AIDED CORTICAL RESPONSES TO FREQUENCY CHANGES AND SPECTROTEMPORAL MODULATION AS PREDICTORS OF HEARING AID BENEFIT IN CHILDREN WITH SENSORINEURAL HEARING LOSS

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CERTIFICATE

This is to certify that this dissertation entitled **"Aided Cortical Responses to Frequency Changes and Spectrotemporal Modulation as predictors of hearing aid benefit in children with Sensorineural Hearing Loss"** is a bonafide work submitted as part of fulfilment of Master of Science (Audiology) of the student with Registration Number **P01II24S023036**. This 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 **"Aided Cortical Responses to Frequency Changes and Spectrotemporal Modulation as predictors of hearing aid benefit in children with Sensorineural Hearing Loss"** has been prepared under my supervision and guidance. It is also being certified that this dissertation has not been submitted earlier to any university for the award of any other Diploma or Degree.

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DECLARATION

This is to certify that this dissertation entitled **"Aided Cortical Responses to Frequency Changes and Spectrotemporal Modulation as predictors of hearing aid benefit in children with Sensorineural Hearing Loss"** is the result of my own study under the guidance of **Dr. Srikar Vijayasarthy,** Assistant Professor, Department 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.

Mysuru

June, 2026

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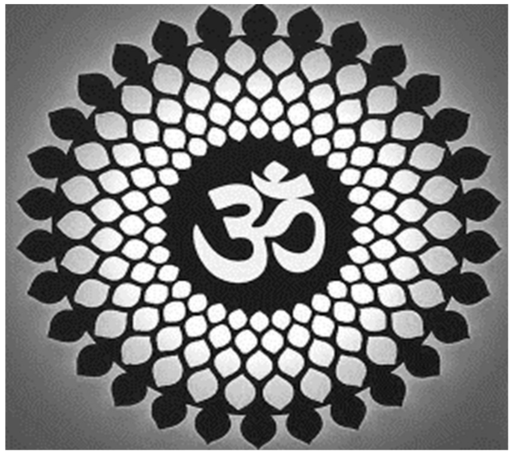

I dedicate this dissertation to Lord Shiva for his divine blessings.

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"Arise, awake, and stop not till the goal is reached."

-Swami Vivekananda

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Abstract

Sensorineural hearing loss (SNHL) is one of the most common hearing problems present from birth in children. Hearing aids are usually the first choice of treatment, but the benefit they provide can vary from child to child. Assessing hearing aid benefit in young children is often difficult because behavioral tests require the child's active participation and may not always give reliable results. The present study investigated the clinical utility of aided LLR and ACC responses for objectively assessing hearing aid benefit in children with SNHL using frequency-specific and spectrotemporally complex stimuli. 22 children aged 3–5 years participated and were divided into Group 1 (moderate to moderately severe hearing loss, n = 10) and Group 2 (severe-to-profound hearing loss, n = 12).

Assessment procedures included tympanometry, aided audiometry, Ling 6 sound testing, Assessment Checklist for Speech- Language Skills (ACSLS) and electrophysiological measures such as LLR and ACC using five suprathreshold stimuli. Pearson correlation analysis revealed that LLR and ACC responses were not related to aided hearing thresholds or Ling 6 test performance. However, in Group 1, spectrotemporal ACC responses showed a strong relationship with expressive language skills ($r = -0.830$, $p < 0.01$, $R^2 = 0.689$) and a moderate relationship with receptive language skills ($r = -0.530$). This relationship was not seen in Group 2, suggesting that the predictive value of ACC decreases as hearing loss becomes more severe. These findings indicate that spectrotemporal ACC may be a useful objective measure for predicting language development in children with moderate to moderately severe hearing loss. The absence of this relationship in children with severe-to-profound hearing loss may also support earlier consideration of cochlear implant candidacy.

Keywords: Auditory Change Complex (ACC), Late Latency Response (LLR), Sensorineural hearing loss, Spectrotemporal Modulation, Cortical Auditory Evoked Potentials, Language Development, Pediatric Audiology, Cochlear Implant Candidacy.

Chapter 1
Introduction

Hearing loss affects approximately 1-3 per 1,000 newborns, making it one of the most common congenital sensory impairments (Smith et al., 2005; Yoshinaga-Itano, 2003). Early identification through universal newborn hearing screening programs has enabled intervention within the first months of life, capitalizing on the critical period for auditory development (Joint Committee on Infant Hearing, 2019; Sharma et al., 2002). For children with moderate to severe hearing loss, hearing aids represent the primary intervention, with the goal of providing adequate auditory access to support speech and language development (Ching et al., 2013; Tomblin et al., 2015). However, the effectiveness of hearing aid intervention varies considerably among children, even those with similar audiometric configurations (Tomblin et al., 2014; Walker et al., 2015).

The assessment of hearing aid benefit in pediatric populations relies heavily on behavioral measures, including aided audiometry, speech perception testing, and language development assessments ((Bagatto et al., 2005) et al., 2005; Scollie et al., 2005). While these measures provide valuable information about functional outcomes, they present significant challenges when applied to young children or those with developmental delays (Eisenberg et al., 2007; Moeller et al., 2007). Behavioral testing requires sustained attention, cooperation, and cognitive understanding of task demands that may be beyond the capabilities of many pediatric patients (Wightman & Allen, 1992; Werner, 2007). Consequently, clinicians often must make critical decisions about amplification adequacy based on incomplete or unreliable behavioral data, potentially delaying optimal intervention strategies.

Electrophysiological measures offer an objective alternative for assessing auditory processing in pediatric populations (Hall, 2007; Kraus & Nicol, 2005). Cortical auditory evoked potentials, including Late Latency Responses (LLRs), have shown promise in evaluating central auditory function and have been successfully used to assess hearing aid benefit in children (Korczak et al., 2012; Sharma & Dorman, 2006). The Auditory Change Complex (ACC) represents a complementary electrophysiological approach that focuses on change detection abilities fundamental to speech perception (Martin & Boothroyd, 1999; Ostroff et al., 1998). Unlike traditional onset responses, the ACC measures cortical responses to acoustic changes within ongoing stimuli, potentially providing more direct insight into the perceptual processing mechanisms underlying speech understanding (Kim, 2015; Tremblay et al., 2003). Recent advances in stimulus design, particularly the use of spectrotemporally modulated signals that mimic the acoustic complexity of speech, have enhanced the ecological validity of ACC measurements (Sohier et al., 2021; Undurraga et al., 2021). These methodological advances create an opportunity to develop more efficient objective measures for evaluating hearing aid benefit in children.

Need for the Study

Assessing hearing aid benefit in pediatric populations presents significant clinical challenges that can have significant implications for intervention timing and outcomes. In children with hearing loss, behavioral aided assessments often yield unclear results due to developmental limitations in attention and cooperation ((Bagatto, Moodie, Scollie, Seewald, Moodie, Pumford, Rachel Liu, et al., 2005)., 2005; Scollie et al., 2005). This limitation may become particularly problematic in children with severe to profound hearing loss, where accurate assessment of hearing aid benefit is crucial for determining whether cochlear implantation should be pursued (Leigh et al., 2016; Mehta et al., 2017). Delays in identifying insufficient hearing aid benefit can postpone a cochlear implant surgery, thereby limiting critical period advantages for speech and language development (Kral & Sharma, 2012; Yuan et al., 2024). Even in children with lower degrees of hearing loss, suboptimal hearing aid gain (arising from challenges inherent to pediatric threshold determination) may affect speech and language development, necessitating the need for objective verification of hearing aid benefit (Mehta et al., 2017).

Traditional objective measures such as aided Late Latency Responses (LLRs) have shown promise in assessing cortical auditory processing in children with hearing aids (Sharma & Dorman, 2006; Visram et al., 2023). The P1 biomarker, in particular, has demonstrated sensitivity to auditory experience and training effects, providing valuable insights into cortical plasticity following amplification (Gilley et al., 2010; Sharma et al., 2005). However, conventional LLR measures may be confounded by audibility factors rather than purely reflecting perceptual processing abilities (Sohier et al., 2021).

