INVESTIGATING THE RELATIONSHIP AMONG ACOUSTIC STAPEDIAL REFLEX THRESHOLDS, AIDED LATE LATENCY RESPONSES, AND OUTCOMES IN PAEDIATRIC COCHLEAR IMPLANTEES

SIMRAN BANGA

Registration No: P01II24S023032

A Dissertation Submitted in Part of Fulfilment of the

Degree of Master of Science (Audiology)

University of Mysore

ALL INDIA INSTITUTE OF SPEECH AND HEARING, MANASAGANGOTHRI,

MYSURU – 570 006

JUNE, 2026

CERTIFICATE

This is to certify that this dissertation entitled **'Investigating the relationship among Acoustic Stapedial Reflex Thresholds, Aided Late Latency responses, and outcomes in Paediatric Cochlear Implantees'** is a bonafide work submitted as part of fulfilment of the degree of Master of Science (Audiology) of the student with Registration Number **P01II24S023032**. 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.

Mysuru
June, 2026

M. Pushpavathi

Dr. M. Pushpavathi
DIRECTOR
All India Institute of Speech and Hearing
Manasagangothri, Mysuru – 570 006

CERTIFICATE

This is to certify that this dissertation entitled **'Investigating the relationship among Acoustic Stapedial Reflex Thresholds, Aided Late Latency responses, and outcomes in Paediatric Cochlear Implants'** 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.

Manjula. P

Mysuru
June, 2026

Dr. P Manjula
GUIDE
All India Institute of Speech and Hearing
Manasagangothri
Mysuru-570 006

DECLARATION

This is to certify that this dissertation entitled **'Investigating the relationship among Acoustic Stapedial Reflex Thresholds, Aided Late Latency responses, and outcomes in Paediatric Cochlear Implants'** is the result of my own study under the guidance of Dr. P Manjula, 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.

Mysuru
June, 2026

Registration no. P01II24S023032

"Shabad guru, surat dhun chela"(Guru Nanak Dev Ji) — The divine Word is the Guru; the consciousness that listens is the disciple.

Dedicated to God and to My Parents

*with heartfelt gratitude for their unwavering love and support, which continually inspires and empowers me, and for making me confident at every step of my life***.**

My deepest thanks to my dearest sister **Harman,** *for always being the best and for bringing so much love, laughter, and joy into my life. Thank you for standing by me through every adventure and for always being there for me.*

Acknowledgements

I'm deeply grateful to the ***All-India Institute of Speech and Hearing, Mysuru****, for offering exceptional education and invaluable resources in the field of speech and hearing.*

I sincerely express my heartfelt gratitude to ***Dr. M. Pushpavathi****, Director, All India Institute of Speech and Hearing, Mysuru, for granting me the permission to undertake my dissertation work.*

I extend my deepest gratitude to my esteemed guide, ***Dr. P Manjula****, for your dedicated mentorship and scholarly guidance, which were central to the successful completion of this dissertation. Your insightful suggestions, constructive feedback, and genuine passion for research have been a constant source of inspiration throughout this journey. I am especially thankful for your patience in addressing my many doubts and for meticulously reviewing and refining my work at every stage. Your encouragement to explore new perspectives greatly enriched my learning experience, and your commitment to academic excellence has left a lasting impression on me. Your mentorship has not only contributed to the completion of this dissertation but has also helped me grow immensely as a student and as a professional. I consider myself truly privileged to have worked under your guidance.*

I would like to sincerely thank ***all the participants*** *of my study for their active participation, without whom this research would not have been possible.*

*I would like to extend my sincere gratitude to****, Sahana Ma'am, Megha Ma'am, Banumati Ma'am, Soumya Akka, Chaitra Ma'am, Teenu Ma'am****,* ***Sharath Sir, Vasantha Lakshmi Ma'am*** *and all the IHDU staff for their timely support and assistance in completing my dissertation.*

I would also like to thank all the faculty members of the Department of Audiology for their timely help and support throughout my dissertation.

A special shoutout and heartfelt thanks to my dearest friend ***Ballu****, the one who always showed up, no matter what. You have been my biggest cheerleader on the days I felt like giving up, and somehow you always knew exactly how to turn my worst days into the best ones. Your encouragement, your silly yet thoughtful ways, and the countless beautiful memories we have made together have meant more to me than words can express. Thank you for being my constant happiness, my go-to person, and for always believing in me even when I stopped believing in myself. This journey would not have been the same without you!*

I would like to acknowledge with gratitude my friends ***Ruchitha, Yashas, Varun, Toshi*** *and all my friends for their constant support, guidance, and encouragement throughout this journey.*

Finally, I am deeply grateful to my batch ***Invictus*** *and especially my* ***MSc Batch Section B****, you have truly been the best batch anyone could ask for. Your constant support, laughter, and camaraderie made every single day at AIISH memorable and joyful. A heartfelt note of gratitude also to my MSc batch* ***Celestials****, whose friendship and warmth made my journey at AIISH so much more than just an academic experience. The beautiful memories we have created together are ones I will carry with me always.*

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract

This study investigated the relationship between acoustically evoked stapedial reflex (ASR) thresholds, CI-aided late latency response (LLR) components, and speech and language outcomes in 23 Kannada-speaking children (mean age: 81.10 months; mean age at implantation: 27.74 months) with bilateral severe-to-profound sensorineural hearing loss using unilateral cochlear implants. Acoustic Stapedial Reflex thresholds and CI-aided LLRs were recorded using a synthetic 40 ms /da/ stimulus. Outcome measures included Speech Identification Scores (SIS) using PB word list, and receptive and expressive language ages obtained by the Assessment of Language Development – Manipal Manual (ALD-MM).

Spearman correlations and multiple linear regression were performed. ASR thresholds were not significantly associated with speech identification scores, language outcomes, or any LLR component. P1 latency showed a strong significant negative correlation with SIS ($\rho = -0.754$, $p < 0.001$; large effect). N1–P2 amplitude was significantly correlated with receptive ($\rho = -0.553$, $p = 0.011$; large effect) and expressive language age ($\rho = -0.465$, $p = 0.039$; moderate effect). CI-aided PTA4 and P1 latency together explained 62.4% of the variance in SIS, and N1–P2 amplitude was the sole independent predictor of both language domains. P1 latency is a robust biomarker of speech identification performance, reflecting thalamocortical pathway maturity, while N1–P2 amplitude provides unique information about language-relevant cortical processing. The independence of peripheral and central measures underscores the need for a multimodal assessment approach in paediatric CI management.

Keywords: cochlear implant; late latency response; acoustic stapedial reflex; P1 latency; N1–P2 amplitude; speech identification score; language outcomes; cortical auditory maturation; ALD-MM

Chapter 1

INTRODUCTION

Hearing loss in early childhood carries consequences that extend far beyond the sensory level. Absence of access to spoken language during the critical years of life can affect the typical course of speech, language, literacy, and psychosocial development in a child with bilateral severe to profound sensorineural hearing loss. In such individuals, amplification or hearing aids provide limited benefit. Cochlear implants (CIs) have revolutionized access to sound for these children and emerging as one of the most effective interventions available. The primary goal of paediatric cochlear implantation is to provide auditory input, which is critical for the development of the central auditory system, and thereby to support speech and language development (Niparko et al., 2010; Ruben, 2018).

A cochlear implant bypasses the damaged hair cells of the cochlea and delivers electrical stimulation directly to the surviving spiral ganglion neurons via an intracochlear electrode array. The microphone and the external processor pick up the sounds and runs it through a speech-coding algorithm and sends the processed signal to the internal receiver-stimulator. This electrically coded signal, though has less spectral and temporal resolution than natural acoustic hearing, provides sufficient auditory information for most children to develop spoken language when implanted early and rehabilitation is consistent (Niparko et al., 2010).

Despite remarkable technological advancements, variability in outcomes remains a major concern in paediatric cochlear implant users. While many children develop adequate functional spoken language skills, some children experience delayed or suboptimal development. This heterogeneity is explained by a complex interaction of factors including age at implantation, duration of deafness / auditory deprivation, neural plasticity, quality of auditory input, cognitive profile, post-implant habilitation, and the richness of the home language environment (Ruben, 2018). Thus, age-appropriate receptive and expressive language skills are contingent upon consistent auditory input, cognitive abilities, and enriched linguistic environments. Longitudinal studies have indicated that children implanted before the age of 12 months can develop language growth trajectories that are statistically comparable to their peers with normal hearing, especially when implantation is combined with early habilitation and consistent use of the device (Hammes et al., 2002; Ching et al., 2009).

Continuous, standardized assessment is needed to monitor success of cochlear implantation. Language development involves receptive and expressive domains. Both receptive and expressive domains are key indices of communicative competence. The multi-lingual Indian clinical setting poses a further challenge in the form of paucity of culturally and linguistically appropriate assessment tools, as most commonly used batteries have been standardized on English-speaking Western populations. Tools such as Assessment of Language Development – Manipal Manual (ALD-MM) developed by Lakkanna et al. (2021) and Assessment Checklist for Speech-Language Skills (ACSLS; Swapna et al., 2010) address this gap. The ALD-MM is a performance-based, norm-referenced diagnostic tool that provides separate receptive and expressive language ages for children from birth to 10 years, thereby enabling speech-language pathologists to objectively track language growth and identify delays within the Indian paediatric population.

Behavioural assessments do not always fully capture the neural processes underlying auditory perception and language development, especially in very young children or children with reduced attention and cooperation. This limitation has spurred greater use of objective electrophysiologic and physiologic measures, which provide valuable information concerning the integrity of the auditory system at many levels of the auditory pathway from brainstem structures to cortical processing centres. These measures might be obtained without behavioural testing and may reflect the maturation of auditory pathways that support spoken language development (King, 2009; Tavartkiladze & Bakhshinyan, 2025).

The acoustic stapedial reflex (ASR) can be obtained by presenting the stimulus to elicit the stapedial reflex through loudspeaker. This stimulus stimulates the child through the CI. This measure provides an objective estimate of loudness growth and comfort levels. The neural pathway of the stapedial reflex involves the VIII cranial nerve, serving as the afferent limb and the facial nerve (VII cranial nerve) as the efferent limb and helps in integrating information from both the peripheral auditory system and the brainstem. In CI users, the afferent limb is activated by the electrically stimulated auditory nerve and the resulting reflex can be detected in the non-implanted ear (or implanted ear) by the standard immittance meter.

