies ranged from 633.2 ms to 649.3 ms, with the highest latency observed in E06 + E03 stimulation. The median and interquartile range (IQR) values of ACC N1' latency for E20, E20+E19, E20+E17, E06, E06+E05, E06+E03 are shown in Table 4.2.

Table 4.2

Median and IQR of the ACC N1' Latency (ms) measured at Apical and Basal electrodes.

Electrode Location	Electrode Stimulation	n	Median	IQR
	E20	19	632.1	62.35
Apical	*E20 + E19*	19	616.0	60.20
	E20 + E17	19	612.7	41.92
	E06	19	647.1	34.93
Basal	*E06 + E05*	19	633.2	42.46
	E06 + E03	19	649.3	60.20

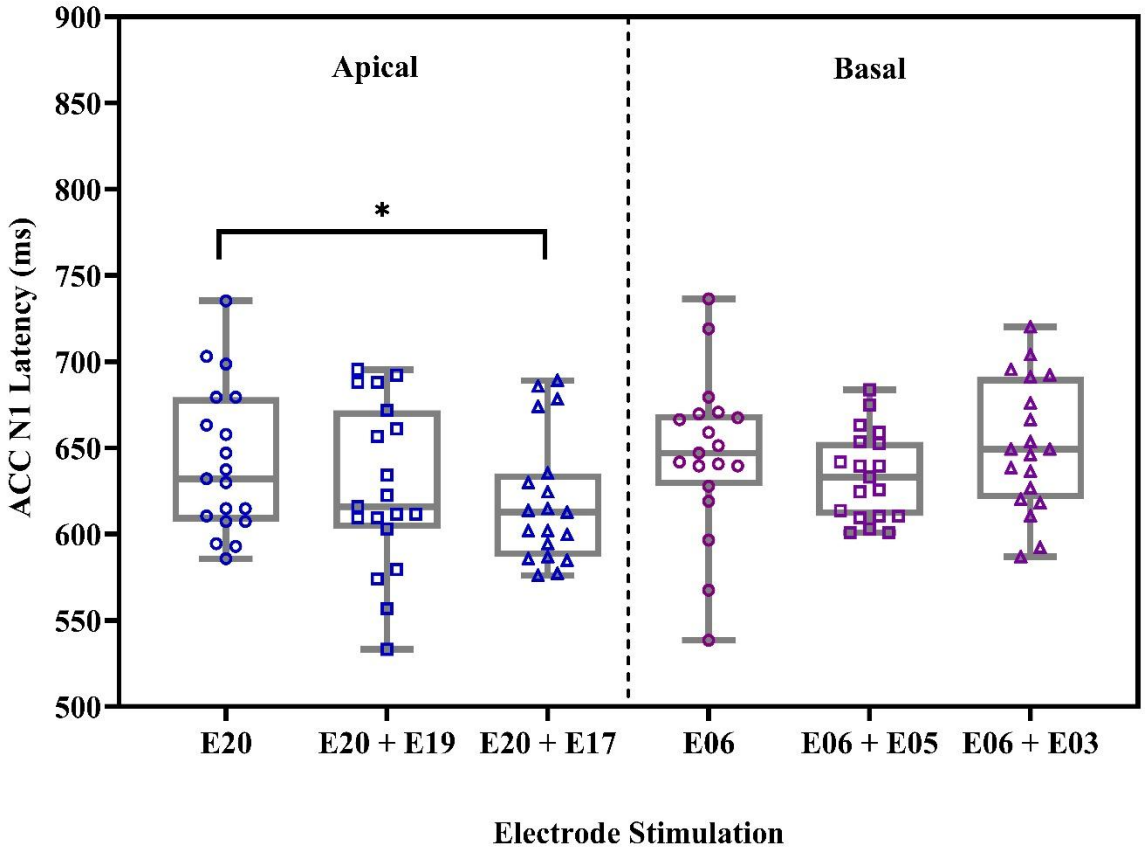
Note. ACC- Acoustic change complex; n – sample size; IQR- interquartile range

A Friedman test incorporating all six conditions was conducted to evaluate overall differences in ACC N1' latency. The results indicated that there was a statistically significant effect, [χ^2 (5, N=19) = 13.612, p = .018, Kendall's W= 0.143], with a small effect size. Pairwise post-hoc comparisons with Bonferroni correction for multiple comparisons identified that the differences in ACC N1' latency between E20 + E17 and E06+E03 (Z = -2.905, p = .055) were close to a significant level. None of the pairwise comparisons showed significant differences in

ACC N1' latency. Similarly to P1' latency, ACC N1' latency was lower (shorter) in the apical +3 adjacent electrode condition (E20+E17) relative to the basal conditions, though the effect was not statistically significant after correction for multiple comparisons in the N1' component. The comparison of ACC N1'Latency is shown in Figure 4.2.

Figure 4.2

Comparison of ACC N1'(ms) latency measured at Apical and Basal electrodes.



Note. Apical electrodes: E20 = 500-525 Hz (Base Frequency), E20+E19 = 500-625 Hz (+1 electrode), E20+E17 = 500-875 Hz (+3 electrode); Basal electrodes: E06 = 4000-4040 Hz (Base Frequency), E06+E05 = 4000-4400 Hz (+1 electrode), E06+E03= 4000-5600 Hz (+3 electrode); * $p < 0.05$

A separate Friedman's Two-Way Analysis of Variance by Ranks was conducted for the apical and basal electrode stimulation conditions. The analysis revealed significant differences in ACC N1' latency across the apical electrode configurations, [χ^2 (2, N = 19) = 8.027, p = .018, Kendall's W = .211], with a small-to-medium effect size. These findings suggest that ACC N1' latency varied as a function of electrode stimulation configuration within the apical region (E20, E20+E19, and E20+E17). Post-hoc pairwise comparisons with Bonferroni correction for multiple comparisons revealed a statistically significant difference only between the E20+E17 and E20 conditions for ACC N1 latency (Z = -2.758, p = .017, r = .63) with a large effect size. Electrode condition E20+E17 demonstrated significantly shorter latency values compared to E20 (E20+E17 < E20). In contrast, the comparisons between E20+E17 and E20+E19 and between E20+E19 and E20 were not statistically significant ($p > 0.05$). In the case of basal electrodes, Friedman test results showed there was no statistically significant difference in ACC N1' latency across the basal electrode stimulation conditions, [χ^2 (2, N = 19) = 5.840, p = .054], indicating that ACC N1 latency did not differ significantly as a function of electrode stimulation configuration within the basal region.

Overall, the findings demonstrated that ACC N1' latency was generally shorter during apical electrode stimulation than during basal electrode stimulation. The apical +3 adjacent electrode condition (E20+E17) elicited the shortest ACC N1' latency among all stimulation configurations, indicating faster cortical processing with wider apical electrode separation. Significant differences in ACC N1' latency were observed within the apical electrode conditions, particularly between E20 and E20+E17, whereas no statistically significant differences were identified within the basal electrode conditions. Although comparisons between the apical +3 adjacent electrode condition and basal stimulation conditions demonstrated overall significant

differences, the pairwise comparisons did not reveal statistically significant differences following Bonferroni correction. Collectively, these findings suggest that apical electrode stimulation, particularly with wider electrode separation, may facilitate more efficient cortical encoding of frequency changes compared to basal electrode stimulation.

4.2. Effect of tone frequency changes on ACC amplitude measures: A within and between comparison of apical and basal electrode stimulations

4.2.1. ACC P1' amplitude across

The results of ACC P1' amplitude revealed that across all stimulus conditions, it was larger for the apical electrodes than for the basal electrodes. The P1' amplitude showed a gradual increase from 4.323 μV in E20 to 4.829 μV in E20+E17 for apical electrode stimulations. In basal electrode conditions, median amplitudes ranged from 3.416 μV to 3.560 μV, with lower amplitudes observed across the basal electrodes. The median and interquartile range (*IQR*) values of ACC P1' amplitude for E20, E20+E19, E20+E17, E06, E06+E05, and E06+E03 are presented in Table 4.3.

Table 4.3

Median and IQR of the ACC P1' Amplitude (μV) measured at Apical and Basal electrodes.

Electrode Location	Electrode stimulation	n	Median	IQR
Apical	*E20*	19	4.323	2.832
	E20+E19	19	4.618	1.981
	E20+E17	19	4.829	1.916
Basal	*E06*	19	3.417	2.138
	E06+E05	19	3.416	1.521
	E06=E03	19	3.560	3.350

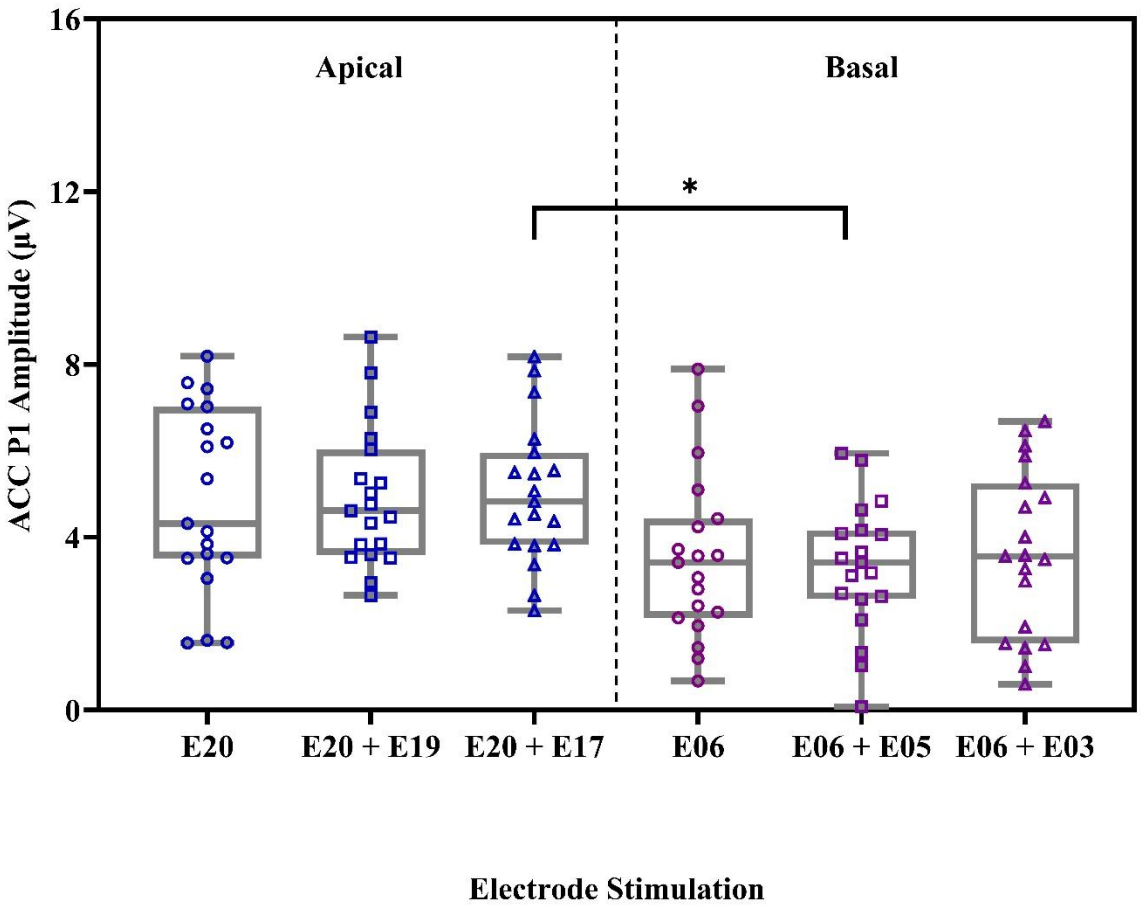
Note. ACC- Acoustic change complex; n – sample size; IQR- interquartile range