The Auditory Change Complex (ACC) represents a promising approach that focuses on change detection abilities crucial for speech perception (Martin & Boothroyd, 1999; Ostroff et al., 1998). By measuring cortical responses to acoustic changes within ongoing stimuli, the ACC may provide a more direct assessment of perceptual processing that is less dependent on simple audibility (Kim, 2015; Small et al., 2012; Tremblay et al., 2003). Recent research has demonstrated that ACC responses to spectrotemporally modulated stimuli can effectively predict speech perception abilities in adults with hearing loss (Sohier et al., 2021; Undurraga et al., 2021).

While ACC has been investigated in the pediatric population (Strahm et al., 2022), studies examining its application for assessing aided benefit in children with hearing aids remain limited (He et al., 2015; Shalaby et al., 2024). Research with cochlear implant users has shown correlations between measures of ACC and behavioral speech perception outcomes, suggesting potential application to assess hearing aid benefit (McGuire et al., 2021; van Heteren et al., 2022). However, since the acoustic processing demands differ significantly between cochlear implants and hearing aids, there is a necessity to validate it in hearing aid users also.

Finally, there is a lack of studies that simultaneously examine both aided frequency-specific auditory processing (using pure tone stimuli) and complex spectrotemporal processing (using speech-like stimuli) within the same sample of children with hearing loss. Such comprehensive assessments could provide insights regarding different levels of auditory processing hierarchy - from basic change detection to complex pattern recognition that underlies speech perception. Furthermore, limited studies have systematically correlated these objective measures with both behavioral audibility measures (aided audiogram) and functional language outcomes in children using hearing aids.

The present study addresses these limitations by investigating ACC responses to both frequency-specific and spectrotemporally complex stimuli in children using hearing aids and correlates these findings with behavioral measures of audibility and language outcomes. This approach may provide clinicians with objective tools for optimizing hearing aid fittings, identifying children at risk for suboptimal outcomes, and making evidence-based decisions regarding intervention strategies, including the timing of cochlear implant candidacy evaluation.

Aim of the study

To investigate the clinical utility of LLR and Auditory Change Complex (ACC) measurements for objectively assessing hearing aid benefit in children with hearing loss, using both frequency-specific and spectrotemporally complex stimuli.

Objectives

1. To correlate measures of aided LLR (frequency-specific and tone complex) with behavioral measures that include aided audiometric thresholds and language development in children with moderately severe and severe to profound sensorineural hearing loss using hearing aids
2. To correlate measures of aided ACC (frequency-specific and spectrotemporal) with behavioral measures that include aided audiometric thresholds and language development in children with moderately severe and severe to profound sensorineural hearing loss using hearing aids
3. To explore the relative predictive value of LLR and ACC measures using frequency-specific tones and spectrotemporally modulated tone complexes in children with moderately severe and severe to profound sensorineural hearing loss using hearing aids

Chapter 2

Review of Literature

Childhood hearing loss can create major challenges in a child's language and cognitive development. It may especially affect important language skills such as syntax, semantics, and pragmatics, which are essential for clear communication, learning, and positive social interaction (Porcar-Gozalbo et al., 2024). Mild to severe hearing loss places children at risk for delays in language development, particularly when the hearing loss is moderate or more severe. However, these risks can be reduced through early access to properly fitted hearing aids that provide clear audibility, especially when they are used consistently (Tomblin et al., 2015).

Lewis (1985) noted that young children often cannot clearly express how well their hearing aids are working, which makes assessment difficult. Similarly, Vlastarakos et al. (2017) found that tracking progress in infants becomes especially challenging when behavioral audiometry is unreliable, making it necessary to rely on electrophysiological tests for appropriate hearing aid fitting.

The neural encoding of speech signals begins at the level of the auditory nerve and continues through the auditory brainstem to the cortical auditory regions. Both speech and non-speech stimuli are used to assess the neural integrity of the auditory pathway. Several auditory evoked potentials (AEPs) are commonly used to study how the auditory system processes acoustic and speech features of sounds. According to Martin, Tremblay, and Korczak (2008), the most commonly used subcortical measures include speech-evoked Auditory Brainstem Responses (speech ABR) and Frequency Following Responses (FFR), while cortical measures include Long Latency Responses (LLR), the P1–N1–P2 complex, Acoustic Change Complex (ACC), Mismatch Negativity (MMN), and P300.

The following section provides an overview of studies on speech-evoked auditory potentials in individuals with normal hearing as well as those with clinical conditions. The studies are discussed under two broad headings:

2.1 Subcortical AEPs – Speech ABR and FFR

2.2 Cortical AEPs – LLR, ACC, P300, and MMN

2.1 Subcortical Auditory Evoked Potentials and Speech Encoding

2.1.1 Speech ABR and FFR

The auditory brainstem plays an important role in processing speech sounds. Sinha and Basavaraj (2010) investigated speech-evoked Auditory Brainstem Responses (ABR) in 30 individuals with normal hearing using a 40 ms synthesized /da/ stimulus. The findings showed that the consonant portion of the stimulus generated peak V, while the vowel portion generated a Frequency Following Response (FFR), showing accurate encoding of the fundamental frequency (F0) and first formant frequency (F1). The authors highlighted that speech-evoked ABR is useful for understanding speech processing at the brainstem level and can be valuable in both clinical and research settings.

Hornickel, Knowles, and Kraus (2011) studied whether speech-evoked ABR gives consistent results over time. They tested 26 typically developing children between 8 and 13 years of age and followed them for one year. The children were tested using a speech sound called /da/, in both quiet and noisy listening conditions. The results showed that the brain responses stayed very similar across the two time points, meaning the test produced reliable and stable results. This suggests that speech-evoked ABR can be a dependable tool for checking how well children process sound and speech-related information.

Koravand et al. (2017) investigated speech processing at the brainstem level in children with mild to moderately severe sensorineural hearing loss using speech-evoked ABRs. The study included

25 children aged 6–14 years with and without hearing loss. Delayed as well as enhanced speech responses were observed in children with hearing loss, indicating that hearing impairment can alter speech processing at the brainstem level.

Ribas-Prats et al. (2019) recorded Frequency Following Responses (FFRs) in 46 healthy newborns using two speech sounds, /da/ and /ga/. They analysed the responses by looking at both time and frequency measures and used this data to build a normative database. The results showed that newborns produced clear and consistent brain responses to both speech sounds. This indicates that FFRs can be successfully recorded very soon after birth, and may help in identifying babies who are at risk of developing speech and language difficulties at an early stage.

Easwar, Purcell, and Wright (2023) investigated whether speech-evoked Envelope Following Responses (EFRs) could serve as an objective measure of hearing aid benefit in children with mild to severe hearing loss. The study tested 18 children using the speech sound /suʃi/, which was played at three different loudness levels 55, 65, and 75 dB SPL in aided and unaided conditions. The results showed that EFR amplitude and detectability improved with hearing aid use and were associated with better speech discrimination. The study suggested that speech-evoked EFRs can serve as a useful objective measure for evaluating hearing aid benefit in children with hearing loss.

2.2 Cortical Auditory Evoked Potentials and Speech Encoding

2.2.1 Long Latency Responses (LLR)

Long Latency Responses are cortical auditory evoked potentials composed of the P1, N1, P2, and N2 components occurring within a time window of approximately 50–500 ms (McPherson & Starr, 1993). P1, N1, and P2 are considered exogenous components because they are mainly influenced by the acoustic characteristics of the stimulus, whereas N2 is considered an endogenous component because it is more strongly influenced by higher-order processes such as perception and cognition (Leite et al., 2018).

Long-latency auditory evoked potentials (LLAEPs) are widely used to study the functioning of the central auditory pathways in individuals with sensorineural hearing loss (SNHL). They also serve as an objective measure to monitor changes in cortical auditory processing following hearing aid or cochlear implant use (Leite et al., 2018).

Auditory long-latency responses (ALLRs) can be elicited using clicks, tone bursts, and speech stimuli. These responses provide an objective understanding of how the brain processes and perceives speech (Purdy et al., 2001; Tremblay et al., 2003). Speech-evoked ALLRs typically show longer latencies and larger amplitudes than click-evoked responses because speech signals are acoustically more complex (Chandra & Barman, 2009; Tremblay et al., 2003).