The electrically evoked stapedial reflex threshold (ESRT) has been widely investigated as a measure to assist CI programming, especially for determining upper stimulation levels in young children (Andrade et al., 2014; Bresnihan et al., 2001; Wolfe et al., 2018). More recently, free-field acoustic stapedial reflex thresholds (ASR) measured via loudspeaker stimulation have been shown to discriminate between CI users with over-stimulated and under-stimulated programs, with direct implications on the adequacy of the auditory input delivered to the child (Franke-Trieger et al., 2021, 2024).

Aided auditory late latency responses (aided LLRs) including the P1, N1, and P2 components reflect cortical activation during aided listening and provide a window into the functional integrity and maturational status of the central auditory system. The P1 component is a well-established marker of cortical auditory maturation (Sharma et al., 2002; Campbell, Cardon, & Sharma, 2011) and is generated by thalamocortical projections to the primary auditory cortex and is characterized by a positive deflection at around 100 - 150 ms in young children (Wunderlich et al., 2006; Ponton et al., 2000). Rapid normalization of the P1 latency is observed in children with early implantation (before 3.5 years of age), whereas children implanted later have prolonged cortical responses, indicating a sensitive period for central auditory development (Sharma et al., 2002; Sharma et al., 2005; Young & Kirk, 2016). As auditory experience and cortical maturation increase, N1 and P2 components emerge and the amplitude of the P1-N1 and N1-P2 peak-to-peak pairs reflects the magnitude of activation in the cortex. Speech and language outcomes have been related to aided LLRs (Xiong et al., 2022). However, some studies have not found a significant relationship (Sahana & Manjula, 2024). Thus, highlighting the need for further investigation in carefully characterized samples.

Need for the Study

Although there is evidence for the prognostic value of aided LLRs, the findings are inconsistent. Some studies have reported positive correlations with language outcomes (Xiong et al.,2022), while others have not found a significant relationship (Sahana & Manjula, 2024). Likewise, while ASRT is commonly used in CI map verification and loudness monitoring, the potential utility of ASRT as a predictor of language outcomes has not been systematically examined with respect to standardized language measures.

Franke-Trieger et al. (2021, 2024) demonstrated that free-field stapedius reflex thresholds can help in indicating over- or under- stimulation in CI maps. This suggested indirect implications for speech development by improved map accuracy. Bresnihan et al. (2001) established ESRT as a reliable objective tool for setting upper stimulation levels of CI map in children, indirectly supporting better conditions for language development. Tavartkiladze and Bakhshinyan (2025) proposed to include stapedius reflex thresholds into the programming battery, in addition with cortical auditory potentials, as reflex thresholds provide an objective anchor for speech-map levels and therefore indirectly predict speech results.

Therefore, there is a need to examine whether ASR threshold (stimulus presentation via loudspeaker) and aided LLRs are correlated with language growth, as measured by the ALD-MM, in children with unilateral CI. Identifying such correlations would provide clinicians with reliable, objective biomarkers for monitoring language development, aid in counselling parents regarding expected outcomes, and support decision-making about whether additional communication modalities may be necessary. Additionally, there is a dearth of studies integrating both peripheral (ASR) and cortical (aided-LLR) measures in relation to standardized language assessment, particularly in Kannada-speaking children in India.

Thus, the present study aims to evaluate the relationship between ASR and aided LLR responses with language development in paediatric CI users, thereby contributing to evidence-based clinical practice.

Aim of the Study

The aim of the study was to investigate the relationship among acoustic stapedial reflex thresholds and aided late latency responses with speech and language outcomes in paediatric cochlear implant users.

Objectives

a) To study the relationship between acoustically evoked stapedial reflex threshold with receptive and expressive language age.

b) To study the relationship between acoustically evoked stapedial reflex threshold with speech identification scores.

c) To study the relationship between CI aided LLR measures (i.e., P1, N1, P2 latencies; P1-N1 and N1-P2 amplitudes) with receptive and expressive language age.

d) To study the relationship between CI aided LLR with speech identification scores.

e) To study the relationship between acoustically evoked stapedial reflex threshold and aided LLR.

Hypotheses

- **Null Hypothesis 1:** There is no significant relationship between acoustically evoked stapedial reflex threshold with receptive and expressive language age in paediatric CI users.
- **Null Hypothesis 2:** There is no significant relationship between acoustically evoked stapedial reflex threshold with speech identification scores in paediatric CI users.
- **Null Hypothesis 3:** There is no significant relationship between aided late latency measures with receptive and expressive language age in paediatric CI users.
- **Null Hypothesis 4:** There is no significant relationship between aided late latency measures with speech identification scores in paediatric CI users.
- **Null Hypothesis 5:** There is no significant relationship between acoustically evoked stapedial reflex threshold and aided late latency responses in paediatric CI users.

Chapter 2

REVIEW OF LITERATURE

Hearing impairment in early childhood has consequences that extend well beyond the sensory level. In a child with bilateral severe-to-profound sensorineural hearing loss, the inability to access spoken language during the initial years of life can impact the normal trajectory of speech, language, literacy, and psychosocial development. Cochlear implantation has emerged as one of the most effective interventions for children with bilateral severe-to-profound sensorineural hearing loss. Cochlear implants provide access to auditory input that is essential for the development of speech and language.

Despite remarkable technological advancements, variability in outcomes continues to be a significant concern in paediatric cochlear implant users. Although numerous children attain functional spoken language skills, some exhibit delayed or suboptimal advancement, underscoring the multifactorial characteristics of language development. The inconsistency in outcomes still exists and therefore it is necessary for researchers and clinicians to investigate objective predictors that can consistently indicate auditory processing and anticipate speech and language performance.

A cochlear implant works by bypassing the damaged hair cells of the cochlea and delivering electrical stimulation directly to the surviving spiral ganglion neurons via an intracochlear electrode array. The external processor captures sound, applies a speech-coding algorithm, and transmits the processed signal to the internal receiver-stimulator. This electrically coded signal is different from natural acoustic hearing in that it has a lower spectral resolution and a different temporal fine structure. However, it gives most kids enough auditory information to learn to speak when the implantation is done early and the rehabilitation is consistent (Niparko et al., 2010).

The relevant literature has been provided under the following subheadings:

2.1 Factors Influencing Spoken Language Development in Children with Cochlear Implants

2.2 Language Assessment in Paediatric Cochlear Implant Users

2.3 Role of Objective Measures in Cochlear Implant Assessment

2.4 Acoustic Stapedial Reflex in cochlear implant users

2.4.1 Anatomy and Physiology of the Stapedial Reflex

2.4.2 Electrically Evoked Stapedial Reflex Threshold in CI Programming

2.4.3 Acoustic Stapedial Reflex via Free-Field Stimulation

2.5 Cortical Auditory Evoked Potentials and Late Latency Responses in Paediatric CI users

2.5.1 P1 component as a biomarker of cortical maturation

2.5.2 Longitudinal Evidence for P1 Maturation Post-Implantation

2.5.3 P1 latency as a predictor of speech and language

2.5.4 Conflicting Evidence and the need for Further Investigation

2.6 Gaps in Literature and Rationale for the Study

2.7 Rationale for the Present Investigation

2.1 Factors Influencing Spoken Language Development in Children with Cochlear Implants

The development of spoken language in children with cochlear implants is influenced by factors including age at implantation, duration of auditory deprivation, neural plasticity, quality of auditory input, and environmental stimulation and a complex interaction of these factors. A large multicentric study by Niparko et al. (2010) demonstrated that children receiving cochlear implants show significant improvement in their ability to understand and communicate spoken language. Their progress was faster than predicted from pre-implant baseline levels. In their study, implantation age was crucial. Faster language development was seen in earlier implantees. Younger children had higher rates of yearly progress in comprehension and expression. But often their performance is worse than that of their normally hearing peers. However, some studies indicate that children implanted before age 1 year can achieve language and auditory comprehension outcomes similar to those of normal hearing peers, especially when implantation occurs before 9–12 months (Pimperton et al., 2012, 2020; Sharma et al., 2002; Pimperton et al., 2021).

Longitudinal studies have shown that children implanted before 12 months can achieve language growth trajectories or auditory processing indices that are statistically similar to normal hearing peers, especially when implantation is combined with early habilitation and consistent device use (Hammes et al., 2002). This indicates that early cochlear implantation under ideal circumstances may promote partial or complete normalization of early auditory and language development. These findings demonstrate that access to sound alone is not sufficient for optimal language acquisition and that underlying neural processing mechanisms also play a critical role.

Ruben (2018) reviewed the literature on language development in paediatric CI users and highlighted that cochlear implantation alone does not guarantee age appropriate language acquisition. He highlighted the crucial significance of early auditory stimulation in language development in the paediatric cochlear implantee. The study emphasized the existence of a sensitive time for language development, during which optimum cortical auditory circuit development results in more positive linguistic outcomes when early implantation occurs, ideally before 12 to 24 months of age. The study again emphasizes the fact that implantation alone does not guarantee age-appropriate language development, even though it greatly increases access to sound and aid in language acquisition. Results are still quite inconsistent, and many children continue to exhibit deficits, particularly in expressive language, even after years of device use (Boons et al., 2012; Niparko et al., 2010). This heterogeneity is explained by variations in neural plasticity, the time of intervention, the brain's capacity to decipher the implant's deteriorated electrical signal, and associated deficits. Overall, the inference of the study by Ruben (2018) is that although cochlear implants are necessary for supplying auditory input, early implantation during the sensitive period and efficient use of auditory input by the growing brain are necessary for successful language development. He identified many variables that modulate outcomes such as the integrity of the auditory nerve and surviving neural populations, the precision of device programming, the child's learning capacity and cognitive profile, the intensity and quality of post-implantation auditory-verbal therapy, and the richness of the home language environment.