Friedman's Two-Way Analysis of Variance by Ranks was conducted to compare ACC P1' amplitude across the six electrode conditions among the study participants (n = 19). The

analysis revealed a statistically significant difference in ACC P1' amplitude across the electrode conditions [χ^2 (5, N=19) = 14.850, p = .011, Kendall's W = 0.151], with a small effect size. Post hoc pairwise comparisons were performed using the Bonferroni correction for multiple comparisons to determine the specific differences between electrode conditions. The results revealed a statistically significant difference between E06+E05 P1' ACC amplitude and E20+E17 P1' ACC amplitude (Z = 2.95, $p = .048$, $r = 0.67$), with a large effect size. However, no statistically significant differences were observed between the remaining pairwise comparisons following Bonferroni correction ($p > .05$). These findings suggest that ACC P1' amplitude varied significantly across the electrode conditions, with greater amplitudes observed predominantly in the low-frequency electrode conditions compared to the high-frequency electrode conditions. The comparison of the ACC P1' Amplitude is shown in Figure 4.3.

Figure 4.3

Comparison of ACC P1' Amplitude (μV) measured at Apical and Basal electrodes.



Note. Apical electrodes: E20 = 500-525 Hz (base frequency), E20+E19 = 500-625 Hz (+1 electrode), E20+E17 = 500-875 Hz (+3 electrodes); Basal electrodes: E06 = 4000-4040 Hz (base frequency), E06+E05 = 4000-4400 Hz (+1 electrode), E06+E03 = 4000-5600 Hz (+3 electrodes); *$p < 0.05$.

A separate Friedman's Two-Way Analysis of Variance by Ranks was conducted for the apical and basal electrode stimulation conditions to evaluate differences in ACC P1' amplitude across the electrode stimulation configurations. In apical electrode stimulation conditions, the analysis revealed no statistically significant difference in ACC P1' amplitude across the three

low-frequency stimulation configurations (E20, E20+E19, E20+E17) [χ^2 (2, N = 19) = 0.316, p = .854]. These findings indicate that ACC P1' amplitude did not vary significantly as a function of electrode stimulation configuration within the apical cochlear region. Similarly, in the basal electrode stimulation conditions, there was no statistically significant difference in ACC P1' amplitude across the three high-frequency stimulation configurations (E06, E06+E05, E06+E03), [χ^2 (2, N = 19) = 4.105, p = .128].

Overall, the findings demonstrated that ACC P1' amplitude was generally greater during apical electrode stimulation than during basal electrode stimulation. A significant overall difference in ACC P1' amplitude was observed across the six electrode configurations, with the apical +3 adjacent electrode condition (E20+E17) eliciting significantly larger amplitudes than the basal +1 adjacent electrode condition (E06+E05). However, no other pairwise comparisons reached statistical significance following Bonferroni correction. Separate analyses within the apical and basal regions revealed no significant differences in ACC P1' amplitude across electrode separations within each region. Overall, these findings suggest that cortical response amplitude was relatively stable within individual cochlear regions but tended to be larger with apical than with basal electrode stimulation.

4.2.2. ACC N1' amplitude

ACC N1' amplitude descriptive statistics showed that it was higher at apical than at basal electrodes across all stimulus conditions. In apical electrode conditions, the median N1' amplitude increased gradually from 1.838 μV in E20 to 2.517 μV in E20+E17. In basal electrode conditions, median amplitudes ranged from 1.323 μV to 2.211 μV, with the lowest amplitude observed in E06+E05. The median and interquartile range (*IQR*) values of ACC N1' amplitude for E20, E20+E19, E20+E17, E06, E06+E05, and E06+E03 are presented in Table 4.4.

Table 4.4

Median and IQR of the ACC N1' Amplitude (μV) measured at Apical and Basal electrodes.

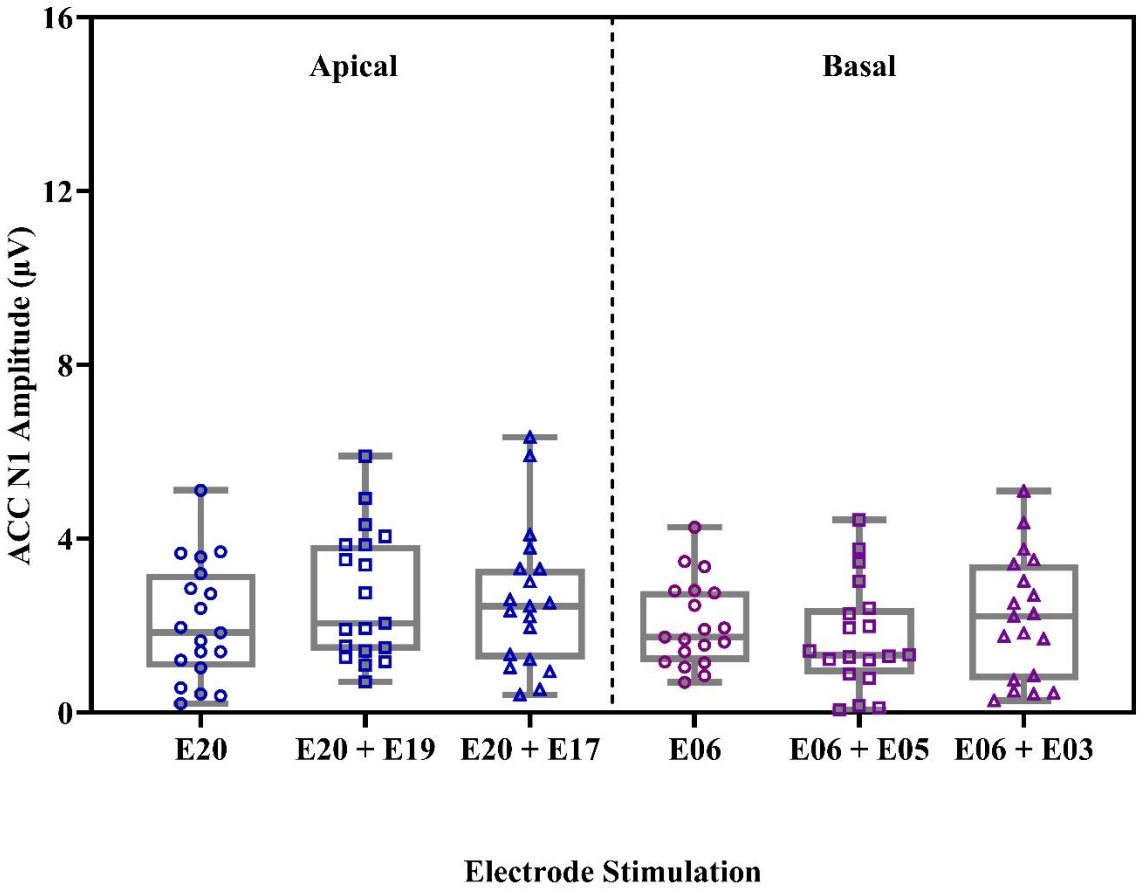
Electrode Location	Electrode stimulation	n	Median	IQR
Apical	*E20*	19	1.838	1.908
	E20+E19	19	2.057	2.401
	E20+E17	19	2.517	2.268
Basal	*E06*	19	1.735	1.490
	E06+E05	19	1.323	1.289
	E06+E03	19	2.211	2.423

Note. ACC- Acoustic change complex; n – sample size; IQR- interquartile range.

A Friedman's Two-Way Analysis of Variance by Ranks was conducted to evaluate differences in the ACC N1' amplitude across six experimental conditions. The Friedman test results indicated that spatial alterations across these channels and regions did not yield any statistically significant differences in N1' response magnitudes [χ^2 (5, N=19) = 5.677, p = .339]. In contrast to findings for P1' amplitude, the ACC N1' amplitude did not show significant differences across electrode stimulation configurations. The comparison of the ACC N1' amplitude is shown in Figure 4.4.

Figure 4.4

Comparison of ACC N1' Amplitude (μV) *measured at Apical and Basal electrodes.*



Note. Apical electrodes: E20 = 500-525 Hz (Base Frequency), E20+E19 = 500-625 Hz (+1 electrode), E20+E17 = 500-875 Hz (+3 electrode); Basal electrodes: E06 = 4000-4040 Hz (Base Frequency), E06+E05 = 4000-4400 Hz (+1 electrode), E06+E03= 4000-5600 Hz (+3 electrode)

A separate Friedman's Two-Way Analysis of Variance by Ranks was conducted for the apical and basal electrode stimulation conditions to evaluate differences in ACC N1' amplitude across the sequential stimulation configurations. In the apical electrode stimulation conditions, the analysis revealed that there was no statistically significant difference in ACC N1' amplitude across the three low-frequency stimulation configurations (E20, E20+E19, E20+E17), [χ^2 (2, N =

19) = 2.947, p = .229]. Similarly, in the basal electrode stimulation conditions, there was no statistically significant difference in ACC N1' amplitude across the three high-frequency stimulation configurations (E06, E06+E05, E06+E03), [χ^2 (2, N = 19) = 0.105, p = .949]. These findings indicate that ACC N1' amplitude remained relatively stable across the basal electrode stimulation configurations.

Overall, the findings demonstrated that ACC N1' amplitude remained relatively stable across both apical and basal electrode stimulation conditions. Although greater median N1 amplitudes were observed in the apical electrode conditions, particularly for the +3 adjacent electrode stimulation (E20+E17), these differences were not statistically significant compared to other electrode stimulations. However, the +3 adjacent electrode separation (E20+E17 & E06+E03) showed higher amplitudes than the base frequency conditions (E20 & E06). Together, these results imply that electrode location and electrode separation had little effect on ACC N1' amplitude, suggesting that cortical neural synchrony remained comparatively stable throughout the stimulation condition.

4.2.3. ACC P1'-N1' Amplitude

The ACC P1'-N1'amplitude was larger for the apical electrodes than the basal electrode under all conditions, according to the descriptive statistics. The apical electrode conditions, the median P1'–N1' amplitude showed a gradual increase from 6.722 μV in E20 to 7.275 μV in E20+E17. In contrast, the basal electrode conditions showed lower median amplitudes, ranging from 4.439 μV to 5.040 μV. The median and interquartile range (IQR) values of ACC P1'–N1' amplitude for E20, E20+E19, E20+E17, E06, E06+E05, and E06+E03 are presented in Table 4.5.