Silva et al. (2017) studied the maturation of LLAEPs in normal-hearing children over nine months using the speech stimulus /ba/ presented at 70 dB HL. Children aged 10–63 months were evaluated, and P1 and N2 were found to be the most consistently observed components. Gradual changes in response latencies over time suggested that LLAEP development is mainly related to maturation of the central auditory nervous system.

Renata et al. (2018) compared LLAEPs before and after hearing aid use in children with sensorineural hearing loss. The study included 18 children with mild-to-moderate bilateral sensorineural hearing loss and 14 age-matched children with normal hearing. Reduced amplitudes and delayed responses were observed in children with hearing loss; however, improvements in response presence and amplitude were noted following hearing aid use. The findings suggested that LLAEPs can be useful for monitoring neuroplastic changes in the auditory pathway after auditory stimulation.

Hassaan (2012) evaluated Aided Evoked Cortical Potentials (AECPs) in 10 children aged 6–12 years with mild to moderately severe sensorineural hearing loss who were regular hearing aid users. Tone bursts and speech syllables such as /ga/ and /wa/ were used as stimuli. Children with longer hearing aid experience demonstrated better cortical responses and improved speech recognition abilities. The study suggested that AECPs can serve as an objective method for assessing hearing aid benefit, especially in young children who may not provide reliable behavioral responses.

2.2.2 Acoustic Change Complex (ACC)

The Acoustic Change Complex (ACC) is a cortical auditory evoked potential that reflects the brain's ability to detect and discriminate changes within an ongoing sound (Sarah et al., 2024).

Ostroff, Martin, and Boothroyd (1998) demonstrated ACC responses in normal-hearing adults using the syllable /sei/ and its individual speech components, suggesting that the response reflects neural activity generated by different phonemes within speech. Supporting these findings, Tobias Burger et al. (2009) showed that consonant–vowel syllables simulated with tone bursts could evoke similar cortical responses. Martin and Boothroyd (1999) further reported a clear N1–P2 change complex only when transitions occurred between tonal and noise stimuli, indicating that ACC is particularly sensitive to acoustic transitions.

Martin and Boothroyd (2000) investigated ACC as an objective measure of auditory discrimination in adults with normal hearing. Using synthetic vowel stimuli with spectral and amplitude changes, they observed clear ACC responses for both types of changes, indicating that ACC is sensitive to acoustic modifications within sound. The authors concluded that ACC may serve as a reliable objective tool for assessing auditory discrimination, especially in individuals unable to provide reliable behavioral responses.

Kelly Tremblay et al. (2003) recorded P1–N1–P2 responses using naturally produced speech sounds such as /bi/, /pi/, /shi/, and /si/ in seven young adults with normal hearing. The responses remained stable and reliable when retested within eight days. Different speech sounds produced distinct neural response patterns, suggesting that these cortical responses may serve as reliable objective measures of speech processing.

Simonsen et al. (2025) developed an electrophysiological version of the Audible Contrast Threshold test (E-ACT) using ACC responses to objectively assess auditory discrimination. The study included 65 adults aged 20–86 years with normal to mild-to-moderate hearing loss. Tonal stimuli produced clearer and more reliable ACC responses than noise-based stimuli. Increased modulation depth resulted in larger amplitudes and shorter latencies. The study suggested that E-ACT may become a useful objective tool for assessing auditory discrimination in infants, young children, and difficult-to-test populations.

Shalaby et al. (2022) investigated the clinical use of ACC in 60 Arabic-speaking children aged 6–12 years using binaural hearing aids. ACC responses were recorded in aided and unaided conditions using speech stimuli presented in noise. Two stimuli vowel /o/ with SNR (0 & 8) were used. The findings showed improved ACC responses and shorter N1 latencies in the aided condition, indicating better speech processing with hearing aid use. Although ACC responses did not strongly correlate with behavioral results, the study suggested that ACC can still be a useful objective measure of auditory processing and hearing aid benefit.

Ching et al. (2023) evaluated the clinical usefulness of ACC in infants aged 3–12 months with normal hearing and hearing loss. ACC responses were successfully recorded in both groups using [szs], [uiu], and spectrally rippled noise stimuli. Infants with severe-to-profound hearing loss showed fewer responses. Better ACC responses were associated with improved everyday listening and auditory performance based on parental reports. The authors suggested that ACC may support early decisions regarding hearing aid benefit and cochlear implant candidacy.

Shalaby et al. (2024a) further investigated the clinical usefulness of ACC in assessing hearing aid benefit in 60 children with hearing loss aged 6–12 years using binaural hearing aids. ACC responses were recorded using a “gap in tone” stimulus. The findings showed that ACC responses were more easily detected and had shorter latencies in the aided condition, indicating improved auditory processing with amplification. The results were also associated with parent-reported auditory performance.

2.2.3 P300

The P300 wave is a cortical response elicited when a person identifies an important or rare sound among frequent sounds. Its amplitude and latency vary depending on task difficulty. Individuals with reduced cognitive abilities often show smaller and delayed responses. P300 is considered an indicator of attention, auditory discrimination, and higher-order cognitive processing (Picton, 1992).

Shintinawy et al. (2009) investigated P300 responses in children using speech stimuli (/ga/ as the standard stimulus and /da/ as the target stimulus) along with tonal stimuli. Similar P300 findings were observed for both speech and tonal stimulation. Comparable findings were later reported in adults by Massa et al. (2011).

2.2.4 Mismatch Negativity (MMN)

Mismatch Negativity (MMN) is a cortical response reflecting the automatic detection of changes in auditory stimuli. Since MMN does not require active attention, it is particularly useful for evaluating infants and difficult-to-test individuals. MMN provides information regarding auditory discrimination, sensory memory, and auditory processing abilities (Naatanen & Escera, 2000).

Ejiri, Okubo, and Okuni (1992) studied MMN in individuals aged 6 months to 43 years and demonstrated that MMN can be recorded even in very young infants. The response became faster with increasing age and reached adult-like patterns by approximately seven years. Some children with intellectual disabilities showed delayed MMN responses. The study highlighted the usefulness of MMN for assessing auditory and cognitive development in children and difficult-to-test populations.

All of these auditory evoked potentials have been used to evaluate speech processing abilities at different levels of the auditory system, however, only a few have strong clinical utility in pediatric populations. Speech ABR and FFR testing may require long recording times and can be difficult in young children because they must remain calm and quiet throughout testing. These tests mainly assess brainstem-level auditory processing. P300 recordings may also be challenging in young children and difficult-to-test individuals because they require active attention and cooperation.

MMN recordings can be influenced by the type of stimulus used, testing conditions, and background noise during recording. In some individuals with hearing or neurological disorders, interpretation of MMN responses may also be difficult (Kraus et al., 1995).

LLR serves as an objective measure for monitoring central auditory nervous system maturation and neuroplasticity during rehabilitation in children and difficult-to-test populations. ACC, on the other hand, detects changes within an ongoing sound stimulus and serves as an objective tool for assessing auditory discrimination, audibility, and hearing aid benefit, especially in young children and difficult-to-test individuals where behavioral responses may be limited or unreliable (Shalaby et al., 2024b).

Despite growing interest in ACC, research on speech encoding in noise using ACC remains limited, particularly with spectrotemporally modulated stimuli that mimic the complexity of real-life speech signals. Furthermore, only a few studies have investigated the use of such stimuli in children for assessing auditory discrimination and hearing aid benefit.

Chapter 3

Methods

The method includes the recording of the aided cortical responses to frequency changes and spectrotemporal modulation as predictors of hearing aid benefit in children with sensorineural hearing loss.

3.1 Participants

The study consisted of two groups of participants: Group 1 consisted of the subjects with Moderate to Moderately severe hearing loss while Group 2 consisted of subjects with Severe to Profound hearing loss.

3.1.1 Moderate to Moderately severe hearing loss (Group 1)

This group included 10 children aged between 3 to 5 years with bilateral congenital moderate to moderately severe hearing loss and unaided air conduction pure tone averages ranging from 55 to 70 dB HL across speech frequencies. All children were bilateral hearing aid users with a minimum hearing aid experience of 2 months and were attending regular speech-language therapy sessions. Only children with normal middle ear function (A or As -type tympanograms), were included in the study.