Ruben (2018) analysis indicated a fundamental clinical reality: auditory access through the CI is a necessary but not sufficient condition for language development. Optimal outcomes require the combination of auditory access, well calibrated device programming, structured rehabilitation, and a linguistically stimulating environment.

Ruben (2018) also pointed out the importance of early auditory stimulation to the development of cortical pathways for language processing. The lack of auditory input in critical periods of development can result in reorganisation of cortical areas, which can diminish the efficiency of auditory processing and subsequent language acquisition. This underscores the need for early detection and intervention, along with monitoring of auditory and linguistic development via behavioural and objective measures.

2.2 Language Assessment in Paediatric Cochlear Implant Users

The assessment of speech and language skills in children with cochlear implants is challenging due to the need for standard, reliable and culturally appropriate assessment tools. Language development is considered to include both receptive and expressive domains, which are important indicators of communicative competence. In the Indian clinical scenario, tracking language outcomes in CI children is further complicated by lack of availability of culturally and linguistically appropriate assessment tools. Most commonly used language assessment batteries have been standardized on English speaking Western population and may not accurately reflect the linguistic abilities of Indian children.

In the Indian context, the Assessment of Language Development – Manipal Manual (ALD-MM) developed by Lakkanna et al. (2021) is relevant. It serves as a comprehensive tool for assessing language abilities in children from birth to ten years of age. The ALD-MM provides receptive and expressive language ages and enables clinicians to track developmental progress and identify delays.

Standardized assessments such as the ALD-MM play a crucial role in linking auditory processing abilities with functional language outcomes. They facilitate for objective quantification of language skills and enable comparisons across individuals. However, behavioural assessments alone may not be sufficient to fully capture the underlying neural processes of auditory perception and language development, especially in young children or children with limited attention and cooperation. This limitation has heightened the dependence on objective electrophysiological measures that can provide insights into the working of the auditory system.

2.3 Role of Objective Measures in Cochlear Implant Assessment

Objective measures are important in the assessment and management of paediatric cochlear implant users. These measures are particularly useful in populations where behavioural responses are unreliable or difficult to obtain. They give information about different levels in the auditory system, from peripheral structures to cortical processing centres. King (2009) indicates the importance of these processes along the auditory pathway, from central processes such as cortical auditory evoked potentials (CAEPs) for higher-order discrimination and neural processing to peripheral structures such as electrically evoked stapedius reflex thresholds (ESRT) for brainstem integrity and loudness perception.

Objective measures can broadly be categorized into peripheral and central measures. Peripheral measures, such as acoustic or electrically evoked stapedius reflex thresholds, reflect the integrity of the auditory pathway at the brainstem level and provide information about loudness perception. Central measures, such as cortical auditory evoked potentials, reflect neural processing at the cortical level and are associated with higher-order auditory functions. They reveal cortical plasticity, spatial selectivity, and direct links between peripheral input quality and speech perception outcomes. Scheperle & Abbas (2015) demonstrated partial independence between peripheral excitation patterns and central cortical representations, limiting universal predictions from peripheral data alone and underscoring the need for combined assessment.

The integration of these measures allows for a comprehensive evaluation of auditory function, enabling clinicians to assess both the quality of auditory input and the efficiency of neural processing. This holistic approach is essential for understanding the factors that contribute to speech and language development in children with cochlear implants. In order to standardize longitudinal evaluation across worldwide centres, consensus procedures such as the HEARING Network's minimal outcome measurements (MOMs) battery combine these objective measures with behavioural speech perception and language monitoring from 6 weeks to 18 years (Mertens et al., 2021). In order to maximize programming and rehabilitation results, Tavartkiladze and Bakhshinyan (2025) support this multimodal approach across CI stages.

2.4 Acoustic Stapedial Reflex in cochlear implant users

2.4.1Anatomy and Physiology of the Stapedial Reflex

The acoustic stapedial reflex (ASR) is a bilateral, involuntary contraction of the stapedius muscle elicited by loud sounds. The stapedius reflex serves as a vital protective mechanism in the middle ear. When the sound is loud, it makes the stapedius muscle contract, which makes the ossicular chain stiffer and cuts down on low-frequency transmission to the cochlea. In clinical practice, the reflex is detected using immittance audiometry, which measures the change in middle-ear acoustic admittance (compliance) that accompanies stapedius contraction in response to a probe tone. In individuals with normal hearing, it activates at 70–100 dB HL and is essential for audiological diagnostics. For cochlear implant (CI) users, the pathway changes fundamentally, as electrical pulses from an intracochlear array directly stimulate spiral ganglion neurons, bypassing acoustic cochlear transduction.

The neural pathway of the stapedial reflex is a polysynaptic arc. The afferent limb is carried by the auditory nerve (cranial nerve VIII) from the cochlea to the cochlear nucleus, from where projections pass via the superior olivary complex and facial nerve motor nucleus to the efferent limb, which is the facial nerve (cranial nerve VII). This arc means that the reflex integrates information from both the peripheral auditory system and the brainstem, and it can be disrupted by pathology at any point along this chain. In cochlear implant users, the afferent limb is activated by the electrically stimulated auditory nerve rather than by acoustic activation of the cochlea, but the remainder of the arc is intact and the stapedius contraction can be detected in the conventional manner via an immittance probe. CI users bypass cochlear hair cells, with speech processor signals electrically driving auditory nerve fibers to engage the brainstem pathway, yielding ipsilateral or contralateral contractions measurable by tympanometry postoperatively in the late 1980s (Jerger et al., 1986; Stephan et al., 1988; Battmer et al., 1990).

2.4.2 Electrically Evoked Stapedial Reflex Threshold in CI Programming

The electrically evoked stapedial reflex threshold (ESRT) is the minimum direct electrical stimulation level of the CI that elicits a detectable stapedius contraction. ESRTs have been thoroughly examined as an objective instrument for directing CI programming, especially for determining the upper stimulation threshold (C-level or M-level) in young children. Setting the right C-levels is very important. If the levels are too high, they can make kids uncomfortable and overstimulated, which can make them not want to wear the device. If the levels are too low, they can make kids under stimulated and less audible, which can hurt the quality of the auditory input that kids need to learn language.

Stephan and Welzl-Muller (2000) examined MCL estimation utilizing the ESRT in six COMBI 40 cochlear implant recipients. An up-down stimulation protocol was used to test the stapedius reflex and loudness scaling at the same time. There was a strong correlation between ESRT and MCL. This research offered substantial evidence that ESRT-based fitting could generate maps aligned with psychoacoustic comfort levels in CI users.

Bresnihan et al. (2001) were among the first to systematically evaluate the use of ESRT in fitting children with cochlear implants. They demonstrated that ESRT provided reliable objective estimates of comfortable loudness levels consistent with behaviourally determined C-levels. This was a practically significant finding and it showed that a physiological measure of reflex threshold could serve as a proxy for the child's loudness perception, enabling safe and accurate mapping even when the child was too young or developmentally unable to provide reliable behavioural responses. Subsequent research has broadly confirmed the utility of ESRT in paediatric CI mapping, and it is now considered a standard component of the objective programming battery in many CI centres.

The systematic review by Andrade et al. (2014) validated that ESRT, whether assessed intraoperatively or postoperatively, is a valid objective measure that can guide CI mapping. They concluded that combining ESRT with other objective measures (e.g., electrically evoked compound action potential, ECAP) and behavioural tests produces faster and safer fitting outcomes, particularly for infants, young children, and individuals with multiple disabilities.

Ciprut and Adigul (2020) compared of ESRT and behavioural MCL in a sample of 46 experienced cochlear implant users equipped with two distinct CI brands (Nucleus and Med-El). Moderate correlations were found for Nucleus users whereas for Med-El patients' higher correlations were observed. In both groups, ESRT thresholds were consistently recorded at stimulus levels above the MCL or C level. This suggested that ESRT might have a tendency to overestimate optimal upper stimulation levels. However, no significant between-group difference in speech recognition scores was identified which supported clinical utility of ESRT for programming especially in uncooperative patients.

Tavartkiladze and Bakhshinyan (2025) conducted a data analysis on the use of objective measures at different stages of cochlear implantation, including pre-operative, intraoperative, and post-operative contexts. Their analyses highlighted the complementary roles of different objective measures and made specific recommendations for incorporating stapedius reflex thresholds into routine programming protocols. They argued that stapedius reflex thresholds provide an objective physiological perspective for MAP levels that, when used systematically, they can reduce the risk of suboptimal fitting and thereby indirectly support better speech outcomes. Their recommendation to combine stapedius reflex data with cortical auditory potential monitoring in the ongoing management of CI users is conceptually aligned with the multi-measure approach adopted in the present study.

The detection rate of ESRT across studies is approximately 65–90% (Battmer et al., 1990; Cinar et al., 2011; Gordon et al., 2004), leaving a significant subset of CI users in whom the reflex cannot be elicited or detected. Factors contributing to absent ESRT include very high stimulation requirements (where the reflex threshold exceeds the patient's uncomfortable loudness level), alterations in middle ear mechanics, and individual variability in the stapedius muscle and its innervation. A retrospective study by Chai et al. (2024) examined patient and device factors (sex, age, electrode location) contributing to ESRT levels in adult CI recipients, confirming that electrode position within the cochlea significantly influences the threshold required to elicit the reflex.

2.4.3 Acoustic Stapedial Reflex via Free-Field Stimulation

ESRT is obtained by delivering electrical stimulation directly through the CI and the measurement of the ASR threshold via free-field acoustic stimulation represents a methodologically distinct paradigm. In the free-field ASR paradigm, the eliciting stimulus is a calibrated acoustic signal delivered from a loudspeaker. The stimulus is an acoustic signal (e.g., narrowband noise, pure tones, or speech) processed by the CI's external speech processor, which converts the signal into multi-channel electrical stimulation delivered to the cochlea. The resulting reflex is thus acoustically initiated but electrically mediated, representing a more ecological measure of CI functioning under real-world listening conditions. The reflexogenic input to the auditory nerve is thus determined by the output of the CI processor after all its signal processing. The reflex is then detected in the non-implanted ear using the standard immittance probe.