Table 4.5

Median and IQR of the ACC P1'-N1' Amplitude measured at Apical and Basal electrodes.

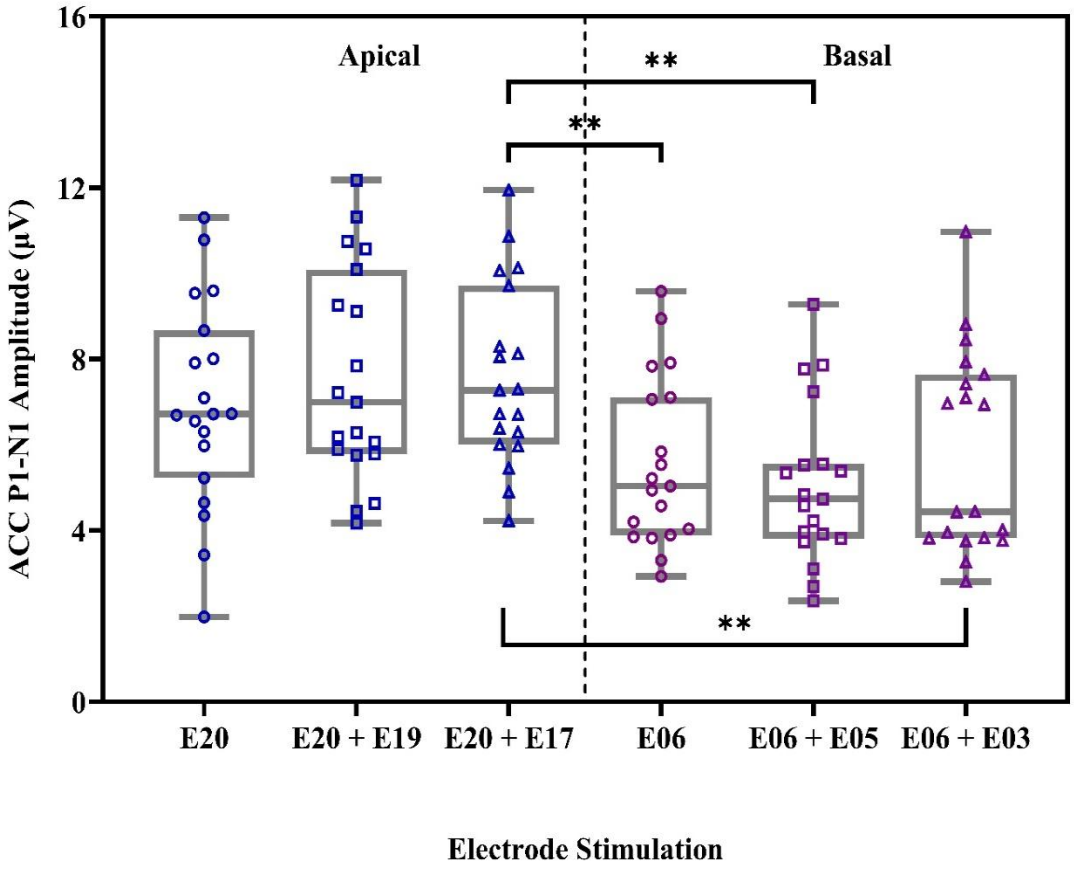
Electrode Location	Electrode stimulation	n	Median	IQR
	E20	19	6.722	2.736
Apical	*E20-E19*	19	6.991	3.837
	E20-E17	19	7.275	2.854
	E06	19	5.040	3.121
Basal	*E06-E05*	19	4.737	1.675
	E06-E03	19	4.439	3.705

Note. ACC- Acoustic change complex; n – sample size; IQR- interquartile range.

Friedman's Two-Way Analysis of Variance by Ranks was conducted to evaluate differences in the 'ACC P1'–N1' peak-to-peak amplitude across six experimental conditions. The omnibus Friedman test revealed a highly statistically significant variation in P1'–N1' amplitudes across these configurations, [χ^2 (5, N=19) = 26.098, p < .001, Kendall's W = 0.275] with a small effect size. To isolate the exact locations of these differences, *post hoc* pairwise comparisons were executed with a Bonferroni correction for multiple comparisons. Following strict alpha adjustment, three specific contrasts emerged as statistically significant: the E06+E03 condition differed significantly from the E20+E17 condition (Z = 3.729, p = .003, r = 0.61) (E06+E03< E20+E17) with large effect size, the E06 condition differed significantly from the E20+E17 condition (Z = 3.642, p = .004, r = 0.59) (E06< E20+E17) with large effect and the E06+E05 condition differed significantly from the E20+E17 condition (Z= 3.468, p = .008, r= 0.56) (E06+E05<E20+E17) also with large effect size. All other pairwise comparisons failed to reach the significance threshold after adjustment (p > .05). Comparison of ACC P1'-N1' amplitude is shown in Figure 4.5.

Figure 4.5

Comparison of ACC P1'-N1' Amplitude (μV) *measured at Apical and Basal electrodes.*



Note. Apical electrodes: E20 = 500-525 Hz (Base Frequency), E20+E19 = 500-625 Hz (+1 electrode), E20+E17 = 500-875 Hz (+3 electrode); Basal electrodes: E06 = 4000-4040 Hz (Base Frequency), E06+E05 = 4000-4400 Hz (+1 electrode), E06+E03= 4000-5600 Hz (+3 electrode); **$p < 0.01$.

A separate Friedman's Two-Way Analysis of Variance by Ranks was conducted for the apical and basal electrode stimulation conditions to evaluate differences in ACC P1'–N1' peak-to-peak amplitude across the sequential stimulation configurations. In the apical electrode stimulation conditions, the analysis revealed that there was no statistically significant difference

in ACC P1'–N1' amplitude across the three low-frequency stimulation configurations (E20, E20+E19, E20+E17), [χ^2 (2, N = 19) = 2.211, p = .331]. Similarly, in the basal electrode stimulation conditions, there was no statistically significant difference in ACC P1'–N1' amplitude across the three high-frequency stimulation configurations (E06, E06+E05, E06+E03), [χ^2 (2, N = 19) = 0.316, p = .854]. These findings indicate that ACC P1'–N1' amplitude remained relatively stable across the basal electrode stimulation configurations.

Overall, the findings demonstrated that ACC P1'–N1' peak-to-peak amplitude was consistently greater in the apical electrode stimulation conditions compared to the basal electrode stimulation conditions. The largest amplitudes were observed in the apical +3 adjacent electrode condition (E20+E17), which showed significantly higher P1'–N1' amplitudes than all three basal stimulation conditions (E06, E06+E05, and E06+E03). These findings indicate enhanced cortical responsiveness and stronger neural synchrony for wider apical electrode stimulation compared to basal stimulation. However, separate analyses within the apical and basal regions revealed no statistically significant differences across electrode separations within each region. All of the findings point to the apical and basal cochlear regions' differences as the main cause of the notable variation in ACC P1'–N1' amplitude, with apical stimulation generally generating larger cortical response magnitudes.

4.3. Effect of tone frequency changes on LLR latency and amplitude measures: A within and between comparison of apical and basal electrode stimulations.

Descriptive examination of P1 latency revealed a gradual decrease across apical conditions with increasing electrode separation, whereas basal conditions showed greater variability with no consistent directional pattern. A similar decrease in N1 latency was observed across apical conditions, whereas basal conditions did not show a comparable systematic pattern.

Regarding amplitude measures, P1 amplitude in the apical region was highest under the base-frequency condition (E20) and showed no clear monotonic trend with increasing electrode separation; the basal region displayed relatively uniform P1 amplitudes across all three conditions. N1 amplitude in the apical region was largest for the +1 adjacent electrode condition (E20+E19), while basal N1 amplitudes showed a gradual increase with wider electrode separation, though they remained generally lower than apical values. For P1–N1 peak-to-peak amplitude, apical conditions yielded slightly higher median values than basal conditions across corresponding stimulation configurations. Statistical analyses, however, did not corroborate these descriptive observations.

Friedman's two-way analysis of variance by ranks was conducted on 19 participants to determine differences in LLR latency and amplitude across all stimulus conditions. There were no significant differences in P1 latency between low frequency conditions, [$\chi 2(2, N = 19) = 2.46$, $p = .292$], or high frequency conditions, [$\chi 2(2, N = 19) = 4.19$, $p = .123$]. Overall, the Friedman test comparing all six latency variables similarly revealed no difference between conditions, [$\chi^2 (5, N = 19) = 8.69$, $p = .122$].

Similarly to then P1 latency, there were no statistically significant differences in N1 latency across low frequency conditions, [$\chi^2 (2, N = 19) = 2.48$, $p = .289$] or high frequency conditions, [$\chi^2 (2, N = 19) = 1.37$, $p = .504$]. The omnibus analysis overall also indicated no significant differences among the six latency variables [$\chi^2(5, N = 19) = 3.51$, $p = .622$].

There were no significant differences in the P1 amplitude across low-frequency conditions, [$\chi 2(2, N = 19) = 4.11$, $p = .128$], or high-frequency conditions, [$\chi 2(2, N = 19) = 0.95$, $p = .623$]. The overall comparison across all six stimulation configurations was also not significant, [$\chi^2 (5, N = 19) = 6.85$, $p = .232$].

The Friedman's Two-Way Analysis of Variance by Ranks revealed no statistically significant differences in N1 amplitude among the low-frequency conditions, [χ^2 (2, N = 19) = 4.53, p = .104]. Similarly, no significant differences were observed among the high-frequency conditions [χ^2 (2, N = 19) = 4.53, p = .104]. Furthermore, the omnibus Friedman test comparing N1 amplitudes across all six stimulation conditions did not reach statistical significance [χ^2 (5, N = 19) = 6.87, p = .231]. These findings indicate that N1 amplitude remained relatively stable across the different electrode stimulation configurations

For P1-N1 amplitude, no statistically significant differences were found across low-frequency conditions, [χ^2 (2, N = 19) = 2.95, p = .229], or high-frequency conditions, [χ^2 (2, N = 19) = 0.11, p = .949]. However, an omnibus Friedman test for all six amplitude variables showed a statistically significant difference between conditions, [χ^2 (5, N = 19) = 12.23, p = .032]. Post hoc pairwise comparisons with the Bonferroni correction did not reveal statistically significant differences after adjustment (p > .05). Overall, the results suggest that most LLR measures did not differ significantly across all stimulus conditions.