3.1.2 Severe to Profound hearing loss (Group 2)

This group include 12 children aged 3 to 5 years with bilateral congenital severe to profound hearing loss and unaided air conduction pure tone averages greater than 70 dB HL across speech frequencies. All children were bilateral hearing aid users with a minimum hearing aid experience of

2 months and were attending regular speech-language therapy sessions. Only children with normal middle ear function (A or As -type tympanograms), were included in the study.

3.2 Instrumentation

A two-channel calibrated Inventis Piano audiometer with free-field facility was used for aided audiometry, while middle ear function was assessed using a Grason-Stadler TympStar Immittance V26 instrument. Auditory evoked potentials were recorded using an Intelligent Hearing Systems (IHS) Opti-Amp system with SmartEP Version 3.94USBeZ software. All instruments were calibrated to ensure accurate and reliable measurements.

3.3 Test environment

All procedures were carried out in an electrically shielded and sound-treated room that meets the ambient noise level criteria specified by ANSI S3.1-1999 (R2008).

3.4 Procedure

3.4.1 Case History

A detailed case history was obtained from all participants to gather information about otological, neurological, psychological, and cognitive conditions. Children with bilateral congenital hearing loss using bilateral hearing aids, having at least 2 months of hearing aid experience, and consistent speech-language therapy were examined. Children with additional disorders, middle ear problems, inconsistent hearing aid use or therapy, or difficulty cooperating during testing were ruled out.

Once the possible deficits were ruled out in all these areas, immittance evaluation, aided audiometry, speech perception, and language evaluations were carried out. Further, only those children who met the criteria in all the above evaluations underwent LLR and ACC recording.

3.4.2 Immittance Evaluation

Tympanometry was carried out using the Grason Stadler Inc. TympStar Pro to record the tympanogram for a probe tone frequency of 226Hz.

3.4.3 Aided Audiogram

The participant was tested in the soundproof room. A two-channel Calibrated Inventis Piano audiometer was used to measure aided thresholds for freefield presentation from 250 Hz to 8 kHz, and the six ling sounds. The modified Hughson-Westlake method was used to establish the thresholds.

3.4.4 Language evaluation

Receptive and expressive language skills were measured using the Assessment Checklist for Speech-Language Skills (ACSLS).

3.4.5 Electrophysiological Evaluation

3.4.5.1 Stimulus Generation

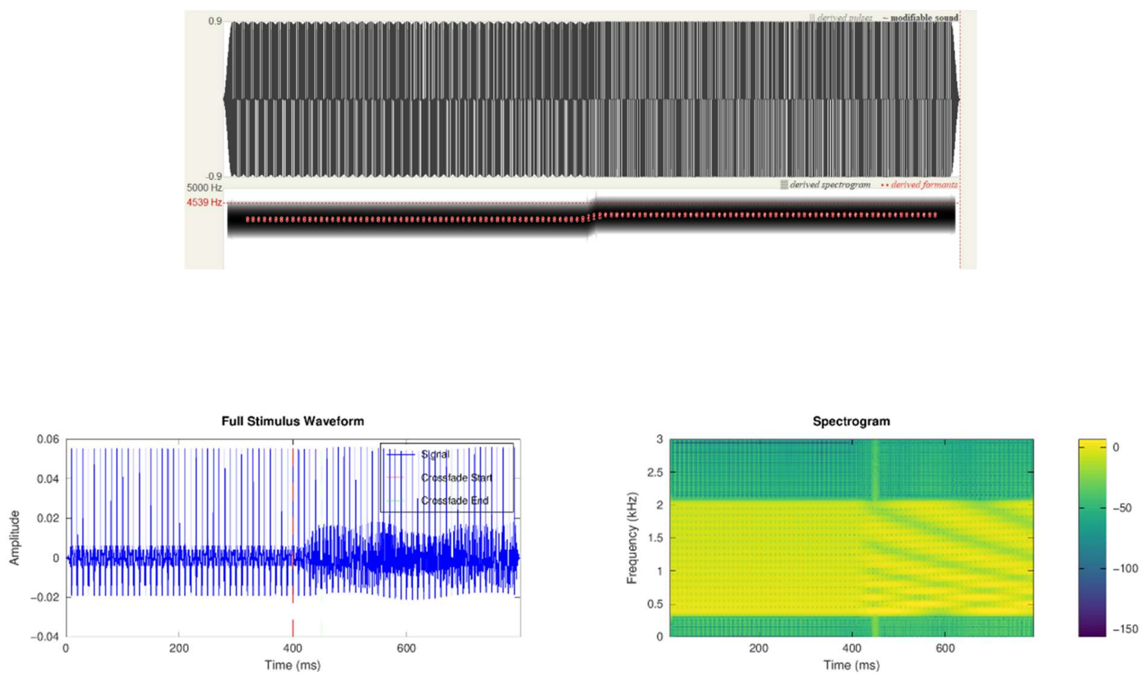
Stimulus generation and characteristics

The stimuli were generated using MATLAB with a sampling rate of at a 44.1 kHz. Each stimulus comprised three sequential segments: (1) a 200 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 200 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. The spectrotemporal modulation (STM) stimuli used in the study consisted of 800-ms tonal complexes made up of 17 frequency components ranging from 350 Hz to 2000 Hz, with each component separated by 100 Hz. These stimuli were designed with a temporal modulation rate of 4 Hz and a spectral modulation density of 2 cycles per octave, resulting in a complex sound signal that varied across both time and frequency.

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 550, 650; at 4000 Hz, targets were 4050, 4150. All audio files were normalised to 90% of full scale and saved as 16-bit PCM .wav files. The waveform of pure tones and Spectrotemporal modulation stimuli are shown in Figure 3.1

Figure 3.1

The Waveform and spectrogram of pure tone (upper panel) and spectrotemporally modulated noise (lower panel)



3.4.5.2 Procedure

Participants were seated in an electrically and acoustically shielded room in a comfortably reclining chair and the electrode sites were cleaned using a skin abrasive paste, and disc electrodes with conductive paste were placed on the scalp and secured with surgical tape. The subject were instructed to relax while watching silent videos. They were instructed to stay awake and keep their body movements minimal while the recording was in progress. Electrode impedance was maintained below 5 kΩ, with relative impedance kept below 2 kΩ throughout the testing session. Participants were given sufficient breaks between recordings for their comfort. The details of the recording of LLR and ACC protocol are provided in Table 3.1 and Table 3.2

Table 3.1

Protocol used for LLR and ACC recording stimulus parameters

Stimulus Parameters

Parameter	Frequency-Specific Stimuli	Spectrotemporal Stimuli
Signal	Pure tones	Tonal complex (17 components, 100 Hz spacing)
Frequency	500 Hz, 4000 Hz	350-2000 Hz
Frequency Changes	500→550 Hz, 500→650Hz; 4000→4050 Hz, 4000→4150 Hz	N/A
Modulation	N/A	4 Hz temporal modulation, 2 cycles/octave spectral modulation
Contrast Level	N/A	-2 dB FS (14 dB nCL)
Stimulus Duration	500 ms	800 ms
Repetition Rate	0.9 Hz	0.9 Hz
Presentation Level	55 dB SPL	45 dB SPL
Presentation Mode	Freefield @ 0^0 azimuth	Freefield @ 0^0 azimuth
Polarity	Alternating	Alternating

Table 3.2

protocol used for LLR and ACC recording parameters

Recording Parameters

Parameter	Specification
Electrode Montage (cortical)	High forehead (active), Contralateral mastoid (reference), Low forehead (ground)
Electrode Montage (ocular)	Above the eye (active), Below the eye (reference)
Ear	Better ear (Right, if hearing loss is similar)
Bandpass Filter	1-30 Hz
Artifact Rejection	75 μV threshold
Analysis Window	-100 to 800 ms
Baseline	-100 to 0 ms
Sweeps per Condition	50 × 2 repetitions = 100 total
Recording Duration	~0.93 minutes per block, ~ 1.86 minutes per condition

To reduce any order effect the stimuli were presented in a random sequence. Each of the five stimuli was recorded in two runs, with 50 sweeps in each run. The total testing time was approximately 45 minutes.