This approach was the focus of two papers by Franke-Trieger and colleagues. Franke-Trieger et al. (2021) compared free-field stapedius reflexes in CI users and normally hearing listeners, showing that the reflex was reliably obtainable via loudspeaker stimulation in CI users and that the thresholds were systematically related to the MAP settings of the processor. This was a key finding: it established that free-field ASRT is not simply an artefact of the measurement approach but reflects genuine loudness processing as mediated by the CI system. The relationship between ASRT and MAP settings suggested that the reflex threshold could serve as a practical check on the adequacy of device programming. If unusually low thresholds are present, it suggests potential overstimulation and absent reflexes at expected levels suggesting possible under stimulation.

Franke-Trieger et al. (2024) further demonstrated that free-field ASR thresholds could help in discriminating CI users with over-stimulated and under-stimulated MAP programs and providing a clinically actionable index of fitting adequacy. The authors discussed the indirect implications of their findings for speech and language development in children, arguing that CI maps validated by ASRT measurement would provide more appropriate auditory input and thereby creating better conditions for language learning. This proposed mechanism, from ASRT through MAP optimization to improved auditory input to language outcomes, provides a strong theoretical basis for investigating a direct empirical relationship between ASRT and language measures, which remains to be established.

2.5 Cortical Auditory Evoked Potentials and Late Latency Responses in Paediatric CI users

Cortical auditory evoked potentials provide insight into auditory processing at the level of the auditory cortex. Late latency responses (LLRs), including the P1, N1, and P2 components, hold significant importance due to their correlation with higher-order auditory processing. LLRs holds particular clinical relevance in the paediatric cochlear implant population due to its morphological and temporal characteristics that reflect the functional integrity and maturational status of the central auditory system. These components are important markers in auditory event-related potentials (ERPs) that show more advanced stages of auditory processing. The LLR consists of a set of deflections (P1, N1, P2, and N2) that originate from generators dispersed throughout the primary and associative auditory cortices. Each component is sensitive to distinct characteristics of cortical development and auditory processing (Picton, 2011).

The morphology of the LLR in young children is very different from that observed in adults. In young children, the LLR waveform has a characteristic morphology that differs substantially from the adult pattern. The P1 component shows a significant positive deflection that happens between 80 and 150 ms after the stimulus. P1 represents activity in thalamocortical projections to the primary auditory cortex that dominates the waveform in early infancy (Ponton et al., 2000). In children under the age of ten, the N1 component is absent or greatly attenuated (small). The N1 component depends on cortical inhibitory interneurons that mature relatively late in paediatric CI users. The P2 component which is represented as a positive deflection is present at approximately 150–200 ms. P2 reflects later integrative cortical processing. The amplitudes of the P1-N1 and N1-P2 peak-to-peak pairs represents the magnitude of cortical activation.

2.5.1 P1 component as a biomarker of cortical maturation

The most reliable measure of central auditory development in CI children is the developmental shortening of P1 latency. It changes from the lengthy values observed in young auditory-deprived children to the shorter adult-like values that appear with maturity and auditory experience. This trajectory forms the basis of the clinical P1 biomarker paradigm established by Sharma et al. (2002) and elaborated by Campbell et al. (2011).

The P1 component has been widely studied as a biomarker of cortical maturation. The study of Sharma et al. (2002) provides the most significant empirical evidence of the sensitive time for central auditory development in CI children. They recorded P1 latencies from children implanted at various ages using the P1 cortical auditory evoked potential. The P1 component is characterized by a positive peak at approximately 100 ms in young children. It is produced by thalamocortical projections to the primary auditory cortex and functions as a reliable biomarker of cortical auditory development. As individuals age and gain auditory experience. P1 latency consistently decreases with age and auditory experience indicating the maturation of central auditory pathways.

In their research, Sharma et al. (2002) illustrated that the timing of cochlear implantation significantly affects cortical plasticity. Children implanted prior to approximately 3.5 years of age demonstrated swift in P1 latency. P1 latencies in children implanted before 3.5 years normalize to levels seen in normal-hearing peers within 6-8 months. Conversely, children implanted between 3.5 and 7 years exhibited only partial normalization, whereas those implanted after 7 years demonstrated consistently extended P1 latencies, even following extended implant usage. These results strongly indicate a sensitive period for auditory cortical development, concluding at approximately 3.5 years, during which neural plasticity is at its peak.

However, it was a cross-sectional design which compared P1 latencies across children implanted at different ages at a single time point so it cannot unambiguously establish causality. Families who pursued early implantation may have differed systematically in socioeconomic status, access to early intervention, and educational engagement. The study also did not control for aetiology of hearing loss, a known source of variance in cortical maturation trajectories, and the normative P1 latency dataset used for comparison was drawn from a relatively limited sample. Despite these limitations, the internal consistency of results from a sufficiently large and well-defined sample, along with corroborative evidence from later longitudinal studies, enhances the validity of the primary conclusion.

Campbell et al. (2011) further elaborated on the clinical application of the P1 component, emphasizing its role as an objective biomarker for assessing auditory pathway development and guiding intervention strategies. The use of CAEPs allows clinicians to monitor cortical responses to auditory stimulation and evaluate the effectiveness of cochlear implant use and rehabilitation.

2.5.2 Longitudinal Evidence for P1 Maturation Post-Implantation

The research group led by Silva and colleagues produced a series of studies tracking cortical auditory maturation in paediatric CI users across different timeframes. Silva et al. (2013) conducted a systematic review of long-latency auditory evoked potentials in CI children. They found that P1 latency undergoes rapid reduction following CI activation and at that early implantation (particularly before 3.5 years) is associated with better cortical auditory pathway development. Silva et al. (2014) reported significant decreases in P1 latency within 3 months of CI activation. Silva et al. (2015) presented a longitudinal case study demonstrating parallel improvements in electrophysiological and behavioural measures over time. Silva et al. (2017) showed that shorter P1 latency was associated with better auditory discrimination skills. Earlier implantation and longer CI use improved maturational outcomes. Across this series, P1 latencies in CI children often remained longer than those of age-matched normal-hearing peers even after extended device use.

Several studies have investigated the relationship between cortical auditory evoked potentials and language outcomes in children with hearing loss. Mostafa et al. (2013) performed a clinical investigation analysing cortical auditory evoked potential (CAEP) results in children with cochlear implants. The study indicated that children with cochlear implants initially exhibited delayed cortical maturation, evidenced by extended P1 latency in comparison to their normal-hearing counterparts. Nevertheless, with ongoing implant utilization, P1 latency diminished and amplitude increased, accompanied by a gradual enhancement in waveform morphology, signifying experience-dependent cortical development. These results supported the significance of early auditory stimulation in promoting optimal cortical maturation and speech development.

2.5.3 P1 latency as a predictor of speech and language

Xiong and colleagues (2022) examined the relationship between P1 latency and functional speech outcomes in a cohort of cochlear-implanted children. They found a significant correlation between P1 latency and both auditory performance scores and speech recognition measures, indicating that children with shorter P1 latencies exhibited enhanced performance on speech-related tasks. Both P1 latency and P1 amplitude fluctuated over time. An increase in amplitude indicated enhanced neural synchrony. The relationship was modulated by the duration of CI use, with longer duration of use associated with decreased P1 latency and better performance. But the study was conducted in one clinical centre in China, limiting generalizability.

Frånlund et al. (2024) found a significant relationship between shortened P1 latencies and higher receptive language scores ($p = 0.015$), indicating that the cortical auditory maturation indexed by the P1 component is meaningfully related to language comprehension. The authors suggested that serial monitoring of P1 latency could be an objective measure to track language development and identify children who would benefit from augmented intervention. They also reported a significant relationship between P1 latency and hearing age (time of cochlear implant use). With a small sample, standardized language tests produced real P1 relationships. However, the same small, homogeneous Swedish cohort does not fit into diverse populations like Kannada speakers as it limits subgroups.

Bakhos et al. (2014) also demonstrated that cortical electrophysiological markers are associated with language abilities in children using hearing aids. Therefore, suggesting that these measures reflect higher-order auditory and linguistic processing.

Lamminmäki et al. (2023) further supported these findings by showing that auditory cortex maturation is closely related to language development, even in children with additional disabilities. These studies collectively highlight the importance of cortical processing in language acquisition and suggest that CAEPs may serve as valuable predictors of language outcomes.

2.5.4 Conflicting Evidence and the need for Further Investigation

Not all studies have found significant correlations between aided LLR measures and language outcomes. Sahana and Manjula (2024) specifically investigated the relationship between aided late latency responses and language age in paediatric CI users. They found no significant relationship between aided late latency responses and language age in children with cochlear implants.

Saravanan et al. (2024), recorded electrically evoked late latency responses through single-electrode CI stimulation rather than the sound-field aided approach, and correlating these with speech perception in paediatric CI users. They found that larger N1 and P1-N1 amplitudes, particularly from apical electrodes were associated with better speech recognition in quiet. While the recording methodology differs from the aided sound-field approach used in the present study, the overall finding supports the view that cortical auditory response amplitude is a functionally meaningful index in CI children.

The existing literature provides a picture of real clinical potential, but also real inconsistency. P1 latency normalization has emerged as a promising biomarker of central auditory development and has been associated with speech and language outcomes across multiple studies. However, the relationship is not universal and further investigation in carefully characterized samples using standardized language assessment tools is warranted.

2.6 Gaps in Literature and Rationale for the Study

A review of the literature reveals several gaps, including limited research on the relationship between ASR thresholds and language outcomes, inconsistent findings regarding the association between LLR and language development, and a lack of studies integrating peripheral and cortical measures. Even, there is a need for research in diverse populations using standardized assessment tools such as the ALD-MM.

The present study aims to address these gaps by investigating the relationship between acoustic stapedial reflex thresholds and aided cortical auditory evoked potentials with speech and language outcomes in paediatric cochlear implant users. By examining both peripheral and cortical measures in relation to receptive and expressive language skills, the study seeks to provide a comprehensive understanding of the factors influencing language development.

2.7 Rationale for the Present Investigation

The present study is motivated by all of the considerations outlined above. It aims to establish whether ASR thresholds measured by free-field stimulation, and aided late latency cortical responses recorded under standard sound-field conditions, are associated with receptive and expressive language outcomes as assessed by the ALD-MM in Kannada-speaking children with unilateral cochlear implants. It examines the relationship between ASR and LLR measures with speech identification scores, and the interrelationship between ASR and LLR.