Table 4.6

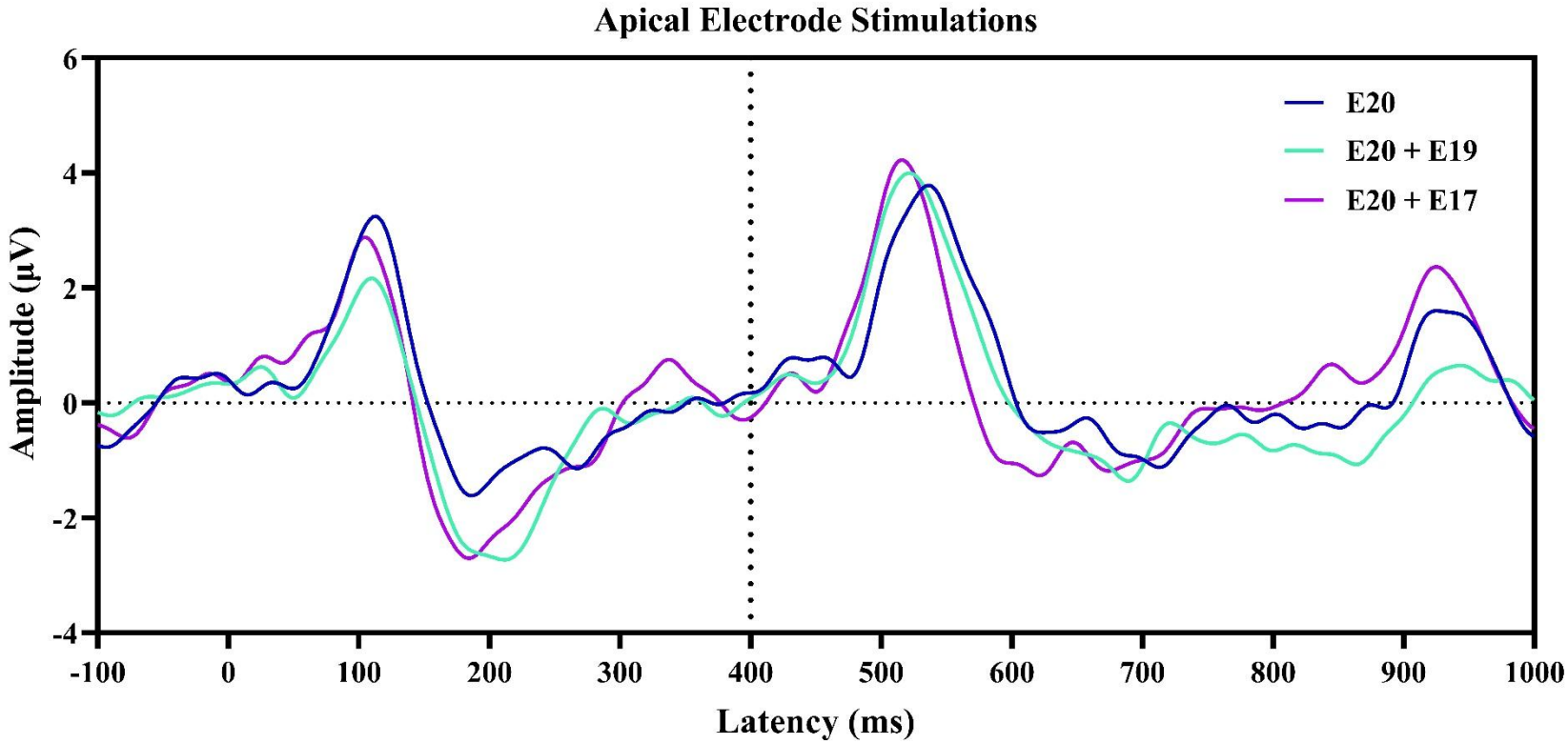
Median and IQR of LLR Latency and Amplitude Across Electrode Locations and Electrode Conditions (n = 19)

Electrode Location	Electrode stimulation	P1 Latency Median and IQR	N1 Latency Median and IQR	P1 amplitude Median and IQR	N1 amplitude Median and IQR	P1-N1 amplitude Median and IQR
Apical	*E20*	113.5 (16.66)	194.6 (41.39)	4.469 (2.724)	2.657 (1.700)	7.269 (2.713)
	E20+E19	111.8 (18.81)	187.0 (25.80)	3.030 (1.526)	4.292 (2.355)	6.512 (2.699)
	E20+E17	108.6 (18.81)	108.6 (18.81)	108.6 (18.81)	108.6 (18.81)	108.6 (18.81)
Basal	*E06*	116.1 (34.40)	116.1 (34.40)	116.1 (34.40)	116.1 (34.40)	116.1 (34.40)
	E06+E05	121.5 (35.48)	121.5 (35.48)	121.5 (35.48)	121.5 (35.48)	121.5 (35.48)
	E06+E03	111.8 (26.34)	111.8 (26.34)	111.8 (26.34)	111.8 (26.34)	111.8 (26.34)

Note. IQR= Interquartile range; LLR= Long latency response

Figure 4.6

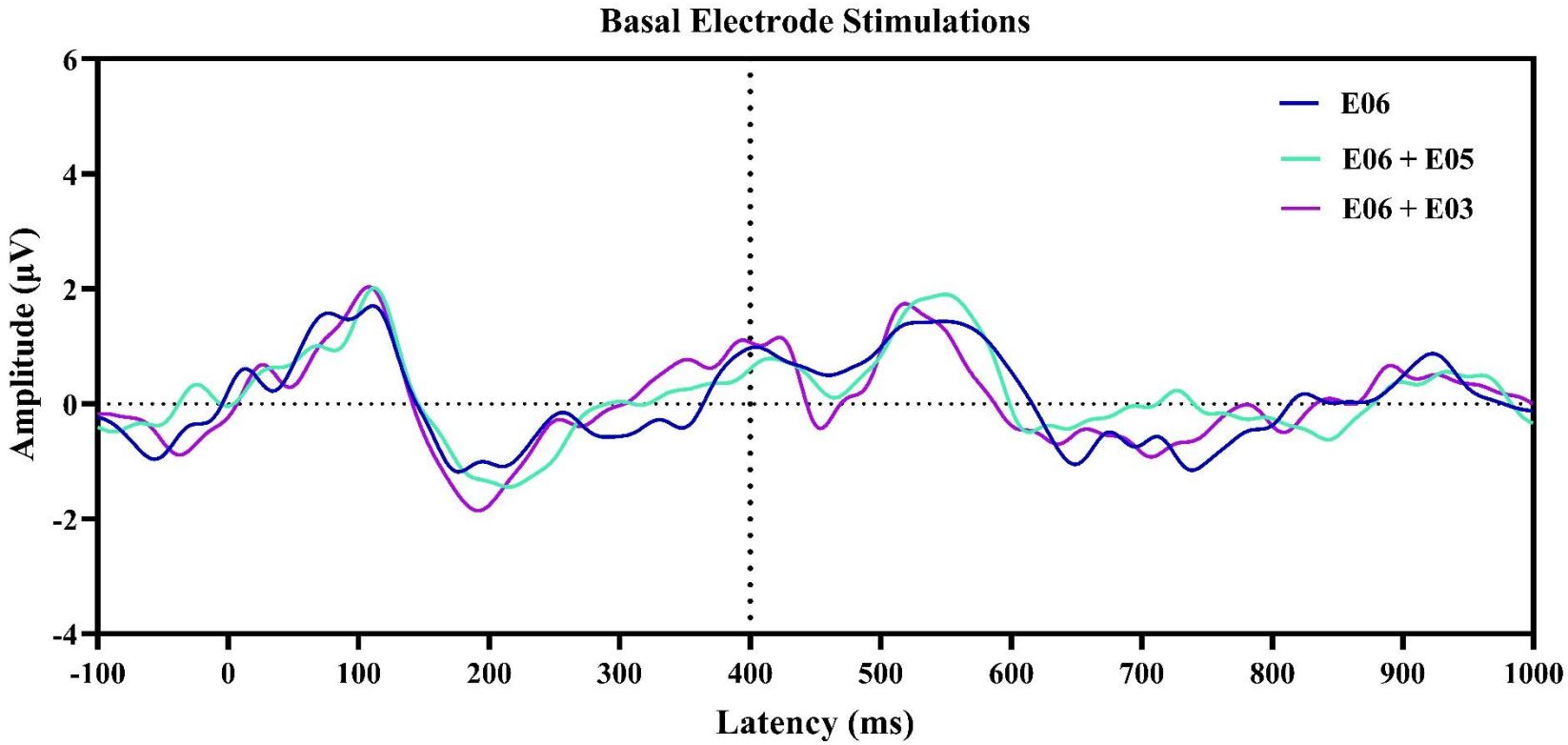
Average Waveforms of the ACC for Apical Electrode Stimulation.



Note. ACC= Acoustic change complex; Apical electrodes: E20 = 500-525 Hz (Base Frequency); E20+E19 = 500-625 Hz (+1 electrode); E20+E17 = 500-875 Hz (+3 electrode).

Figure 4.7

Average Waveforms of the ACC for Basal Electrode Stimulation.



Note. ACC= Acoustic change complex; Basal electrodes: E06 = 4000-4040 Hz (Base Frequency); E06+E05 = 4000-4400 Hz (+1 electrode); E06+E03= 4000-5600 Hz (+3 electrode).

4.4. The relationship between speech perception results and the latency and amplitude of acoustic change complex reactions.

To examine the relationship between speech perception performance and the electrophysiological measures (latency and amplitude) of ACC for the different stimulation conditions (E20, E20+E19, E20+E17, E06, E06+E05, and E06+E03), a series of Spearman's rank-order correlations (ρ) was performed.

For the E20 stimulation condition, there were no significant correlations between speech perception scores and either P1' latency (ρ = -0.116, p = .637) or N1' latency (ρ = −0.118, p = .630). Similarly, for the E20+E19 stimulation condition, where neither P1' latency (ρ = -0.551*, p = .014) nor N1' latency (ρ = -0.610**, p = .006) showed a significant relationship with speech perception performance. Correlation analysis revealed two significant associations between ACC amplitude measures and speech perception performance. In the apical stimulation condition, a statistically significant moderate negative correlation was observed between speech perception scores and N1′ amplitude under the same-electrode stimulation condition (E20) (ρ = −0.494, p = .032), indicating that participants with better speech perception performance exhibited larger N1′ responses. In the basal stimulation condition, a statistically significant moderate positive correlation was observed between speech perception scores and P1′–N1′ amplitude under the +1 adjacent electrode stimulation condition (E06+E05) (ρ = 0.499, p = .030), suggesting that participants with higher speech perception scores demonstrated larger peak-to-peak ACC amplitudes. No significant correlations were observed between speech perception scores and any of the remaining ACC latency or amplitude measures across the apical and basal stimulation conditions. Figure 4.8 showing the scatter plots illustrating significant Spearman rank-order

correlations between speech perception scores and ACC latency and amplitude across apical and basal electrode conditions.

Overall, these findings indicate that ACC latency measures obtained from basal electrode stimulation conditions were not significantly associated with speech perception performance. Table 4.7 shows the correlation between speech perception performance and ACC latency across apical and basal electrodes. Table 4.8 shows the correlation between Speech Perception Performance and ACC amplitude across apical and basal Electrodes.