3.4.6 Response Analysis

The replicated waves were averaged and analysed. The peaks were identified by visually examining the recorded waveforms. The latency of P1, N1 and P2 as LLR and the positivities and negativities of the ACC complex as P1', N1' and P2' were marked. But only P1 of LLR and P1' of ACC were used for analysis. The latency of each peak was recorded in milliseconds (ms).

Chapter 4

Results

The present study investigated the clinical utility of Late Latency Response (LLR) and Auditory Change Complex (ACC) measurements for objectively evaluating central auditory processing and predicting hearing aid benefit in children with sensorineural hearing loss. The analysis was conducted across two distinct participant groups stratified by the degree of hearing loss: Group 1 comprised 10 children with moderate to moderately severe hearing loss, and Group 2 comprised 12 children with severe to profound hearing loss. Relationships between electrophysiological parameters (P1 component latencies) and behavioral parameters (aided pure-tone thresholds, Ling 6 sound detection thresholds, and language ages) were evaluated systematically using Pearson product-moment correlation coefficients *(r)* to address the primary objectives of the study. Prior to analysis, parameters were assessed for normality with Shapiro-Wilk test and it was found that most of the variables were found to be normally distributed ($p > 0.05$

4.1 Descriptive Statistics

Descriptive statistics summarizing the demographic, audiological, behavioral, and language measures across the two clinical groups are presented in Table 4.1.

Variable	Group 1 Mean (SD) [n=10]	Group 1 Range	Group 2 Mean (SD) [n=12]	Group 2 Range
Chronological Age (months)	38.9 (4.4)	33.0–48.0	50.0 (12.2)	34.0–65.0
Age at Intervention (months)	5.2 (2.9)	3.0–11.0	14.1 (8.9)	3.0–28.0
Aided Listening Age (months)	33.6 (4.2)	27.0–40.0	36.7 (13.1)	12.0–61.0
Aided Threshold 500 Hz (dB HL)	38.0 (8.9)	20.0–50.0	34.6 (6.2)	25.0–50.0
Aided Threshold 1000 Hz (dB HL)	38.0 (6.7)	25.0–50.0	40.4 (8.1)	30.0–55.0
Aided Threshold 4000 Hz (dB HL)	42.0 (9.2)	30.0–55.0	52.1 (16.0)	30.0–90.0
Receptive Language Age (months)	16.5 (8.3)	11.0–32.0	27.6 (12.4)	11.0–51.5
Expressive Language Age (months)	12.9 (6.7)	8.0–28.0	18.3 (9.5)	5.0–39.0

Note. SD = Standard Deviation. Aided thresholds are reported in dB HL. Language tracking derived from Scales of Early Communication Skills for Hearing Impairment (SECS). Note. G1 = moderate to moderately severe hearing loss group (n = 10); G2 = severe to profound hearing loss group (n = 12).

Figure 4.1

Representative waveform of a good cortical responses in individual with hearing loss

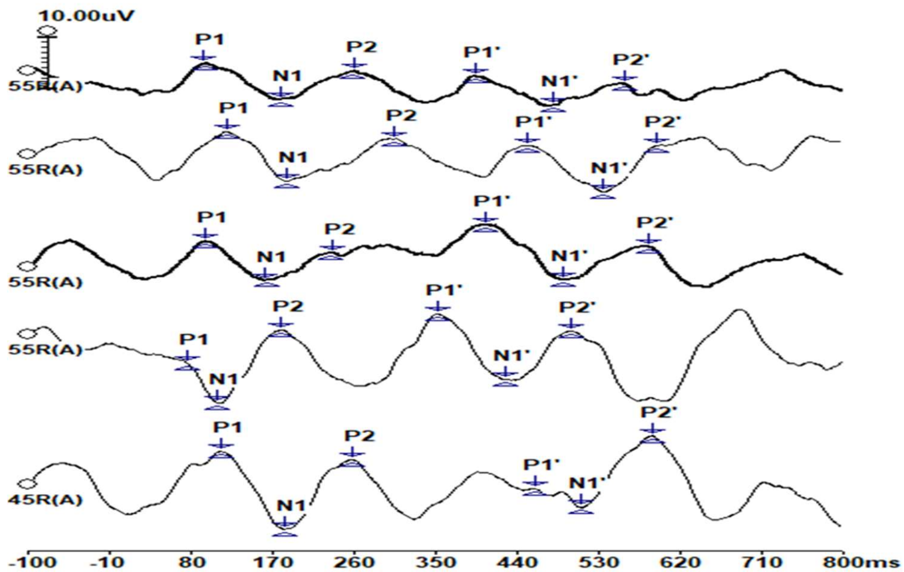
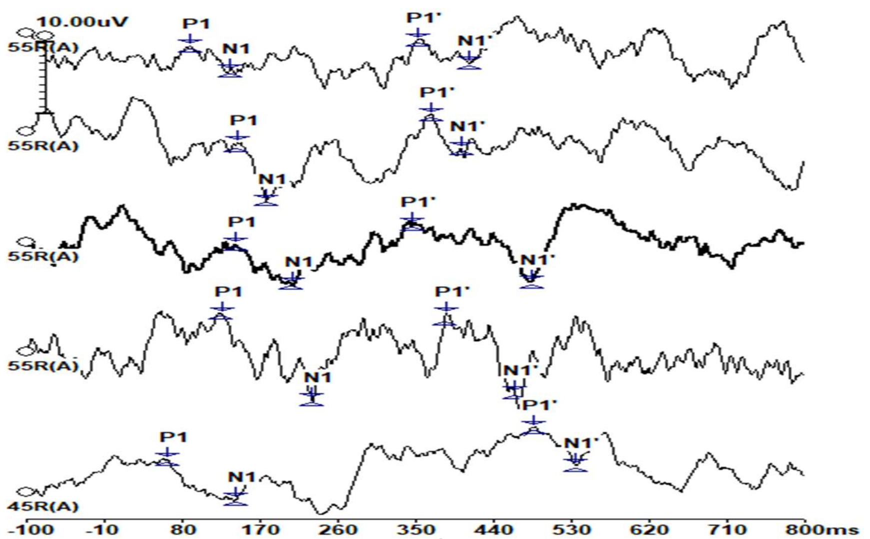


Figure 4.2

Representative Waveform of a poor cortical responses in individual with hearing loss



4.2 Correlation of Aided LLR Latencies with Behavioral Measures

The first objective targeted the relationship between frequency-specific aided LLR onset latencies and behavioral profiles. Based on the underlying stimulus design, the 200 ms initial baseline tone ensures that the LLR P1 latency to the 550 Hz condition (L_550P1) and the 4050 Hz condition

(L_4050P1) capture the true onset responses to 500 Hz and 4000 Hz processing respectively. The subsequent measures at 650 Hz and 4150 Hz represent redundant onset iterations and were excluded from this analysis to reduce increased false positive results from multiple redundant comparisons.

Pearson product-moment correlations revealed that suprathreshold aided LLR P1 latencies did not demonstrate a statistically significant relationship with frequency-matched behavioral aided thresholds in either participant group. In Group 1 (Moderate-to-Moderately Severe), the correlation between the 500 Hz aided threshold and LLR latency for 500 Hz was weak and non-significant (r = 0.143, p = 0.694). Similarly, the 4000 Hz aided threshold did not significantly correlate with the corresponding onset latency (r = -0.445, p = 0.197). For Group 2 (Severe-to-Profound), the correlations remained statistically non-significant for both the low-frequency onset (r = -0.481, p = 0.114) and the high-frequency onset (r = -0.477, p = 0.117).

Furthermore, spectrotemporal LLR P1 latencies demonstrated weak, non-significant correlations with functional language scores in Group 1 for both Expressive Language Age (r = -0.360, p =0.09) and Receptive Language Age (r = -0.30, p =0.2). In Group 2, the association between *P1* latencies and Receptive Language Age was entirely flat (r = 0.130, p = 0.3), showing a complete absence of predictive clinical utility for language milestones via standard onset LLR markers.

4.3 Correlation of Aided ACC Latencies with Behavioral Measures

The second objective explored the relationship between cortical change detection processing via the Auditory Change Complex (ACC) and behavioral outcomes. Mirroring the LLR threshold findings, suprathreshold ACC P1 latencies did not significantly correlate with absolute behavioral pure-tone thresholds. For Group 1, the 500 Hz threshold showed negligible correlation with the small frequency-change latency *(550 Hz)* (r = 0.074, p = 0.838) and a non-significant moderate correlation with the large frequency-change latency *(650 Hz)* (r = 0.450, p = 0.192). The 4000 Hz threshold matched with *ACC P1 latency* yielded an r of -0.295 (p = 0.408). In Group 2, the correlations were also non-significant (r = -0.564, p = 0.056) (Figure 4.3).