The selection of both peripheral (ASR threshold) and central (aided LLR) measures reflect the theoretical position that language development in CI children depends on the integrity of the auditory system at multiple levels: adequate peripheral stimulation delivered by a well-fitted CI map, and appropriate central auditory maturation as reflected by normalizing cortical potentials. By examining both measures concurrently in the same sample, the study can assess their independent and combined contributions to language outcomes in a way that no previous study has attempted.

If significant correlations are found, the clinical implications are substantial. Audiologists would have access to objective, non-behavioural biomarkers that can be obtained even in very young children and that provide prognostically meaningful information about expected language trajectories. This could enable earlier identification of children at risk for poor language outcomes, guide programming adjustments, inform counselling of families, and support decisions about the need for augmentative communication strategies. If correlations are not found, this too would be clinically informative, emphasizing that language development in CI children is shaped by factors beyond auditory access alone and that expectations must be tempered accordingly.

Chapter 3

METHOD

The present study aimed to investigate the relationship among acoustic stapedial reflex thresholds, aided late latency responses (LLR), and speech and language outcomes in paediatric cochlear implant (CI) users. Participants underwent standard non-invasive audiological assessments, including case history, otoscopy, and tympanometry as part of the inclusion criteria. The audiological measures to evaluate the objectives of the study included objective measures (i.e., acoustic stapedial reflex testing, aided LLR testing), and behavioural outcome measures (Assessment of Language Development – Manipal Manual *i.e.,* ALD-MM) and Speech Identification Scores (SIS).

Study Design

The present study followed a single group correlational design (Creswell, 2014). The variables measured for analysis included acoustic stapedial reflex thresholds, aided cortical auditory potentials (latencies: P1, N1, P2, N2; amplitudes: N1-P1, N1-P2), speech and language outcome measures obtained using the ALD-MM and SIS. Demographic and implant-related factors (age at implantation, age at testing, duration of CI use, and aetiology of hearing loss) were also recorded.

Ethical Clearance

Ethical approval for the present study was obtained from the Institutional Review Board (IRB) of the All-India Institute of Speech and Hearing (AIISH), Mysuru (Ref. No.: SH/IRB/M.4/AUD.10/2025–26; Date: 06.01.2026) mentioned in the appendix. The study received ethical approval prior to the commencement of data collection.

Written informed consent was obtained from the parents or guardians of all participants prior to their inclusion in the study. The procedure complied with the ethical standards prescribed by the institute for bio-behavioural research (Venkatesan & Basavaraj, 2009).

Participants

The study included a sample of 23 children with congenital bilateral severe-to-profound sensorineural hearing loss using unilateral cochlear implants, aged 4 to 9 years. All participants had received at least one year of listening, speech, and language therapy following CI activation. A purposive sampling technique was employed to recruit participants who met the inclusion criteria.

Inclusion Criteria

Children meeting the following criteria were included in the study:

- Congenital bilateral severe to profound hearing loss
- Native speakers of Kannada language
- Using unilateral CI, with or without a hearing aid in the contralateral ear
- Minimum one year of CI use
- Stable and adequate CI map with aided thresholds within 30 dB HL at audiometric frequencies
- Consistent CI use of at least eight hours/day
- Contralateral acoustic stapedial reflexes present

Exclusion Criteria

Children meeting any of the following criteria were excluded from the study:

- Bilateral CI users

- Children with visual, motor, neurological, auditory neuropathy spectrum disorder (ANSD), or cognitive impairment
- Children with additional or associated disorders

Test Environment, Equipment, and Test Material

All audiological assessments were carried out in a single- or double-room air-conditioned, sound-treated test suite. Speech and language assessments were conducted in a regular room. Ambient noise levels were maintained within permissible limits (re: ANSI S3.1-1999; R2013). Recordings for aided LLR were conducted in an electrically shielded, sound-treated room.

Equipment for Tympanometry

A calibrated clinical immittance meter was used to record the tympanogram with a 226-Hz probe tone frequency and to measure the acoustic stapedial reflex. A clinical-grade, calibrated loudspeaker was positioned at one metre distance and 0° azimuth for delivering controlled stimulus levels in the test room. The loudspeaker was connected to a laptop for stimulus delivery.

Auditory Evoked Potential Equipment

A calibrated two-channel evoked potential system was used to record LLRs. The system included the facility to record aided LLRs, with capabilities for cortical response recording, artefact rejection, and response averaging. It was connected to a calibrated sound-field loudspeaker.

Cochlear Implant

Each participant used his or her own cochlear implant with a speech processor loaded with a stable, verified programme (MAP). Good working status of the CI was ensured before data collection. The details of the cochlear implants used by each participant are presented in Table 3.1.

Table 3.1

Participant Demographic Details and Cochlear Implant Details

Participant No.	Age (Months)	Gender	Cochlear Implant (Manufacturer and Model)	Speech Processor (Model)
1	84	Male	MED-EL Synchrony	Sonnet
2	84	Male	Cochlear CI422	CP802
3	85	Male	Cochlear CI422	CP802
4	96	Female	Cochlear CI422	CP802
5	73	Male	MED-EL Concerto 2	Sonnet
6	84	Male	MED-EL Sonata Ti100	Opus II
7	84	Male	Cochlear CI422	CP802
8	101	Male	Cochlear CI422	CP802
9	104	Female	Cochlear CI422	CP802
10	53	Male	Cochlear CI422	CP802
11	68	Female	Cochlear CI422	CP802
12	54	Female	Cochlear CI422	CP802
13	108	Male	Cochlear CI422	CP802
14	66	Female	Cochlear CI422	CP802
15	74	Female	Cochlear CI422	CP802
16	93	Male	Cochlear CI422	CP802
17	66	Male	Cochlear CI422	CP802
18	55	Male	Cochlear CI422	CP802
19	72	Male	MED-EL Sonata Ti100	Opus II

20	108	Male	Cochlear CI422	CP802
21	72	Female	Cochlear CI422	CP802
22	72	Male	Cochlear CI422	CP802
23	72	Female	Cochlear CI422	CP802

Note. CI = cochlear implant.

Language Assessment Tool

The *Assessment of Language Development—Manipal Manual* (ALD-MM; Lakkanna et al., 2021) was used for language assessment. This standardized tool consists of test items and scoring charts to obtain receptive and expressive language age.

Speech Identification Test Material

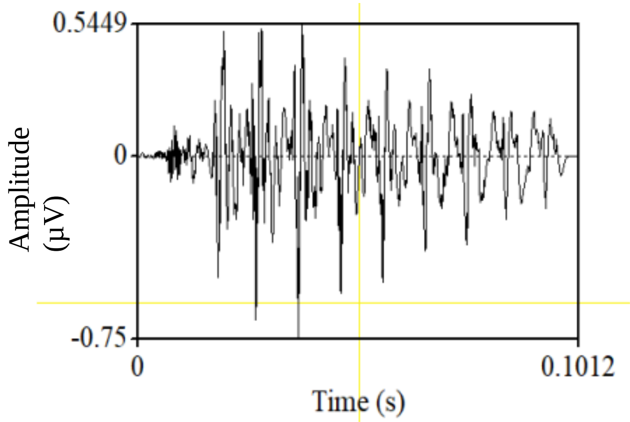
The Speech Identification Test for Kannada-speaking children (Vandana & Yathiraj, 1998) was used to obtain speech identification scores. The test comprises of two lists of 50 phonetically balanced bisyllabic Kannada words. Corresponding half-lists of 25 words each were also developed. The testing procedure involved a closed-set picture identification task, in which a picture book featuring four pictures per page was presented to the child, with one picture serving as the target word. The test was administered at 45 dB HL under quiet condition.

Stimuli for Recording ASR and Aided LLR

A synthetic /da/ speech token was used for both the acoustic stapedial reflex threshold measurement and aided LLR recording. The /da/ stimulus is characterized by high-frequency spectral energy cues that are important for speech perception. The same stimulus was used for both tests to maintain consistency in stimulus and to allow comparisons across the two measures. Figure 3.1 presents the waveform of the synthetic /da/ speech stimulus used for recording the acoustic stapedial reflex threshold (ASRT) and aided LLR.

Figure 3.1

The Waveform of the Synthetic /da/ Speech Stimulus



Note. X-axis**:** Time in seconds, Y-axis: Relative amplitude of the /da/ speech stimulus, Adapted from "Effect of Bimodal Hearing Device on Speech Identification in Noise, Localization, Emotion Perception, and Late Latency Responses in Children," by P. Sahana, 2025.

Testing Environment

All testing was conducted in a quiet, distraction-free room. For acoustic stapedial reflex threshold measurement and aided LLR recording, the child was awake and seated comfortably, watching a muted cartoon on a laptop screen, in a sound treated room.

Procedure

Case History and Baseline Evaluation

Each participant underwent a structured case history interview to collect demographic background information and to confirm the inclusion criteria. The information recorded included chronological age, gender, language used at home, age at detection and diagnosis of hearing loss, age at cochlear implantation, cochlear implant model, duration of therapy, and average daily hours of CI use.

Otoscopy and Tympanometry

Otoscopy was performed to rule out contraindications for further audiological testing. Tympanometry was subsequently conducted to exclude middle ear pathology prior to proceeding with acoustic reflex and LLR measurements.

Acoustically Evoked Stapedial Reflex Threshold Measurement

The stimulus to elicit the acoustically evoked stapedial reflex (ASR) threshold was presented through a loudspeaker connected to an audiometer. The test stimulus was the synthetic speech token /da/. The stimulus was picked up and processed by the participant's cochlear implant, and the contralateral reflex was measured using an immittance meter.

The lowest presentation level of the speech stimulus required to elicit a reproducible stapedius reflex was recorded for each participant. This approach was selected because loudspeaker presentation closely simulates the child's everyday aided listening environment. The ESRT monitoring mode was used to record reflex responses. Measuring the ASR threshold in the sound field also served as a check on device fitting (Franke-Trieger et al., 2024).