Table 4.7

Correlation Between Speech Perception Performance and ACC Latency across apical and basal Electrode (n = 19)

Electrode Location	Electrode Stimulation Condition	ACC Latency	Spearman's ρ	*p-value*
Apical	*E20*	P1’	-0.116	.637
		N1’	-0.118	.630
	E20+E19	P1’	-0.551	.014*
		N1’	-0.610	.006**
	E20+E17	P1’	-0.288	.232
		N1’	-0.157	.520
Basal	*E06*	P1’	0.374	.115
		N1’	0.189	.438
	E06+E05	P1’	0.447	.055
		N1’	0.216	.374
	E05+E03	P1’	0.005	.983
		N1’	0.279	.247

Note. ACC= acoustic change complex; ρ = Spearman's rho; *$p < .05$; **$p < .01$

Table 4.8

Correlation Between Speech Perception Performance and ACC Amplitude across apical and basal Electrode (n = 19)

Electrode Location	Electrode Stimulation Condition	ACC Amplitude	Spearman's ρ	*p*
		P1’	-0.167	.494
	E20	N1’	-0.494	.032*
		P1’–N1’	-0.409	.082
		P1’	-0.142	.561
Apical	*E20+E19*	N1’	-0.279	.247
		P1’–N1’	-0.195	.424
		P1’	-0.088	.720
	E20+E17	N1’	0.117	.632
		P1’–N1’	0.122	.619
		P1’	0.143	.559
	E06	N1’	-0.152	.534
		P1’–N1’	0.112	.648
		P1’	0.436	.062
Basal	*E06+E05*	N1’	0.154	.529
		P1’–N1’	0.499	.030*
		P1’	-0.029	.905
	E06+E03	N1’	0.136	.578
		P1’–N1’	0.196	.422

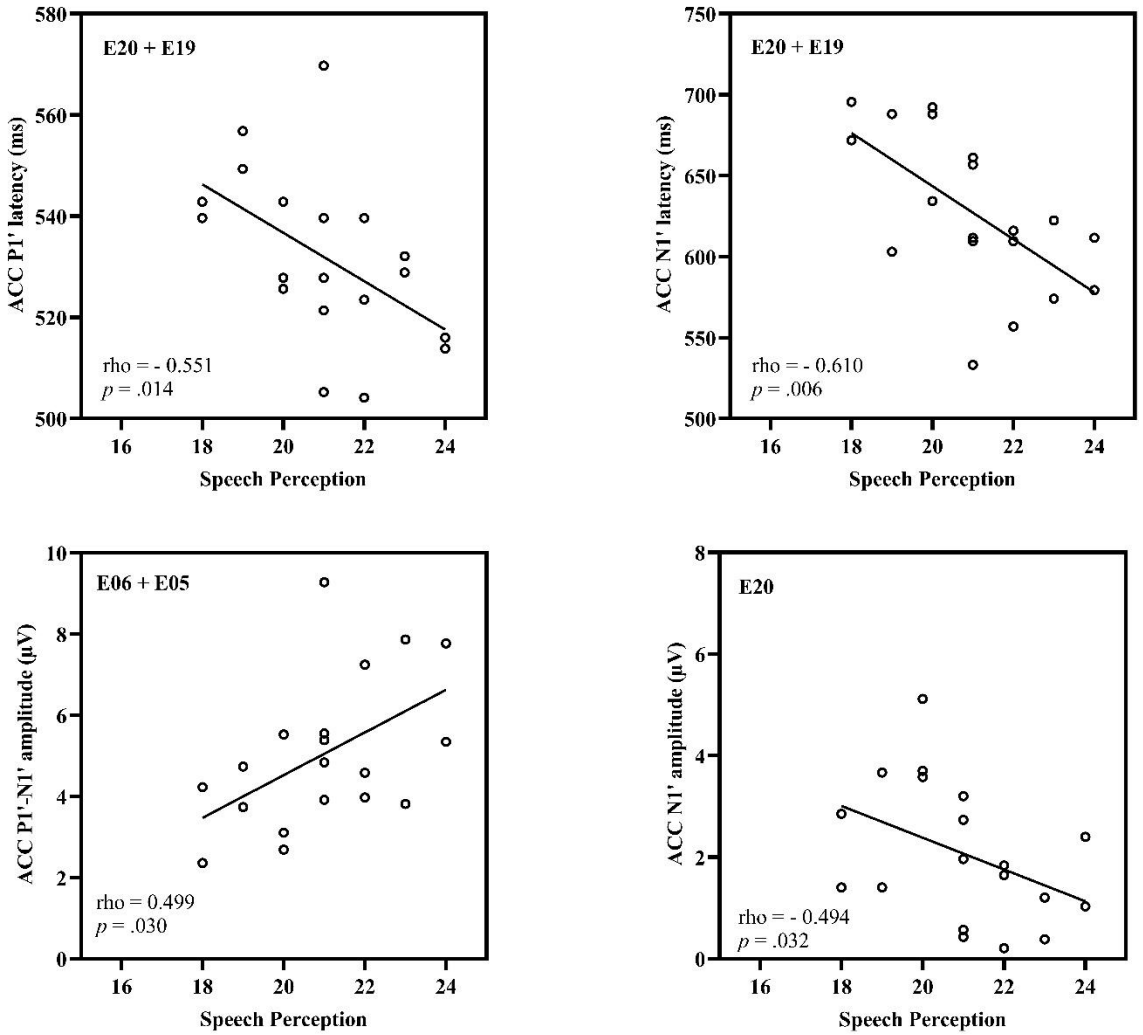
Note. ACC= acoustic change complex; ρ = Spearman's rho; *$p < .05$

Overall, the correlation analyses revealed that speech perception performance was associated with selected ACC measures across specific electrode stimulation conditions. Significant negative correlations were observed between speech perception scores and P1′ and N1′ latencies under the apical E20+E19 condition, indicating that better speech perception was associated with faster cortical processing. Additionally, significant relationships were observed for N1′ amplitude under the E20 condition and P1′–N1′ amplitude under the basal E06+E05 condition, suggesting that better speech perception was associated with stronger cortical responses. No significant correlations were identified for the remaining ACC measures. These findings indicate that specific ACC latency and amplitude measures may serve as objective indicators of auditory discrimination and speech perception abilities in cochlear implant users. Figure 4.8 is showing the scatter plots illustrating significant Spearman rank-order correlations

between speech perception scores and ACC latency and amplitude across apical and basal electrode conditions.

Figure 4.8

Scatter plots illustrating significant Spearman rank-order correlations between speech perception scores and ACC latency and amplitude across apical and basal electrode conditions (n = 19).



Note. ACC= Acoustic change complex; Top panels depict the apical +1 adjacent electrode stimulation condition (E20+E19), ACC P1′ latency (top left; ρ = −0.551, *p* = .014) and ACC N1′ latency (top right; ρ = −0.610, *p* = .006). The bottom-left panel illustrates the basal +1 adjacent electrode stimulation condition (E06+E05) and ACC P1′–N1′ amplitude (ρ = 0.499, p = .030). The bottom-right panel depicts the apical same electrode stimulation condition (E20 and ACC N1′ amplitude (ρ = −0.494, p = .032). Table 4.9 summarises the overall results of the present study.

Table 4.9

Overall summary of Friedman test results for ACC latency and amplitude measures across apical and basal electrode stimulation conditions (n = 19)

Outcome Measure	Comparison	Statistical Significance	Effect Size	Significant Pairwise Comparisons
ACC P1' Latency	All six conditions	Significant	Medium	E20+E17 < E06; E20+E17 < E06+E05; E20+E17 < E06+E03
	Apical conditions	Significant	Medium	E20+E17 < E20
	Basal condition	Not significant	-	-
ACC N1' Latency	All six conditions	Significant	Small	-
	Apical	Significant	Small- Medium	E20+E17 < E20
	Basal	Not significant	-	None
ACC P1'Amplitude	All six conditions	Significant	Small	E20+E17 > E06+E05
	Apical	Not significant	-	-
	Basal	Not significant	-	-
ACC N1' Amplitude	All six conditions	Not significant	-	-
	Apical	Not significant	-	-
	Basal	Not significant	-	-
ACC P1'-N1' Amplitude	All six conditions	Significant	Small	E20+E17 > E06; E20+E17 > E06+E05; E20+E17 > E06+E03
	Apical	Not significant	-	-
	Basal	Not significant	-	-

Note. ACC = Acoustic Change Complex; Kendall's W values: <0.10 = negligible, 0.10–0.29 = small, 0.30–0.49 = Medium, and ≥0.50 = large effect. E20+E17 < E06 (shorter latency); E20+E17 > E06 (larger amplitude); Significant ($p < .05$); Not significant ($p \geq .05$).

Chapter V

Discussion

The study aimed to assess the acoustic change complex (ACC) responses elicited by changes in tone frequency at apical and basal electrode locations in paediatric cochlear implant (CI) users and to examine the relationship between ACC electrophysiological measures and speech perception outcomes.

5.1. Effect of tone frequency changes on ACC latency measures

The present study demonstrated that ACC P1' latency was significantly shorter under apical electrode stimulation (low-frequency region, ~500 Hz) than compared to basal electrode stimulation (high-frequency region, ~4000 Hz), particularly with the wider electrode separation condition (E20+E17 < E06+E03). These findings are broadly consistent with the tonotopic organisation of the auditory system and with accumulating evidence suggesting that apical cochlear regions exhibit distinct electrophysiological response characteristics relative to basal regions in CI users. Larger frequency transitions (i.e., the +3 adjacent electrode conditions) produced the shortest latencies within the apical region, suggesting that greater acoustic change is associated with faster cortical detection of the transition.

Several prior studies have reported similar patterns, in which larger frequency changes elicit shorter cortical latencies in CI users. Martin et al. (2010) observed that the ACC was sensitive to the magnitude of the acoustic change, with larger frequency differences yielding more robust and earlier cortical responses. Similarly, Alain & Tremblay, (2007) demonstrated that the latency of cortical auditory evoked potentials (CAEPs) was inversely related to the salience of the acoustic change, a finding echoed in the paediatric CI literature by Gilley et al. (2008) who reported shorter P1 latencies for more prominent frequency deviations in children

with CIs. The current findings extend this body of work by showing that this latency–change magnitude relationship is specifically pronounced within the apical cochlear region, where wider electrode separations elicited the shortest ACC P1' latencies.

The present study's findings contrast with those of McGuire et al. (2021) who showed no statistically significant differences in ACC latency by frequency; however author reported there was no statistical difference between the latencies of N1' and P2', the latencies of the ACC responses evoked using the 250 Hz base frequency were found to be less in comparison to those evoked using the 1 kHz and 4 kHz base frequencies. In their study, the author did not analyse P1′ latency, as their study involved adult participants, in whom the P1 component is typically less prominent and therefore was not included in the latency analysis. According to the researchers, low-frequency stimuli are more salient in terms of spectral content and are often associated with better frequency change detection among individuals with CI. This rationale may explain the shorter P1′ latency observed with apical versus basal stimulation (500 Hz versus 4000 Hz). Apical cochlear regions are frequently associated with better neural survival and reduced current spread compared with basal regions, potentially resulting in more synchronised neural activation and faster cortical responses.