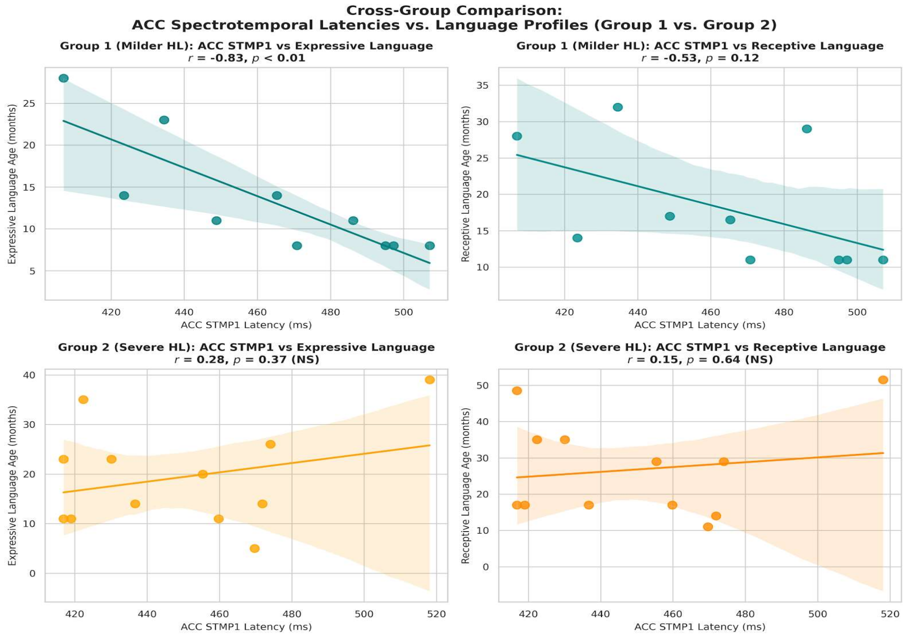


Figure 4.3 *Cross-group comparison of Auditory Change Complex (ACC) spectrotemporal latencies versus developmental language ages.* The upper panel displays Group 1 (moderate-to-moderately severe hearing loss, n = 10), where shorter (more efficient) cortical change detection processing speeds are predictive of advanced expressive (r = -0.83) and receptive (r = -0.53) language profiles. The lower panel displays Group 2 (severe-to-profound hearing loss, n = 12), demonstrating a complete decoupling and flat scatter profiles (p > 0.05) between cortical latencies and behavioral language ages, reflecting peripheral acoustic degradation. Shaded areas represent the 95% confidence intervals for the fitted regression lines.

An important finding of the study was the relationship between spectrotemporal ACC latencies and language development. In Group 1, spectrotemporal ACC latency showed a strong and statistically significant negative correlation with Expressive Language Age (r = -0.830, p < 0.01) and a moderate negative correlation with Receptive Language Age (r = -0.530). These results indicate that children with shorter and faster ACC latencies tended to have better expressive and receptive language skills. This suggests that more efficient cortical detection of sound changes is associated with stronger language development in children with milder hearing loss. Conversely, this relationship was entirely absent in Group 2 (ACC P1 latency vs. Receptive Language Age: $r = 0.150$, p = 0.2; ACC P1 latency vs. Expressive Language Age: $r = 0.150$. p = 0.4), mirroring the severe clinical degradation of speech-like signals within a profound cohort.

4.4 Ling 6 Sound Detection Thresholds

To cross-verify these findings, Ling 6 phoneme detection thresholds were analyzed. As a behavioral test of audibility, individual Ling 6 phonemes showed highly significant, strong positive correlations with their corresponding pure-tone behavioral thresholds across both groups. For example, low-frequency phoneme /u/ correlated strongly with *aided 500 Hz threshold* in Group 1 (r = 0.711, p = 0.021) and Group 2 (r = 0.687, p = 0.014). High-frequency phoneme /s/ correlated strongly with *aided 4000 Hz threshold* in Group 1 (r = 0.816, p = 0.004) and Group 2 (r = 0.689, p = 0.013).

Consistently, when these Ling 6 thresholds were correlated against the cortical parameters, they mirrored the pure-tone findings precisely, showing no significant relationships with the fixed-level cortical latencies. For example, /u/ detection vs. low frequency *P1* in Group 1 was completely non-significant (r = 0.233, p = 0.517), confirming that behavioral sensitivity metrics operate independently from suprathreshold cortical processing speeds.

4.5 Relative Predictive Value of LLR vs. ACC Measures

The final objective sought to evaluate the relative predictive clinical value of these two modalities. The statistical data demonstrates that neither LLR nor ACC latencies obtained at a suprathreshold level (65 dB SPL) can serve as valid predictors of absolute behavioral audibility thresholds or Ling 6 detection levels, rendering a comparative threshold-prediction analysis unnecessary.

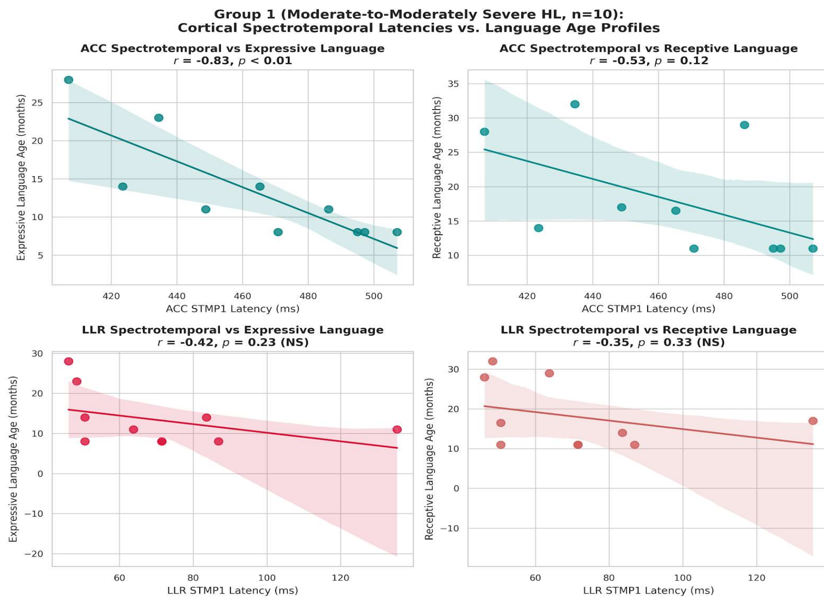


Figure 4.4 *Cortical spectrotemporal latencies versus language age profiles for the moderate-to-moderately severe hearing loss cohort (Group 1, n = 10).* The upper row illustrates the performance of the Auditory Change Complex (ACC) spectrotemporal latency marker (A_STMP1), demonstrating a highly robust, statistically significant negative correlation with Expressive Language Age ($r = -0.83, p < 0.01$). The lower row illustrates traditional Late Latency Response (LLR) onset latencies (L_STMP1), demonstrating weak, non-significant linear trends across both language sub-scales ($p > 0.05$). Shaded areas represent the 95% confidence intervals for the fitted regression lines.

However, for the prediction of functional developmental language outcomes, the ACC demonstrates clear clinical superiority over traditional LLR. While spectrotemporal LLR latencies provided weak and non-significant language age predictions across both cohorts, the spectrotemporal ACC latency accounted for approximately 69% of the variance ($R^2 = 0.689$) in Expressive Language Age, 44% of the variance ($R^2 = 0.442$) within the moderate-to-moderately severe group. This clinical value confirms that the ACC acts as a highly sensitive biomarker for the higher-level neural change detection mechanisms necessary for language acquisition, far outperforming standard onset responses in the moderate- moderately severe hearing loss group, but not in the higher degrees of hearing loss.