An immittance probe was inserted into the contralateral (non-implanted) ear, ensuring an airtight acoustic seal. Tympanometry was performed prior to acoustic reflex measurement to confirm normal middle ear function. The child was instructed to sit quietly, either on the caregiver's lap or on a child's chair, while watching a muted cartoon on a laptop.

Cochlear Implant Processor Set-up

Each participant was tested with his or her own cochlear implant processor with the stable programme (MAP) activated. The loudspeaker was placed at 0° azimuth, at ear level, and 1.0 m from the participant.

Stimulus Type and Presentation

A clinically calibrated synthetic /da/ speech stimulus of 40-ms duration was used to measure acoustic reflexes. The stimulus was delivered with varied levels and sufficient interstimulus interval to prevent adaptation effects. Intensity was increased in 5 dB steps until the lowest level eliciting a detectable response was identified and recorded as the minimum threshold level.

Reflex Detection

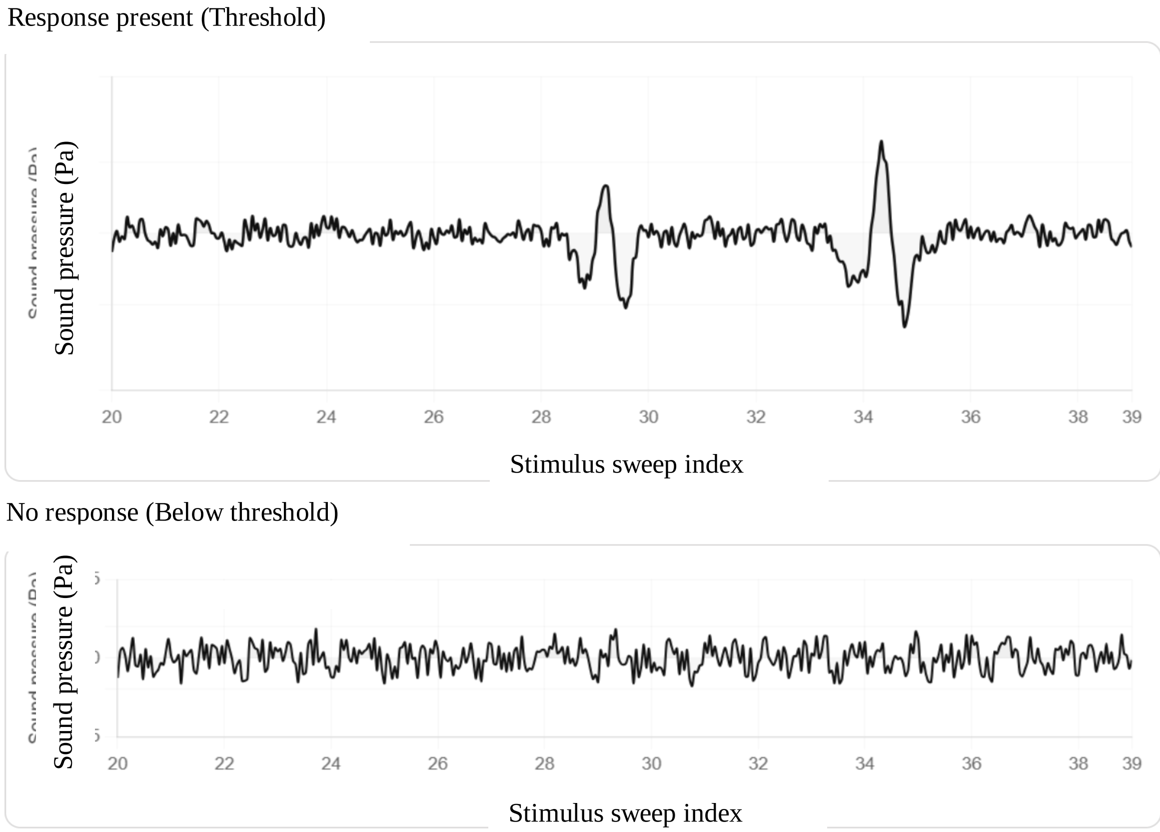
The stapedius reflex was identified by the presence of a repeatable clear deflection following stimulus presentation, indicative of stapedius muscle activation. (Figure 3.2). If no response was observed at the highest safe level, the result was recorded as "no response," and the participant was excluded from the study. When reflex was present, the lowest level at which the reflex was elicited was noted for each participant.

Reliability Measurement

All measurements were repeated once. Care was taken to ensure that the intended stimulus intensity was accurately delivered to the CI processor. The contralateral reflex threshold was noted for each participant.

Figure 3.2

Acoustically evoked stapedial response waveform



Both waveforms' panels - the 'response present' panel with the two biphasic peaks at different levels of stimulus, and the 'no response' panel showing flat waveform.

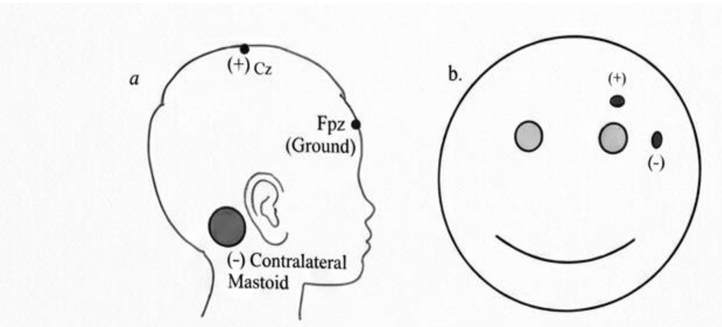
Aided Late Latency Response Recording

Late latency responses (LLR) were recorded for all implanted children using a calibrated two-channel IHS SmartEP system. The participant was seated with the head positioned 1.0 m from the loudspeaker, placed at 0° azimuth. The participant was seated comfortably on a chair in an air-conditioned sound treated room. A cotton swab with prepping gel was used to clean electrode placement sites on the scalp of the participant. Disposable electrodes with conduction gel were applied at the appropriate locations.

The ground electrode was placed at the forehead (Fpz), the reference (inverting) electrode was positioned at the mastoid contralateral to the implanted ear, and the active (non-inverting) electrode was positioned at the vertex (Cz) for the vertical montage. Ocular monitoring was carried out using a bipolar electrode at the lateral outer canthus, referenced to the superior orbit. The electrode montage for LLR recording and ocular monitoring is illustrated in Figure 3.3

Figure 3.3

Electrode Montage for Recording Aided LLR and Ocular Monitoring



Note: (a) Electrode montage configuration used for recording long latency responses (LLR), (b) Electrode montage configuration used for ocular monitoring, Fpz = forehead ground; Cz = vertex active; CI = cochlear implant. Ocular monitoring electrodes are placed at the lateral outer canthus and superior orbit.

Electrode impedance was ensured to be within 5 kΩ to minimise response contamination and excessive artefact rejection. Continuous electroencephalographic (EEG) activity was monitored throughout the session. A minimum of two recordings were obtained to ensure replicability of responses. During LLR recording, the participant was relaxed and watched a muted cartoon on a laptop. An appropriate pause between recordings was provided when required.

Stimulus Presentation

A synthetic /da/ speech token of 40-ms duration was presented from a calibrated loudspeaker at a standardised level of 70 dB SPL with the participant's processor activated and set to his or her normal listening programme. A trigger cable was used to synchronise stimulus onset with the IHS SmartEP system for accurate cortical response recording. A two-channel setup was used to record aided LLR (Channel 1) and monitor ocular movements (Channel 2). Silver cup electrodes were placed at the vertex (Cz), lower forehead (Fpz), and the mastoid contralateral to the CI. For ocular monitoring, two electrodes were placed approximately 1 to 2 cm from the upper and lower eyelids of the eye contralateral to the cochlear implant. Intra-electrode and inter-electrode impedance values were below 5 kΩ and 2 kΩ, respectively. The stimulus and acquisition parameters used for LLR recording are presented in Table 3.2.

Table 3.2

Stimulus and Acquisition Parameters for Aided Late Latency Response Recording

Parameter	**Details**
Stimulus Parameters	
Type of stimulus	Synthetic speech token /da/
Loudspeaker position	1.0 m from participant at 0° azimuth
Stimulus intensity	70 dB SPL
Repetition rate	1.1/s
Polarity	Alternating
Number of sweeps	200 (artifact-free); repeated twice to verify waveform stability
Acquisition Parameters	

Analysis time	Pre-stimulus: 100 ms; Post-stimulus: 500 ms
Filter settings	1 - 30 Hz
Notch filter	Off
Amplification	50,000x
Number of channels	2 (ALLR + Ocular monitoring)
Number of recordings	2
Transducer	Loudspeaker
Electrode placement	Non-inverting electrode (+): Vertex (Cz) Inverting electrode (−): Mastoid contralateral to CI Ground electrode: Forehead (Fpz) Ocular monitoring: Bipolar electrode at lateral outer canthus referenced to the superior orbit

Note: LLR = late latency response; CI = cochlear implant; Cz = vertex; Fpz = forehead; ALLR = aided late latency response; dB SPL = Decibels Sound Pressure Level.