Regarding electrode separation effects, the finding that the +3 adjacent electrode condition (E20+E17) produced significantly shorter P1' latency than the +1 (E20 + E19) and same-electrode conditions (E20) within the apical region is consistent with evidence that greater spectral distance between the onset and transition frequency enhances the salience of the acoustic change, thereby facilitating earlier cortical detection. Hughes & Stille, (2009) reported that ACC amplitude and latency were both sensitive to the magnitude of frequency change, with larger transitions producing more robust responses. The current data extend this finding to the electrode

separation dimension of CI stimulation, demonstrating that increasing the spectral distance between stimulated electrodes in the apical region systematically reduces P1' latency. No equivalent significant differences were observed within the basal electrode conditions, possibly because the absolute frequency differences produced by adjacent electrode separations in the high-frequency basal region were proportionally smaller, or because basal-region cortical processing in this paediatric sample was less sensitive to these incremental changes. Consistent with the P1' findings, ACC N1' latency was generally shorter for apical than for basal electrode stimulation conditions, with the apical +3 adjacent electrode condition (E20+E17) demonstrating the shortest N1' latency. However, unlike P1' latency, these differences did not remain statistically significant following Bonferroni correction, although comparisons between E20+E17 and basal conditions yielded large effect sizes ($r = 0.64$ to 0.67).

The N1' component of the ACC is thought to reflect inhibitory or offset-related neural processing of the acoustic transition (Martin et al., 2008; Martin & Boothroyd, 2000).The convergence of apical and basal N1' latencies relative to P1' latencies may indicate that while the initial cortical detection of the frequency change (indexed by P1') is faster for apical stimulation, the subsequent processing of the transition offset (N1') is more comparable across cochlear regions. This interpretation aligns with the proposal by Tremblay et al. (2014) that different ACC components reflect distinct stages of acoustic change processing, with earlier components being more strongly modulated by the physical characteristics of the change and later components reflecting higher-level integration processes. McGuire et al. (2021)who reported that ACC N1′ latency was significantly associated with both frequency-change detection ability and speech perception outcomes in cochlear implant users. Although N1′ latency did not differ significantly across base frequencies (0.25, 1, and 4 kHz), shorter N1′ latencies were associated with better

CNC word and phoneme recognition scores and lower frequency-change detection thresholds. The authors suggested that N1′ latency reflects the efficiency of cortical sensory encoding of frequency changes, with earlier responses indicating more effective neural processing of spectral information.

Another interesting outcome, in line with Van Heteren et al. (2022) is that the largest electrode spacing (E20+E17) yielded the shortest N1' latency. Specifically, the researchers found that greater changes in acoustic frequency were associated with shorter N1 latency and greater N1-P2 amplitude in adult CI users. The study's findings suggested that increased acoustic contrast makes the frequency change more salient, thereby facilitating its detection. In other words, the current study supports their interpretation. McGuire et al. (2021)found a trend toward reduced latency of the ACC peak and a significantly greater amplitude in response to low-frequency (250 Hz) stimuli than to high-frequency (1 and 4 kHz) stimuli among CI users. While latency did not differ significantly between these two groups, the author hypothesised that low-frequency sounds would contain more meaningful spectral content, thereby enabling more effective frequency change detection and, consequently, more efficient cortical processing. This might be analogous to what happened here when apical stimulation was used.

Liang et al. (2018)investigated ACC responses in adult cochlear implant users using pure tones with base frequencies of 160 Hz and 1200 Hz, with 0%, 5%, and 50% upward frequency changes. The author reported that ACC responses are highly modulated by the magnitude of frequency change. Higher levels of frequency changes produced greater N1′ – P2′ amplitude values and lower N1′ latencies in comparison with small changes in frequency. The effect of shorter latency with greater frequency contrasts indicates greater efficiency in processing more noticeable auditory changes in the brain and a higher level of neuronal

involvement, while the increased amplitude indicates higher neural activity. Furthermore, a significant correlation was observed between ACC parameters and the frequency change detection threshold, suggesting the objectivity of ACC responses in this task.

In contrast to the present study, previous studies reported significant changes in N1 latency across different electrode stimulation conditions. However, no such differences were observed for N1′ latency in the current study. The discrepancies in findings across studies may be attributed to differences in the study population, the stimuli used for ACC recording, and the electrodes employed during ACC recording.

Based on the above results, the null hypothesis 1a. ‘There are no significant differences in latency measures of acoustic change complex responses to tone frequency changes measured across the apical and basal electrode stimulation’ was rejected. The null hypothesis - 2a. ‘There are no significant differences in the latency measures of acoustic change complex response to tone frequency changes across stimulating the same electrode, +1 adjacent electrode and +3 adjacent electrode in the apical region’, was rejected. Finally, the null hypothesis - 3a. ‘There are no significant differences in the latency measures of acoustic change complex response to tone frequency changes across stimulating the same electrode, +1 adjacent electrode and +3 adjacent electrode in the basal region’, was accepted.

5.2. Effect of Tone Frequency Changes on ACC Amplitude Measures

The current study found that ACC P1' amplitude was consistently larger for apical compared to basal electrode stimulation, with the apical +3 adjacent electrode condition (E20+E17) yielding significantly greater P1' amplitude than the basal +1 condition (E06+E05). McGuire et al. (2021)examined the effects of frequency manipulation on the ACC across three base frequencies: 250 Hz, 1000 Hz, and 4000 Hz. The study findings did not reveal significant

changes in latency or amplitude measures; the researchers noted a pattern of greater ACC amplitudes and shorter latencies when using a base frequency of 250 Hz compared with 1000 Hz and 4000 Hz. As the researchers indicated, the use of low frequencies might be more effective at providing salient information about place-pitch and at producing stronger neural synchronisation, thereby leading to greater ACC activation. Our findings of greater P1′ amplitudes with apical stimulation appear to support this notion, as the apical electrode codes for lower frequencies. Within each cochlear region (apical & basal), P1', N1’ and P1’-N1’ amplitude did not differ significantly across stimulus conditions.

In contrast to the present study findings, Liang et al. (2018) reported that larger frequency changes elicited more robust ACC responses, characterised by greater N1′–P2′ amplitudes and earlier cortical responses. The authors suggested that ACC amplitude reflects cortical encoding of spectral differences and frequency discrimination. The stronger ACC responses may arise when auditory stimuli provide clearer spectral contrasts, thereby facilitating more synchronised neural firing within central auditory pathways. The author reported that a greater frequency difference is associated with greater ACC responses, as evidenced by higher N1′–P2′ amplitudes. Similarly, Van Heteren et al. (2022) reported significant increases in the ACC N1′–P2′ peak-to-peak amplitude with increasing magnitude of the acoustic frequency difference. The study used baseline frequencies of 160 Hz and 1200 Hz to show that increasing frequency differences (50%) elicited significantly greater N1′–P2′ amplitudes than lower frequency differences (5%). The above results indicate that the magnitude of ACC amplitude can be regarded as a neural marker of auditory change saliency. The author also observed that the ACC elicited by the 1200 Hz baseline frequency had a higher amplitude but shorter latency than that elicited by the 160 Hz baseline frequency.

Alternatively, the current study did not observe any increase in P1′ amplitude with increasing inter-electrode distance at the apical or basal electrode stimulation. The absence of statistically significant amplitude differences in the present study may also be explained by channel interaction and current spread inherent to CI stimulation. Due to channel interaction, the effects of different stimulating sites on the neuronal population in the cochlea can be significantly overlapping. As adjacent electrodes are activated, overlapping electric fields can reduce the distinctiveness of neural excitation patterns, limiting the expected increase in cortical response magnitude. This interpretation is consistent with the observations of Debruyne et al. (2017) who emphasised that variability in electrode discrimination abilities among CI users may influence the effectiveness with which spectral information is encoded and represented in the cortex. Hence, an increase in electrode separation did not yield sufficient differences in neural population recruitment to detect a change in amplitude.

The presence of ACC responses observed in the same-electrode condition (E20 & E06) in this investigation can be attributed to cortical discrimination of stimulus modifications rather than a shift in the site of excitation, as observed during normal acoustic hearing. This explanation is consistent with findings indicating that ACC responses are due to changes in the brain's perception of the stimulation pattern, rather than to a change in the location of cochlear excitation (He et al., 2014; McGuire et al., 2021; Van Heteren et al., 2022). Goldsworthy, (2015) reported that adult CI users can discriminate frequency changes of 1.5-9.9 % across 500, 1000, and 2000 Hz. The CI encodes frequency changes through changes in temporal (rate) and place-related (electrode) neural activation (Gransier et al., 2021) reported that the ACC can be elicited with a change in the pulse rate in CI users. One possible explanation for the ACC responses observed in the same-electrode condition is the spread of excitation associated with CI

stimulation. Although the frequency change remained within the single-electrode allocation range, changes in the input frequency may have altered the distribution of neural excitation within the electrode's electrical field, thereby recruiting different neural populations. Such differences in neural activation may be sufficient for the auditory cortex to detect a change and generate an ACC response (He et al., 2014). Unlike P1' amplitude, ACC N1' amplitude did not differ significantly across any of the six electrode conditions, and within the apical or basal electrodes produced statistically significant variations in N1' amplitude. These findings indicate that N1' amplitude was relatively stable across stimulation configurations, a result that is broadly consistent with the view that the N1' component reflects more generalised cortical encoding of acoustic change that is less sensitive to the specific location of cochlear stimulation.

The dissociation between P1' and N1' amplitude effects observed in the present study aligns with evidence from the general CAEP literature suggesting that P1 and N1 components are generated by partially distinct neural populations and may reflect different aspects of auditory cortical processing. In particular, it has been proposed that the P1 component in children reflects thalamocortical input to primary auditory cortex, whereas the N1 component reflects more distributed corticocortical processing (Ponton et al., 2000; Sharma et al., 2011). Gordon et al. (2013) reported no significant differences in amplitude and latency measures of eLLR between apical and basal electrodes.

In contrast, some studies have reported that electrode location affects N1 amplitude. Firszt et al. (2002) found that N1 amplitude from electrically evoked potentials varied with electrode position in adult CI users, and Beynon et al. (2005) observed N1 amplitude differences related to the frequency region stimulated. The discrepancy between these findings and the present results may partly be attributed to the developmental stage of the paediatric sample, in

which the N1 component is still maturing and may therefore be less sensitive to electrode location. The differences in findings across studies could be due to differences in stimulus characteristics and study populations.

The ACC P1'–N1' peak-to-peak amplitude was consistently larger for apical than for basal electrode stimulation, with the apical +3 adjacent electrode condition (E20+E17) yielding significantly greater P1'–N1' amplitude than all three basal conditions (E06, E06+E05, and E06+E03). These findings converge with the P1' amplitude results and reinforce the conclusion that the overall cortical response magnitude to frequency change is enhanced by apical electrode stimulation in paediatric CI users.

He et al., (2014)reported that greater electrode separations elicited more robust eACC responses than smaller separations. The authors observed that responses became clearer and more prominent as the distance between stimulating electrodes increased. The author suggested that greater electrode separation produces more distinct neural excitation patterns, thereby enhancing cortical discrimination of the stimulation change.