Chapter 5

Discussion

The primary aim of the present study was to investigate the clinical utility of Late Latency Response (LLR) and Auditory Change Complex (ACC) measurements for objectively assessing pediatric hearing aid benefit using frequency-specific and spectrotemporally complex stimuli. Pediatric amplification verification poses extreme clinical challenges due to the developmental limits of behavioral tracking in young children (Lewis, 1985; Vlastarakos et al., 2017). Objective physiological measures that go beyond simply assessing audibility and instead evaluate higher-level sound discrimination and cortical processing are therefore very important (Martin et al., 2008). The findings of the present study show a clear difference between measures of hearing sensitivity (thresholds) and measures of suprathreshold central auditory processing speed, which has important implications for the diagnosis and rehabilitation of children with hearing loss.

5.1 Cortical Latencies and the Prediction of Behavioral Aided Thresholds

A principal finding of this study is the complete absence of a statistically significant correlation between suprathreshold frequency-specific cortical latencies (both LLR and ACC) and absolute behavioral aided thresholds across both clinical cohorts. For instance, in Group 1, the correlation between the 500 Hz aided threshold and the true onset LLR P1 latency was entirely non-significant ($r = 0.143$, $p = 0.694$). Similarly, absolute pure-tone thresholds showed no systematic tracking with frequency-matched ACC change latencies (e.g., ACC P1 vs. 500 Hz threshold: $r = 0.074$, $p = 0.838$). This decoupling contradicts traditional subcortical prediction frameworks, where threshold-evoked responses directly map onto audiometric configurations (Easwar et al., 2023; Ribas-Prats et al., 2019).

This divergence can be explained by the physiological distinction between absolute sensitivity thresholds and suprathreshold central processing. The behavioral aided thresholds capture the absolute floor of physical audibility. In contrast, the electrophysiological protocol utilized fixed-level suprathreshold inputs (55 dB SPL for frequency-specific tones; 45 dB SPL for spectrotemporal complexes). Modern digital hearing aids apply highly non-linear Wide Dynamic Range Compression (WDRC) algorithms. Consequently, while two children may display differing absolute behavioral audibility thresholds, a suprathreshold 55 dB SPL tone is actively compressed and amplified to provide a highly audible, comfortable sensation level for both. Once a sound is elevated comfortably above the threshold floor, the absolute latency of the cortical P1 component reflects central neural processing efficiency, synaptic synchrony, and structural maturation rather than simple peripheral audibility.

This explanation is strongly supported by the intuitive cross-verification analysis of the Ling 6 sound detection thresholds. The individual phoneme detection levels (/a/, /i/, /u/, /m/, /s/, /sh/) represent behavioral threshold measures that track the physical boundaries of audibility, resulting in highly significant, powerful positive correlations with frequency-matched pure-tone aided thresholds across both Group 1 and Group 2 (e.g., /s/ vs. aided 4000 Hz threshold in Group 1: $r = 0.816$, $p = 0.004$). However, when these Ling 6 behavioral sensitivity thresholds were correlated against the fixed-level cortical latencies, they decoupled completely, showing non-significant relationships across the board. This reinforces that while behavioral threshold tracking tools are highly consistent with each other, they operate via entirely separate underlying mechanisms from fixed-level suprathreshold cortical encoding speeds.

5.2 Cortical Predictors of Functional Language Development

While fixed-level cortical latencies did not serve as valid indices for absolute peripheral sensitivity, a critical clinical breakthrough emerged regarding the prediction of functional communication milestones. In the moderate-to-moderately severe hearing loss cohort (Group 1), spectrotemporal ACC latencies demonstrated a remarkably strong, statistically significant negative correlation with Expressive Language Age ($r = -0.830$, $p < 0.01$) and a prominent moderate negative linear relationship with Receptive Language Age ($r = -0.530$). This empirical trend demonstrates that shorter, more rapid cortical change detection speeds directly predict advanced language development in children with milder hearing loss. Traditional spectrotemporal LLR onset latencies, however, yielded only weak, non-significant correlations with language metrics (Expressive: $r = -0.36$; Receptive: $r = -0.30$).

Physiologically, these findings confirm that the ACC is uniquely sensitive to the micro-structural acoustic transitions within ongoing stimuli that are fundamental to speech perception (Martin & Boothroyd, 1999, 2000; Ostroff et al., 1998). While the traditional LLR P1 component simply reflects the gross onset of an acoustic energy block, the ACC represents the central nervous system's capacity to resolve and discriminate rapid dynamic transitions embedded inside continuous sound fields (Sarah et al., 2024; Simonsen et al., 2025). This capacity for rapid neural change tracking forms the bedrock of phonemic boundaries, lexical segmentation, and speech feature extraction. Therefore, children who show superior, faster cortical change detection processing speeds (shorter ACC latencies) are structurally equipped to map acoustic soundscapes efficiently, translating directly into superior behavioral scores on language assessment tools (ACSLS). This aligns with the work of Ching et al. (2023) and Shalaby et al. (2024a), who observed that clear and well-formed ACC change markers correlate strongly with parent-reported functional auditory performance and daily communicative integration.

5.3 The Severe-to-Profound Drop-Off

In sharp contrast to the milder hearing loss cohort, Group 2 (the severe-to-profound hearing loss group) demonstrated a complete elimination of the systematic relationship between spectrotemporal ACC latencies and language age profiles. The correlation between ACC-P1 (spectro-temporal) and Expressive Language Age flattened completely, shifting to a weak, non-significant positive layout ($r = 0.280$, $p = 0.37$), while its link to Receptive Language Age was entirely absent ($r = 0.150$, $p = 0.64$). This statistical breakdown represents a highly significant clinical 'drop-off' effect.

This finding reflects the severe distortion and neural desynchronization characteristic of profound cochlear damage. When peripheral sensorineural hearing loss exceeds 70 dB HL, there is widespread destruction of outer and inner hair cells, accompanied by a significant loss of spiral ganglion neurons. Under heavy acoustic amplification, the amplified signal can achieve audibility, but the underlying central representation becomes severely blurred, lacking the fine spectrotemporal resolution required to elicit clean neural change detection markers. Consequently, the cortical processing speed becomes highly variable, decoupled from developmental language milestones, and degraded by peripheral distortion. Clinically, this empirical drop-off serves as an objective indicator: if a child with severe-to-profound hearing loss presents with highly delayed, degraded, or decoupled ACC responses despite consistent hearing aid use, it suggests that conventional acoustic amplification cannot provide the high-fidelity coding necessary for central language optimization. This provides an evidence-based justification for early cochlear implant candidacy evaluation to restore central temporal and spectral resolution during the critical period of neuroplasticity (Ching et al., 2023; Sharma et al., 2002).

5.4 Relative Predictive Clinical Value: LLR versus ACC

The final objective of the study was to compare how well LLR and ACC could predict hearing and language outcomes. For estimating hearing thresholds, neither LLR nor ACC latencies recorded at a fixed suprathreshold level were useful predictors of behavioral hearing sensitivity. However, when predicting language outcomes, ACC showed a clear advantage over traditional LLR measures. LLR onset latencies showed only weak and non-significant relationships with language scores in both groups. In contrast, spectrotemporal ACC latency was a strong predictor of language ability in Group 1, explaining about 69% of the variation in Expressive Language Age ($R^2 = 0.689$). This overwhelming predictive advantage establishes that the ACC acts as a far more sensitive clinical biomarker for tracking central speech feature processing and language readiness. Integrating suprathreshold spectrotemporal ACC protocols into standard pediatric test batteries will provide audiologists with a highly sensitive tool to verify whether amplified sound is being converted into meaningful neural codes at the level of the auditory cortex.

Chapter 6

Summary and Conclusion

The present study investigated the clinical utility of Late Latency Responses (LLR) and Auditory Change Complex (ACC) as objective measures of hearing aid benefit in children with sensorineural hearing loss. 22 children aged 3 to 5 years participated in the study, including 10 children with moderate to moderately severe hearing loss and 12 children with severe to profound hearing loss. All participants were bilateral hearing aid users receiving regular speech-language therapy. Frequency-specific and spectrotemporally modulated stimuli were used to examine whether cortical auditory responses could predict aided hearing performance and language development.