Waveform Analysis

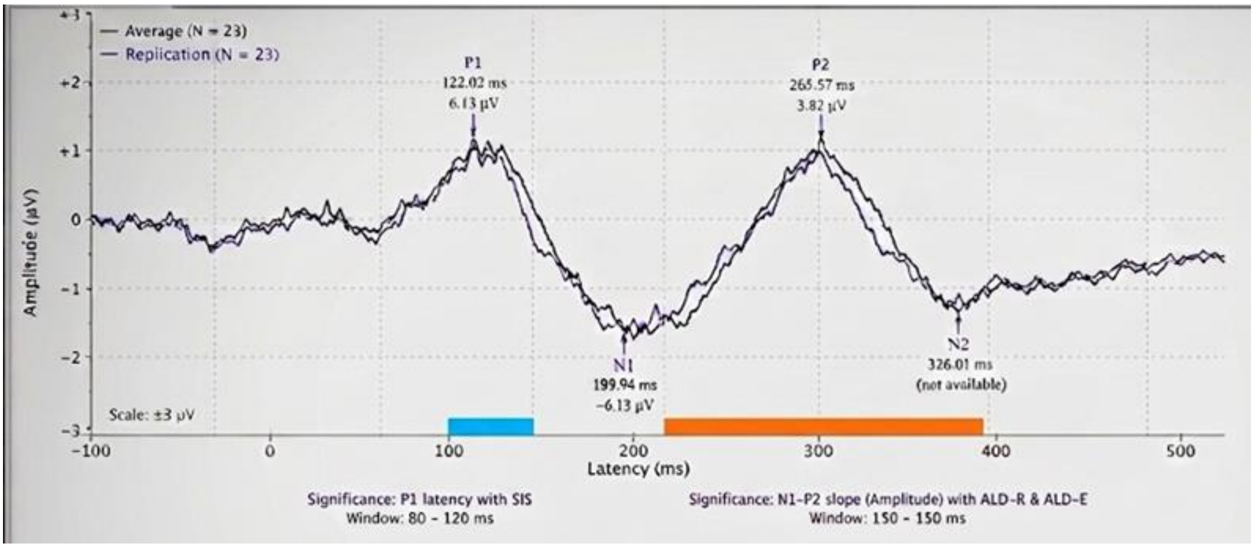
All recorded LLRs were visually inspected offline for waveform quality, replicability, and peak identification accuracy. Three experienced audiologists independently examined the LLRs of each participant. The recorded waveforms were inspected for the presence, morphology, and reproducibility of the major cortical peaks i.e., P1, N1, P2, and N2. To confirm response reliability, two replicated waveforms were obtained for each recording condition. The consistency of waveform morphology and peak occurrence across replicated recordings confirmed replicability.

The absolute latencies of P1, N1, P2, and N2 peaks were manually identified from the averaged waveform. The peaks were defined as the most prominent positive and negative deflections within the expected latency windows for CAEPs. Audiologists independently reviewed the replicated traces and identified peaks based on waveform morphology, latency range, and consistency across runs. Discrepancies in peak identification were resolved through consensus review.

Peak-to-peak amplitude measurements were also obtained: P1–N1 amplitude was measured from the positive peak of P1 to the negative peak of N1, and N1–P2 amplitude was measured from the negative peak of N1 to the positive peak of P2. All raw EEG recordings, averaged waveforms, and marked traces were saved for documentation and further verification. Artifact rejection and waveform reproducibility were continuously monitored throughout the recording and analysis process. Figure 3.4 presents the grand average aided LLR waveform across all participants.

Figure 3.4

Grand Average Aided Late Latency Response Waveform



Note: The grand average waveform illustrates the major cortical peaks (P1, N1, P2, N2) derived from aided LLR recordings, LLR = late latency response.

Language Assessment using ALD-MM

The ALD-MM was administered according to the procedures described in the test manual; the procedure begins with the selection of an appropriate starting level based on the child's chronological age which ensures that the test is neither too easy nor too difficult at initiation. In each task, the examiner presented a stimulus (e.g., picture, verbal question, or prompt), and the child was required to respond appropriately. Receptive language tasks involved comprehension-based responses, such as pointing to correct pictures or selecting appropriate options, whereas expressive tasks require the child to produce verbal responses, such as naming objects, forming sentences, or explaining concepts.

Receptive and expressive language ages were obtained for each participant. The assessment was conducted in the child's native language (Kannada). The child was instructed to perform tasks targeting vocabulary, grammar, and conceptual understanding. Testing continued until the child produced five consecutive incorrect responses to a subtest within each domain. The raw scores were converted into language age equivalents according to the ALD-MM manual. Each child therefore yielded a receptive language age and an expressive language age, which served as the primary outcome measures in the study.

Speech Identification Testing

The speech stimuli were presented through the loudspeaker, of the audiometer, located at 45 degrees Azimuth at one meter distance. The phonetically balanced (PB) word list for Kannada-speaking children (Vandana, 1998) was presented in live voice at 45 dB HL under quiet condition. A closed-set picture identification task was used to estimate the SIS. Each correctly identified word was awarded a score of 1, and each incorrectly identified or unidentified word was scored as 0. The total number of correct responses was recorded for each participant.

Reliability of Test Procedures

The reliability of the test procedures was established to ensure consistency, stability over time, and reproducibility of results. This was achieved by re-administering all test procedures to a subset of participants. Of the total sample of 23 participants, seven were selected for test–retest assessment.

Statistical Analyses

The data were entered and analysed using IBM SPSS Statistics, Version 26. Appropriate statistical tests were employed to address each study objective. The normality of data distributions was initially assessed using the Shapiro-Wilk test, which revealed that some variables were normally distributed ($p>0.05$) and others were not ($p < 0.05$). Descriptive statistics were subsequently computed for all study variables and are reported as measures of central tendency (mean and median) and variability (SD and interquartile range [IQR]).

Given the non-normal distribution of some variables, Spearman rank-order correlation was used for correlation analyses to assess the relationships among study variables. A p value of < 0.05 was considered statistically significant. However, the regression residuals were examined and found to approximate a normal distribution, thereby satisfying the assumption required for regression analysis. Multiple linear regression analysis was performed to identify the predictive relationships among variables and to determine the relative contribution of each independent variable to the dependent outcome measures.

Chapter 4

RESULTS

The primary aim of the study was to investigate the relationship of acoustically evoked stapedial reflex thresholds and aided late latency responses with speech language outcomes in paediatric cochlear implant users. A total of 23 children aged between 4 and 9 years with bilateral severe to profound hearing loss using unilateral cochlear implants were included in the study. The objective measures included acoustically evoked stapedial reflex thresholds, aided late latency responses (latencies and amplitudes of P1, N1, P2, and N2), and behavioural outcome measures included Speech Identification Scores (SIS) and Assessment of Language Development-Manipal Manual (ALD-MM).

The statistical analyses were initiated with assessment of data distribution using the Shapiro-Wilk test for normality. The results indicated that some data were distributed normally ($p>0.05$) whereas others showed non-normal distribution ($p<0.05$). Even though the data were not normally distributed but their residues were normally distributed. Descriptive statistics, Spearman correlation analysis, and regression were performed using IBM SPSS software (version 26). The participants demonstrated variability in their cortical auditory responses and speech-language outcomes.

The results are being organized into the following subsections based on the objectives of the study:

1. **1.** Relationship Between Acoustically Evoked Stapedial Reflex Thresholds and Receptive and Expressive language
2. **2.** Relationship Between Acoustically Evoked Stapedial Reflex Thresholds and Speech Identification Scores

3. Relationship Between Aided Late Latency measures and Receptive and Expressive language

4. Relationship Between Aided Late Latency Response measures and Speech Identification Scores

5. Relationship Between Acoustically Evoked Stapedial Reflex Thresholds and Aided Late Latency Response Thresholds with Speech Identification Scores

6. Predictors of Outcomes from Acoustically evoked stapedial reflex thresholds and Aided Late Latency Response measures

7. Test-retest reliability

4.1 Descriptive Statistics

Descriptive statistics consisting of mean, median, standard deviation (SD), and interquartile range (IQR) were computed for all the continuous variables. The sample included 23 participants with a mean chronological age of 81.10 months (SD = 16.08; median = 84.00 months). The mean age at cochlear implantation was 27.74 months (SD = 15.19; median = 24.00 months), indicating a wide range of age at implantation across participants. Such variation in implantation age is commonly reported in paediatric CI cohorts in India and has implications for the interpretation of auditory and language outcomes (Niparko et al., 2010; Ruben, 2018).

Cochlear implant aided pure tone average (PTA4) thresholds averaged 21.58 dB HL (SD = 6.36, IQR = 10.00 dB), which is broadly within acceptable fitting targets, indicating that the devices were mostly well fitted and thresholds were within acceptable limits. The relatively low standard deviation (SD = 6.36 dB HL) and a narrow interquartile range (IQR = 10.00 dB) also indicate considerable consistency of aided thresholds across participants, suggesting homogeneity of data in the study sample. The aided thresholds were within the speech banana for the soft most speech sounds to be accessible, indicating that the participants had adequate audibility for conversational speech.

The acoustic stapedial reflex (ASR) thresholds were recorded in sound field, were fairly consistent. An average of 68.95 dB SPL with a narrow IQR of just 5 dB was obtained. Considering the aided LLR measures, the mean P1 latency of the aided late latency response (LLR) was 122.02 ms (SD = 33.86), followed by mean N1 latency of 189.94 ms (SD = 43.52), P2 latency of 265.37 ms (SD = 61.12), and N2 latency of 326.01 ms (SD = 62.89). Average peak-to-peak amplitudes for the P1-N1 and N1-P2 components were 6.13 µV and 3.82 µV, respectively.

Consistency in the test procedures was ensured by the use of a 40-ms synthetic /da/ speech stimulus in both acoustic stapedial reflex threshold and aided late latency (LLR) evaluations. Stimulus presentation was standardized to minimize variability due to differences in stimulus characteristics.

Regarding speech and language outcomes, the mean closed set speech identification scores for the phonetically balanced (PB) word list were 94.74% (SD = 6.40; median = 96%), indicating generally high speech identification performance in the group. In contrast, greater variability was observed in language outcomes. The mean receptive language age on the Assessment of Language Development - Manipal Manual (ALD-MM) was 53.74 months (SD = 17.04; median = 66.00 months), and the mean expressive language age was 43.34 months (SD = 15.75; median = 45.00 months). The descriptive statistics including mean, median, standard deviation (SD), and interquartile range (IQR) measures for all participants are presented in Table 4.1.