The peak-to-peak measure is considered to be a more robust index of cortical response magnitude than individual component amplitudes, as it is less susceptible to baseline variability and individual differences in scalp topography (Stapells, 2008). The significant advantage of the apical +3 condition across all three basal conditions for this composite measure, therefore, provides stronger evidence for a genuine apical stimulation advantage in overall cortical responsiveness to frequency change. These findings are consistent with the view that the low-frequency auditory cortex, accessed via apical CI electrodes, shows greater neural density and exhibits more robust, synchronised cortical responses to acoustic changes (Kral et al., 2019; Schoenmakers et al., 2021). Brown et al. (2008) used the electrically evoked auditory change

complex (eACC) and found a general trend of increasing eACC amplitude with increasing separation between stimulating electrodes. The authors suggested that larger electrode separations produce greater changes in the neural excitation pattern, thereby eliciting stronger cortical responses. However, unlike the findings of Brown et al. (2008) the present study did not observe significant increases in amplitude with increasing electrode separation in either cochlear region.

Based on the above results, the null hypothesis 1b, "There are no significant differences in amplitude measures of acoustic change complex responses to tone frequency changes measured across the apical and basal electrode stimulation," was partially rejected. The null hypothesis 2b, "There are no significant differences in the amplitude measures of acoustic change complex responses to tone frequency changes across stimulating the same electrode, +1 adjacent electrode, and +3 adjacent electrode in the apical region," was accepted. The null hypothesis 3b, "There are no significant differences in the amplitude measures of acoustic change complex responses to tone frequency changes across stimulating the same electrode, +1 adjacent electrode, and +3 adjacent electrode in the basal region," was accepted.

5.3. Latency and amplitude of the LLR across electrode stimulation conditions

The present study found no statistically significant differences in LLR P1 latency or amplitude, or in N1 latency or amplitude, across any of the six electrode conditions, nor within the apical or basal electrode stimulations. The only LLR P1–N1 amplitude measure showed a significant difference across all six stimulation conditions, though no specific pairwise comparisons remained significant after Bonferroni correction. These results suggest that, within the stimulation paradigm employed in this study, the LLR did not differentiate between electrode locations or magnitudes of frequency change.

The LLR reflects the onset response to the initial segment of the tonal stimulus, whereas the ACC specifically captures the cortical response to the acoustic change within the stimulus. The LLR components in response to the onset of the initial segment have the same base frequency. For the apical electrode, the base frequency was 500 Hz; for the basal electrode, it was 4000 Hz.

When the focus of interest is frequency discrimination, the ACC may therefore be a more targeted and sensitive electrophysiological measure than the LLR. This view is supported by (Martin & Boothroyd, 2000) and (Martin et al., 2008)who demonstrated that the ACC provides more direct information about the cortical encoding of acoustic change than onset-based responses, and that LLR onset responses may reflect more general aspects of auditory processing that are not specific to frequency discrimination.

Several studies have reported that LLR latency and amplitude in paediatric CI users are primarily influenced by factors such as age at implantation, duration of CI use, and the quality of the electrode–neuron interface, rather than by specific stimulation configurations (Gilley et al., 2008; Sharma et al., 2011). In the present study, the absence of significant LLR differences across electrode conditions is therefore consistent with the view that the LLR onset response may be a relatively stable measure in paediatric CI users once basic auditory development has been established, and that finer-grained electrophysiological differentiation of cochlear stimulation conditions may require change-specific measures such as the ACC.

In contrast, Ponton et al. (2000) and Gordon et al. (2013) found that LLR P1 amplitude and latency did vary with stimulation level and electrode configuration in some paediatric CI populations, suggesting that LLR measures can be sensitive to stimulation parameters under certain conditions. The discrepancy with the present findings may be related to differences in the

specific stimulation parameters, the developmental characteristics of the samples, or the use of acoustic (rather than electrical) stimuli in the present ACC paradigm. Future research using larger samples and systematically manipulating both electrode location and stimulation level may help clarify the conditions under which LLR measures are sensitive to cochlear stimulation parameters in paediatric CI users.

5.4. Relationship Between Speech Perception Performance and ACC Electrophysiological Measures Across Electrode Stimulation Conditions

In the present study, correlation analysis revealed two significant associations between ACC amplitude measures and speech perception performance. A significant moderate negative correlation was observed between speech perception scores and N1′ amplitude under the apical same-electrode stimulation condition (E20), indicating that better speech perception performance was associated with larger N1′ responses. Additionally, a significant moderate positive correlation was found between speech perception scores and P1′–N1′ amplitude under the basal +1 adjacent electrode stimulation condition (E06+E05), suggesting that participants with higher speech perception scores exhibited larger peak-to-peak ACC amplitudes.

Contrary to the hypothesis that shorter ACC latencies would reflect more efficient auditory processing and thus correlate with higher speech perception scores, the majority of stimulation conditions did not yield statistically significant latency–performance relationships. In the apical region, the E20+E19 condition produced statistically significant negative correlations for both P1’ latency (Spearman rho = −0.551, p = .014) and N1’ latency (Spearman rho = −0.610, p = .006), indicating that participants with better speech understanding demonstrated faster cortical responses to the acoustic change. This finding is consistent with prior literature suggesting that reduced cortical response latency reflects more efficient subcortical and cortical

auditory processing in CI users (Alain & Tremblay, 2007; Sharma et al., 2005). Sharma et al. (2005) demonstrated that central auditory system maturation in paediatric CI users, indexed by P1 latency, is strongly related to the age of implantation and subsequent auditory experience, and that shorter latencies are associated with better speech and language outcomes. Similarly, Alain & Tremblay, (2007) reported that shorter N1 latencies in adult CI users were associated with superior phoneme discrimination abilities, supporting the view that faster cortical processing reflects a more refined auditory representation.

The absence of significant latency correlations E20+E17 (+3 adjacent electrode apical) conditions suggests that the spread of neural activation may modulate the degree to which latency reflects perceptual performance. The findings by Bierer & Faulkner, (2010) demonstrated that the spatial selectivity of cochlear stimulation significantly influences cortical response characteristics and perceptual performance in CI users. Specifically, narrower channel interactions were associated with both faster cortical responses and improved spectral resolution, providing convergent evidence for the role of stimulation spread in shaping the latency–perception relationship.

In the basal region, no statistically significant correlations were observed between ACC latency and speech perception scores across any stimulation condition (E06, E06+E05, E06+E03). Basal electrodes stimulate high-frequency regions typically associated with consonant perception, and the variable degree of residual neural survival in the basal turn may introduce greater individual variability, reducing the strength of the latency–perception relationship (Holden et al., 2013). The author emphasised that neural survival in the basal region is particularly heterogeneous across CI recipients, which may account for the weaker and inconsistent correlations observed in this region. A near-significant positive correlation observed

for P1' latency under E06+E05 (Spearman ρ = 0.447, p = .055) may warrant further investigation in larger samples.

McGuire et al. (2021)reported significant negative correlations between ACC N1′ latency and both CNC word and phoneme recognition scores in adult cochlear implant users (r = -0.40, p < 0.05), indicating that shorter cortical response latencies were associated with better speech perception performance. The authors concluded that ACC latency reflects the efficiency of cortical sensory encoding of frequency changes and may account for a portion of the variability observed in speech perception outcomes. This interpretation is consistent with the significant negative correlations observed in the present study under the apical E20+E19 condition. In contrast, ACC amplitude (N1′–P2′) did not demonstrate significant correlations with speech perception outcomes. These findings suggest that cortical processing speed, as reflected by ACC latency measures, may be a more sensitive indicator of speech perception abilities than response amplitude**.**

Similarly, Van Heteren et al.(2022) found that earlier ACC responses were associated with better auditory discrimination abilities, further supporting the relationship between efficient cortical processing and functional hearing performance. The author reported that shorter ACC N1 latencies were associated with better frequency discrimination and superior speech perception, while larger N1–P2 amplitudes reflected more robust cortical encoding of auditory changes. The authors suggested that earlier ACC responses indicate more efficient neural processing of acoustic change information, which facilitates accurate speech perception. Meehan et al. (2024), which concluded that ACC measures are frequently associated with speech perception performance and may serve as objective indicators of auditory discrimination ability.

According to Liang et al.,(2018), who investigated the correlation between ACC measures, frequency discrimination abilities, and speech perception performance among cochlear implant recipients. The authors found a significant correlation between N1′ latency and speech perception performance ($R^2 = 0.36$, $p < 0.05$), such that individuals with lower N1′ latency scores had higher CNC word recognition scores. Furthermore, N1′ latency was correlated with behaviour frequency-difference thresholds in detecting frequency changes. This implies that individuals with rapid frequency changes have excellent auditory discrimination skills.

The ACC P1' amplitudes, on the other hand, were not correlated with speech perception outcomes, although they increased with increasing frequency change. A significant negative correlation was observed between ACC N1′ amplitude and speech perception scores under the apical E20 stimulation condition, indicating that participants with better speech perception exhibited larger (more negative) N1′ amplitudes. This finding is consistent with previous studies demonstrating that stronger ACC responses are associated with more effective auditory discrimination and speech processing abilities (He et al., 2014; Van Heteren et al., 2022). Larger N1′ amplitudes may reflect more robust cortical encoding of acoustic changes, particularly within the apical cochlear region, which conveys important low-frequency speech information. However, the absence of significant amplitude–speech perception relationships in other stimulation conditions suggests that this association may be influenced by electrode location and individual variability in neural processing. Larger N1 responses are generally interpreted as reflecting greater neural synchrony and stronger cortical engagement with the auditory input (Martin et al., 2008). The author findings demonstrated that N1 amplitude in CI users is positively associated with the ability to detect acoustic changes, suggesting that larger N1 responses reflect a more robust cortical representation of spectral and temporal contrasts critical

for speech understanding. However, it is not clear on negative association between N1' amplitude and speech perception outcomes.

Peak-to-peak amplitude provides a composite index of the overall magnitude of the cortical response to an acoustic change, and its association with better speech perception suggests that stronger differential cortical responses to spectral change support higher perceptual accuracy. This finding is broadly consistent with the work of Tremblay et al. (2006), who reported that ACC amplitude measures in normal-hearing listeners and hearing aid users were predictive of phoneme discrimination ability, and that larger ACC responses were associated with greater perceptual benefit from amplification. In CI users specifically, Friesen and Tremblay (2006) also observed that amplitude measures of cortical auditory evoked potentials were sensitive to differences in speech processing outcomes.

Based on the above results, "The null hypothesis 4b, "There is no significant relationship between the amplitude measures of acoustic change complex responses and speech perception scores," was partially rejected.

Chapter VI

Summary and Conclusions

A cochlear implant (CI) is an implantable hearing device and the most commonly used treatment option for individuals with severe to profound hearing loss. Speech perception skills of an individual are greatly enhanced by CI (Bazon et al., 2015). The present study aimed to compare Acoustic Change Complex (ACC) responses to changes in tone frequency across different electrode locations and to assess the relationships between speech perception and the ACC responses among paediatric CI users.