The study was undertaken in response to the challenges of assessing hearing aid benefit in young children, where behavioral measures may be difficult to obtain reliably. Objective electrophysiological measures such as the LLR and ACC provide valuable information about cortical auditory processing without requiring active participation from the child. While the LLR reflects cortical detection of sound, the ACC assesses the brain's ability to detect changes within an ongoing auditory signal. The use of spectrotemporally complex stimuli was intended to better represent the acoustic characteristics of natural speech and provide a more functionally relevant assessment of auditory processing.

The first objective was to examine whether aided LLR P1 latencies were related to frequency-specific aided thresholds and language outcomes in both groups. The results showed no significant relationship between LLR latencies and aided pure-tone thresholds. At 500 Hz, the correlation between the aided threshold and LLR onset latency was weak and non-significant in Group 1 ($r = 0.143$, $p = 0.694$) and Group 2 ($r = -0.481$, $p = 0.114$). A similar pattern was observed at 4000 Hz in Group 1 ($r=-0.445$, $p= 0.197$) and Group 2 ($r=-0.477$, $p=0.117$). In addition, spectrotemporal LLR latencies showed weak and non-significant correlations with both expressive and receptive language ages in both groups. These findings suggest that LLR onset measures have limited value in predicting aided hearing performance or language outcomes in children with sensorineural hearing loss.

The second objective was to examine whether aided ACC latencies were related to aided thresholds and language outcomes in both groups. Similar to the LLR findings, ACC P1 latencies showed no significant relationship with aided pure-tone thresholds. For example, the correlation between ACC P1 latency and the aided 500 Hz threshold in Group 1 was weak and non-significant ($r = 0.074$, $p = 0.838$). Similar findings were observed for the other frequency-specific and spectrotemporal stimuli.

However, a different pattern emerged when ACC latencies were compared with language outcomes. In Group 1, spectrotemporal ACC latencies showed a strong negative correlation with expressive language age ($r = -0.830$, $p < 0.01$) and a moderate negative correlation with receptive language age ($r = -0.530$). Spectrotemporal ACC latency explained approximately 69% of the variance in expressive language scores ($R^2 = 0.689$) and 44% of the variance ($R^2= 0.442$) in receptive language scores. These findings indicate that children with shorter ACC latencies tended to have better language outcomes, suggesting more efficient cortical processing of acoustic changes.

In Group 2, which included children with severe to profound hearing loss the brain's response timing did not show any significant relationship with language performance. The correlations for both expressive language ($r = 0.280$, $p = 0.37$) and receptive language ($r = 0.150$, $p = 0.64$) were weak and not statistically significant. This is notably different from Group 1, where a significant association was observed between faster brain responses and better language outcomes. These findings suggest that in children with more severe hearing loss, the link between cortical change detection and language development may be weaker, possibly because they have reduced access to detailed spectrotemporal information even when using hearing aids.

The third objective was to compare the predictive value of LLR and ACC measures. The results showed that neither LLR nor ACC latencies were related to aided behavioral thresholds, indicating that these measures do not reflect audibility at suprathreshold levels. However, differences emerged when language outcomes were considered. LLR onset latencies showed weak and non-significant relationships with language age in both groups. In contrast, spectrotemporal ACC latency showed a strong relationship with language outcomes in Group 1 and accounted for a substantial proportion of the variance in expressive language age ($R^2 = 0.689$). These findings suggest that ACC is a more useful measure than LLR for predicting language development in children with moderate to moderately severe hearing loss.

The Ling 6 analysis further supported these findings. Ling 6 detection thresholds showed significant positive correlations with the corresponding aided pure-tone thresholds in both groups. For example, low-frequency phoneme /u/ correlated strongly with *aided 500 Hz threshold* in Group 1 ($r = 0.711$, $p = 0.021$) and Group 2 ($r = 0.687$, $p = 0.014$). High-frequency phoneme /s/ correlated strongly with the aided *4000 Hz threshold* in Group 1 ($r = 0.816$, $p = 0.004$) and Group 2 ($r = 0.689$, $p = 0.013$). This confirms that Ling 6 thresholds are reliable measures of behavioral audibility. However, Ling 6 thresholds did not show significant correlations with cortical response latencies, indicating that behavioral audibility measures and suprathreshold cortical responses reflect different aspects of auditory functioning.

It can be concluded that suprathreshold aided LLR and ACC latencies are not related to aided behavioral thresholds and therefore reflect central auditory processing rather than audibility. Among children with moderate to moderately severe hearing loss, spectrotemporal ACC latency showed a strong relationship with expressive language age ($r = -0.830$, $p < 0.01$; $R^2 = 0.689$), making it a valuable predictor of language outcomes. In contrast, LLR measures showed no significant association with language development. No significant ACC-language relationship was observed in children with severe to profound hearing loss, suggesting reduced effectiveness of hearing aid amplification in supporting efficient cortical processing in this group. Overall, spectrotemporal ACC appears to have greater clinical utility than LLR for assessing functional hearing aid benefit and predicting language outcomes in children with sensorineural hearing loss.

Limitations of the Study

While the present study provides valuable findings, certain limitations are present and should be considered when interpreting the results. The number of participants was small, with only 10 children in Group 1 and 12 children in Group 2 which may affect the implementation of the result in the larger papulation, only children between 3 and 5 years of age were included meaning the results may not represent younger or older children with hearing loss, the children used different hearing aid models and this variability in technology may have influenced the cortical responses recorded, language skills were measured using the ACSLS checklist which may not be sensitive enough to detect small differences in language abilities and since the study was conducted at a single point in time following the same children over a longer period would be needed to better understand how ACC responses develop with continued hearing aid use.

Implications and Future Directions

Spectrotemporal ACC shows promise as a useful tool for assessing hearing aid benefit in young children. Since the test does not require any active response from the child, it is easy to use with young age groups. When used together with behavioral assessments, it provides a clearer picture of how well a child hears through their hearing aids. Future studies should include more children across different ages and hearing loss levels. Long-term follow-up is needed to see whether early ACC responses can predict later language development and identify children who need additional support.

With more research and wider clinical use, spectrotemporal ACC has the potential to improve how hearing aid benefit is evaluated and guide better decisions for children with hearing loss.

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Appendix - 1

Table A1

Test of Normality for Variables Being Assessed in LLR and ACC for Moderate to Moderately severe hearing loss group

Variables	Shapiro-Wilk Statistic	df	P value
Receptive language age	0.779	10	0.012
Expressive language age	0.757	10	0.006
a	0.971	10	0.903
i	0.941	10	0.596
u	0.899	10	0.247
s	0.928	10	0.464
sh	0.954	10	0.736
m	0.876	10	0.142
Aided 500Hz threshold	0.863	10	0.103
Aided 4000Hz threshold	0.888	10	0.191
LLR 550P1 latency	0.921	10	0.400
LLR 650P1 latency	0.973	10	0.919
LLR 4050P1 latency	0.895	10	0.224
LLR 4150P1 latency	0.859	10	0.093
LLR STMP1 latency	0.855	10	0.084
ACC 550P1 latency	0.975	10	0.937
ACC 650P1 latency	0.919	10	0.388
ACC 4050P1 latency	0.950	10	0.688
ACC 4150P1 latency	0.867	10	0.113
ACC STMP1 latency	0.926	10	0.447

Table A2

Test of Normality for Variables Being Assessed in LLR and ACC for Severe to Profound hearing loss group

Variables	Shapiro -Wilk Statistic	df	P value
Receptive language age	0.883	12	0.140
Expressive language age	0.937	12	0.517
a	0.895	12	0.191
i	0.972	12	0.911
u	0.940	12	0.553
s	0.930	12	0.449
sh	0.960	12	0.791
m	0.930	12	0.447
Aided 500Hz threshold	0.919	12	0.351
Aided 4000Hz threshold	0.969	12	0.879
LLR 550P1 latency	0.984	12	0.984
LLR 650P1 latency	0.923	12	0.380
LLR 4050P1 latency	0.896	12	0.197
LLR 4150P1 latency	0.865	12	0.088
LLR STMP1 latency	0.786	12	0.010
ACC 550P1 latency	0.864	12	0.085
ACC 650P1 latency	0.900	12	0.221
ACC 4050P1 latency	0.966	12	0.855
ACC 4150P1 latency	0.925	12	0.398
ACC STMP1 latency	0.899	12	0.212