A total of 19 paediatric CI users aged between 6 and 9 years, all with over 1 year or more than one year of CI usage, were included in this study. The ACC were recorded using the frequency tones stimuli presented through loudspeakers under calibrated sound field conditions, and the LLR P1, N1 and P1-N1 and ACC P1', N1' and P1'-N1' were measured. Open-set speech perception was assessed using the word list from the picture identification test for Kannada-speaking children (Vandana., 1998) in the implanted ear only, with the contralateral hearing aid turned off. The major findings of the present study are as follows-

The present study successfully recorded ACC responses to tone frequency changes in all 19 paediatric cochlear implant users at apical (E20) and basal (E06) electrode locations, with the P1′–N1′ complex being the most consistently identified response. Apical stimulation produced significantly shorter ACC latencies and larger amplitudes than basal stimulation, indicating more efficient cortical processing and stronger neural encoding of low-frequency information. Larger frequency transitions, represented by wider electrode separations, generally elicited shorter

latencies and larger amplitudes, particularly in the apical region, suggesting enhanced cortical discrimination of greater frequency changes. Although significant differences were observed between apical and basal stimulation conditions, ACC measures showed limited variation across electrode separations within the same cochlear region, indicating that stimulation site had a greater influence on cortical responses than electrode separation alone. N1′ amplitude remained relatively stable across all stimulation conditions, while LLR measures did not differ significantly across electrode configurations, suggesting comparable baseline cortical auditory processing.

Correlation analysis revealed limited but significant associations between ACC measures and speech perception performance. Better speech perception was associated with larger N1′ amplitudes in the apical same-electrode condition (E20) and larger P1′–N1′ amplitudes in the basal +1 adjacent electrode condition (E06+E05). No significant correlations were observed between speech perception scores and ACC latency measures or the remaining ACC amplitude measures. Overall, these findings suggest that ACC, particularly its amplitude characteristics, may serve as a useful objective measure of cortical frequency discrimination and speech perception abilities in paediatric cochlear implant users.

The findings collectively demonstrate that apical electrode stimulation supports more efficient cortical processing, as evidenced by consistently shorter ACC latencies and larger amplitudes compared to basal electrode stimulation, reflecting enhanced neural encoding in low-frequency cochlear regions, which may be due to better neural survival in the apical region. Furthermore, wider electrode separation — particularly the +3 adjacent electrode condition (E20+E17) — elicited the shortest latencies and largest P1'–N1' amplitudes, underscoring the role of frequency transition magnitude in driving cortical auditory discrimination. In contrast,

basal electrode stimulation showed limited cortical sensitivity to frequency changes, with no statistically significant differences in ACC latency or amplitude across electrode separations within the high-frequency region, suggesting reduced neural responsiveness at basal cochlear sites. Notably, selected ACC measures demonstrated significant associations with speech perception performance, particularly under the apical +1 adjacent electrode condition, supporting the clinical utility of ACC as an objective electrophysiological marker of auditory discrimination ability in paediatric CI users. The LLR latency and amplitude measures did not show significant differences between basal and apical electrode stimulations, as the base frequency is the same within the apical (500 Hz) or basal electrode (4000 Hz) stimulation.

Correlation analysis revealed limited but clinically relevant associations between ACC measures and speech perception performance. Significant negative correlations between speech perception scores and both P1′ and N1′ latencies were observed only in the apical +1 adjacent electrode condition (E20+E19), indicating that better speech perception was associated with faster cortical processing of acoustic changes. In addition, speech perception scores showed a significant negative correlation with N1′ amplitude in the apical same-electrode condition (E20) and a significant positive correlation with P1′–N1′ amplitude in the basal +1 adjacent electrode condition (E06+E05), suggesting that stronger cortical responses were associated with better speech perception abilities. No significant correlations were observed for the remaining ACC latency or amplitude measures. Overall, these findings support the potential of ACC, particularly latency and amplitude measures under specific stimulation conditions, as objective indicators of auditory discrimination and speech perception performance in paediatric cochlear implant users.

6.2. Clinical Implications

The present findings have several implications for the clinical use of the ACC in paediatric CI users. First, the demonstration that ACC P1' latency and amplitude are sensitive to electrode location and electrode separation in paediatric CI users supports the clinical utility of the ACC as an objective measure of electrode discrimination/cortical frequency discrimination. The ACC may therefore be a valuable tool for evaluating the effectiveness of CI programming strategies aimed at optimising frequency resolution, particularly in children who are unable to provide reliable behavioural responses. The ACC P1’ latency can be useful to objectively measure frequency discrimination.

The ACC measure for tone frequency changes could be a useful measure and has clinical importance for individualised electrode deactivation strategies in CI programming. The optimised electrode configurations could improve speech perception outcomes and serve as a valuable tool for personalised CI programming.

Overall, the present findings have important implications for the clinical application of the ACC as an objective measure of auditory processing in CI users. The demonstration that selected ACC measures are significantly associated with speech perception performance across specific stimulation conditions supports the use of the ACC as a complement to behavioural assessments, particularly in populations for whom reliable behavioural audiometry is challenging, such as young children, individuals with cognitive impairments, or newly implanted users The present findings extend this work by identifying specific electrode configurations for which ACC measures are most meaningfully related to speech perception outcomes.

6.3 Limitations

The present study utilised a cross-sectional design; longitudinal studies are needed to determine whether ACC responses can predict changes in speech perception outcomes over time.

Second, all participants demonstrated reasonably good to excellent speech perception, and none had poor speech perception. Consequently, the restricted range of performance may have reduced the strength of observed correlations and limited the generalisability of the findings to poorer-performing paediatric cochlear implant users.

Additionally, ACC responses were examined only for apical and basal electrode regions. While these regions represent the extremes of the cochlear tonotopic array, responses from the middle cochlear region were not evaluated. Future studies incorporating stimulation across the full electrode array may provide a more comprehensive understanding of cortical frequency-change processing and its relationship to speech perception performance.

6.3. Future Directions

Future research should include larger and more diverse paediatric CI samples to improve the generalizability of these findings. Longitudinal studies tracking ACC responses alongside speech perception outcomes over time would help establish the clinical predictive value of ACC measures. Exploring additional cochlear regions and a broader range of frequency transitions could further clarify the tonotopic organisation of cortical responses in CI users. Additionally, integrating ACC-based objective measures into audiological rehabilitation protocols may support more individualised and outcome-driven CI programming for children. Future studies should include larger and more diverse paediatric cochlear implant samples and employ longitudinal designs to examine changes in ACC responses and speech perception over time. Investigating additional cochlear regions and a broader range of frequency transitions may further enhance understanding of cortical responses to tone frequency changes in CI users. These findings contribute to the growing literature on cortical auditory evoked potentials in paediatric CI users

and have implications for the clinical application of the ACC in evaluating and optimising CI function

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Appendix 1.

ಸೂಚಿತ ಸಮ್ಮತಿ ಪತ್ರ (Informed Consent)

ಈ ಅಧ್ಯಯನದ ಕ್ರಮಗಳು ಮತ್ತು ಪ್ರಕ್ರಿಯೆಗಳ ಕುರಿತು ನನಗೆ ಮಾಹಿತಿ ನೀಡಲಾಗಿದೆ. ಈ ಅಧ್ಯಯನದಲ್ಲಿ ಮಾನವ ವಿಷಯವಾಗಿ ಭಾಗವಹಿಸುವುದರಿಂದ ಉಂಟಾಗಬಹುದಾದ ಸಾಧ್ಯ ಅಪಾಯಗಳು ಮತ್ತು ಲಾಭಗಳನ್ನು ನಾನು ಸ್ಪಷ್ಟವಾಗಿ ಅರ್ಥಮಾಡಿಕೊಂಡಿದ್ದೇನೆ. ನಾನು ಅಧ್ಯಯನದಲ್ಲಿ ಭಾಗವಹಿಸಲು ನಿರಾಕರಿಸುವ ಹಕ್ಕು ಹೊಂದಿದ್ದೇನೆ ಅಥವಾ ಯಾವುದೇ ಸಮಯದಲ್ಲಿ ನನ್ನ ಸಮ್ಮತಿಯನ್ನು ಹಿಂತೆಗೆದುಕೊಳ್ಳಬಹುದು ಎಂಬುದನ್ನು ತಿಳಿದಿದ್ದೇನೆ. ಈ ಅಧ್ಯಯನಕ್ಕೆ ಒಳಪಟ್ಟಿರುವ ಸಂದರ್ಭದಲ್ಲಿ, ಸಂಶೋಧನಾ ತಂಡದಿಂದ ನಡೆಯುವ ಮೌಲ್ಯಮಾಪನಗಳಿಗೆ ಹೆಚ್ಚುವರಿ ಸಮಯ ನೀಡಬೇಕಾಗಬಹುದು ಮತ್ತು ಆ ಮೌಲ್ಯಮಾಪನಗಳಿಂದ ನನಗೆ ನೇರ ಪ್ರಯೋಜನವಾಗದೇ ಇರಬಹುದು ಎಂಬುದನ್ನೂ ತಿಳಿದಿದ್ದೇನೆ. ಈ ನಿಯಮಗಳಲ್ಲಿ ಯಾವುದೇ ಉಲ್ಲಂಘನೆ ಕಂಡುಬಂದಲ್ಲಿ, ಈ ಸಂಸ್ಥೆಯಲ್ಲಿ ಲಭ್ಯವಿರುವ ಚಿಕಿತ್ಸಾ ಸೇವೆಗಳನ್ನು ಪಡೆಯುವ ಹಕ್ಕು ನನಗೆ ನಿರಾಕರಿಸಲಾಗುವುದಿಲ್ಲ ಎಂಬ ಭರವಸೆಯೊಂದಿಗೆ, ನಾನು ಅಧ್ಯಕ್ಷರು AEC ಅವರಿಗೆ ಲಿಖಿತವಾಗಿ ದೂರು ನೀಡುವ ಸ್ವಾತಂತ್ರ್ಯ ಹೊಂದಿದ್ದೇನೆ.

ನಾನು, _____, ಸಹಿ ಮಾಡುವ ನಾನು, ಈ ಸಂಶೋಧನೆ / ಅಧ್ಯಯನ / ಕಾರ್ಯಕ್ರಮದಲ್ಲಿ ಭಾಗವಹಿಸಲು ನನ್ನ ಸಮ್ಮತಿಯನ್ನು ನೀಡುತ್ತೇನೆ.

ಪೋಷಕ / ಸಂರಕ್ಷಕರ ಸಹಿ: _____

(ಹೆಸರು ಮತ್ತು ವಿಳಾಸ): _____

ಸಾಕ್ಷಿಯ ಸಹಿ: _____

(ಸಾಕ್ಷಿಯ ಹೆಸರು): _____

ಸಂಶೋಧಕರ ಸಹಿ: _____

ಹೆಸರು ಮತ್ತು ಹುದ್ದೆ: ಮಿಸ್ ವರ್ಷಾ ಜಾಖರ್, 2ನೇ ಎಂಎಸ್‌ಸಿ (AUD)