Table 4.1

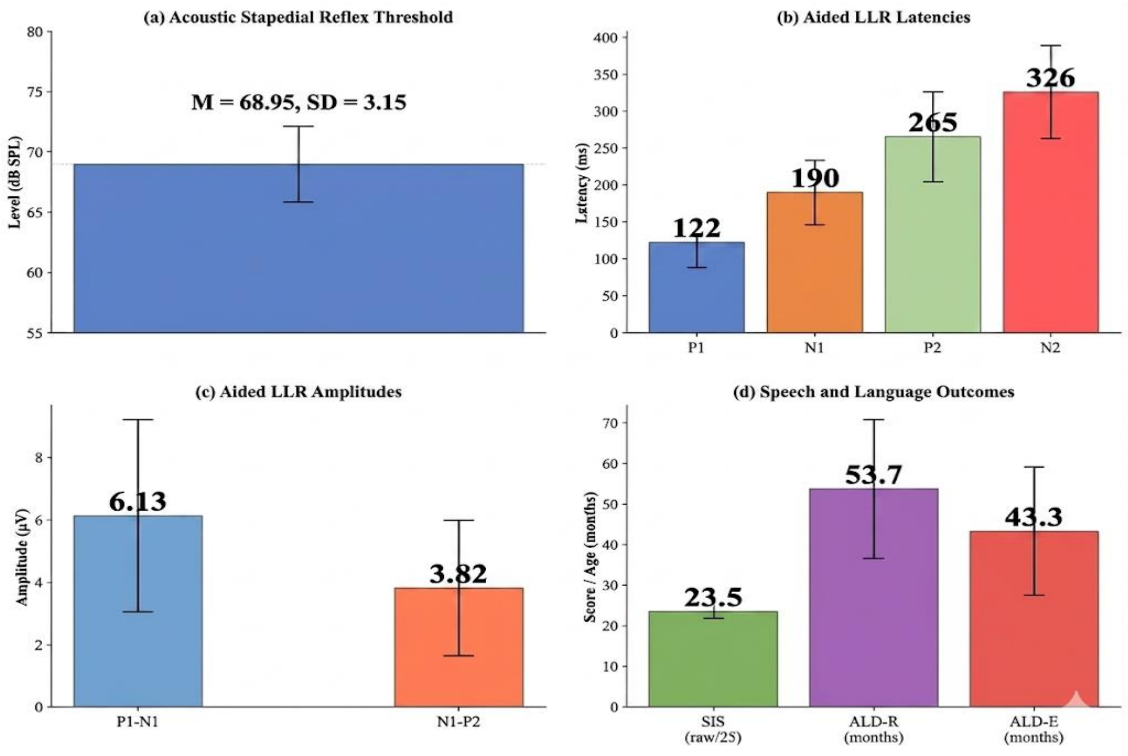
Descriptive Statistics for All Study Variables (n = 23)

Variables	**Mean**	**Median**	**SD**	**IQR**
ASR Level (dB SPL)	68.95	70.00	3.15	5.00
P1 Latency (ms)	122.02	122.55	33.86	32.26
N1 Latency (ms)	189.94	188.13	43.52	37.63
P2 Latency (ms)	265.37	265.52	61.12	86.08
N2 Latency (ms)	326.01	337.55	62.88	72.02
P1-N1 Amplitude (µV)	6.13	6.24	3.08	2.88
N1-P2 Amplitude (µV)	3.82	3.87	2.17	3.30
SIS (Max. score = 25)	23.50	24.00	1.60	2.00
ALD-R (months)	53.74	66.00	17.04	21.00
ALD-E (months)	43.34	45.00	15.75	24.50

Note: SD = Standard Deviation; IQR = Interquartile Range; ASR = Acoustic Stapedial Reflex; ALD-R = Receptive Language Age; ALD-E = Expressive Language Age (Assessment of Language Development – Manipal Manual; Lakkanna et al., 2021).

Figure 4.1

Bar charts depicting descriptive statistics (mean ± 1 SD) for all study variables grouped by domain: (a) acoustic stapedial reflex threshold, (b) aided LLR latencies, (c) aided LLR amplitudes, and (d) speech and language outcomes.



Note: Error bars represent ±1 SD, SIS = Speech Identification Score; ALD-R/E = Receptive/Expressive language age.

4.2 Evaluation of Data Distribution

Before proceeding with inferential analyses, the Shapiro-Wilk (S-W) test was used to test the normality of each variable distribution. The sample size (n = 23) was relatively small; therefore, the Shapiro-Wilk test was the main criterion used to determine the distribution of the data, as it is more sensitive and appropriate for samples below 50 (Franke-Trieger 2018). Results from the Kolmogorov-Smirnov (K-S) test with Lilliefors correction are also reported.

The results showed that some variables were significantly different from the normal distribution. Specifically, there were significant deviations from normality for implant age, aided audiogram thresholds, tympanogram category, ASR level, P1-N1 amplitude, speech identification scores (SIS), and receptive language age (ALD-R) based on the Shapiro-Wilk test ($p < .05$). In contrast, age at testing, P1, N1, P2, and N2 latencies, N1-P2 amplitude, and expressive language age (ALD-E) appeared to be normally distributed ($p > 0.05$). Some of the variables were not normally distributed, but their residues were normally distributed. The non-normal distribution of ALD-R is consistent with findings reported by Frånlund et al. (2024) and Sahana and Manjula (2024), who similarly noted a wide variability and skewness in distributions in language age among paediatric CI users.

Spearman's rank-order correlation was used throughout the study. Table 4.2 presents the normality test statistics for all study variables.

Table 4.2

Tests of Normality for All Study Variables (n = 23)

Variable	K-S Stat.	K-S Sig.	S-W Stat.	S-W Sig.	Distribution
ASR Level	0.315	0.000	0.779	0.001	Non-normal
P1 Latency	0.112	0.200*	0.981	0.953	Normal
N1 Latency	0.139	0.200*	0.963	0.641	Normal
P2 Latency	0.142	0.200*	0.966	0.685	Normal
N2 Latency	0.112	0.200*	0.978	0.912	Normal
P1-N1 Amplitude	0.193	0.060	0.816	0.002	Non-normal
N1-P2 Amplitude	0.119	0.200*	0.943	0.301	Normal
SIS	0.268	0.001	0.795	0.001	Non-normal
ALD-R	0.290	0.000	0.851	0.007	Non-normal
ALD-E	0.155	0.200*	0.945	0.319	Normal

Note: K-S = Kolmogorov-Smirnov with Lilliefors correction; S-W = Shapiro-Wilk. * $p < 0.05$, indicating significant deviation from normality. Variables with S–W $p < 0.05$ were treated as non-normally distributed for subsequent correlation analyses. ASR = Acoustic Stapedial Reflex; ALD-R = Receptive Language Age; ALD-E = Expressive Language Age; SIS = Speech Identification Score.

1) Relationship Between Acoustically Evoked Stapedial Threshold and Receptive and Expressive language age

Spearman rank-order correlation analysis was performed to examine the relationship between CI aided acoustic stapedial reflex (ASR) threshold and receptive (ALD-R) and expressive (ALD-E) language age.

The acoustically evoked stapedial threshold was negatively correlated with ALD-R scores ($\rho = -0.359$), but the association was not statistically significant ($p = 0.093$). Likewise, the acoustically evoked stapedial threshold was negatively correlated with ALD-E scores ($\rho = -0.339$), which was also not statistically significant ($p = 0.114$).

Results showed that higher ASR thresholds were associated with lower receptive and expressive language age, but these relationships were not statistically significant. Table 4.3 provides the correlation between acoustically evoked stapedial reflex threshold and receptive (ALD-R) and expressive (ALD-E) age.

Table 4.3

Spearman Rank-Order Correlation (ρ) of ASR Level with Receptive and Expressive Language Age (n = 23)

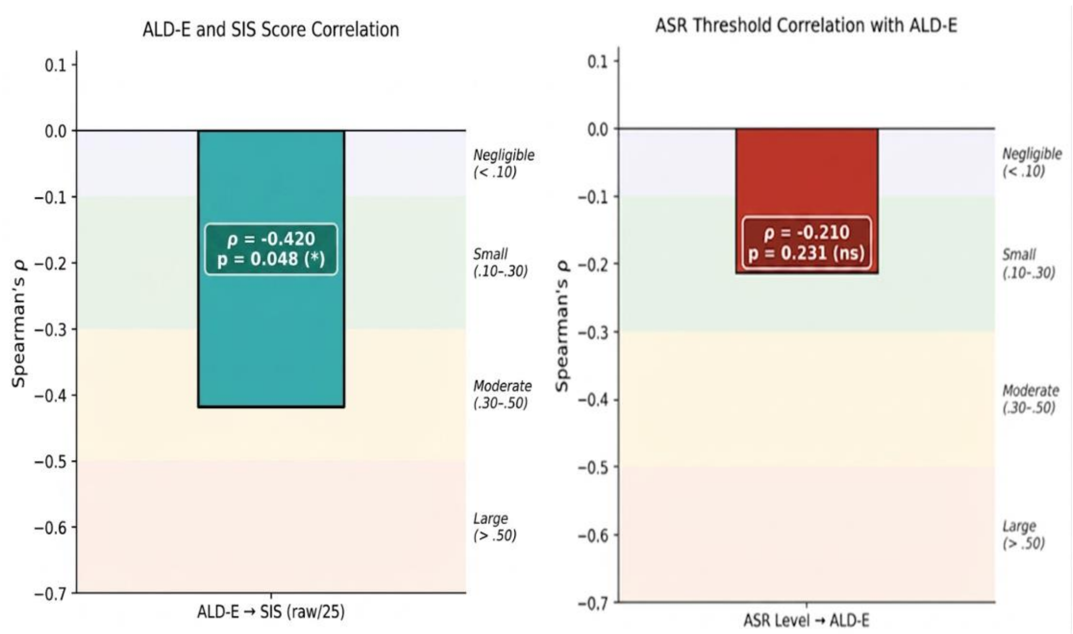
Variables	***ρ***	***p-value***	**Interpretation**
ASR Level & ALD-R	−0.359	0.093	Not significant

ASR Level & ALD-E	−0.339	0.114	Not significant

Note: ρ = Spearman's rho. ASR = Acoustic Stapedial Reflex threshold (dB SPL); ALD-R = Receptive Language Age; ALD-E = Expressive Language Age (Assessment of Language Development - Manipal Manual; Lakkanna et al., 2021). Statistical significance set at $p < 0.05$ (two-tailed)

Figure 4.2

Spearman correlation coefficient (ρ) between ASR Level with Receptive Language Age (ALD-R) and Expressive Language Age (ALD-E).



Note: Horizontal bands indicate effect size categories based on Cohen (1988). The coefficient falls within the moderate range for ALD-E &SIS; the coefficient falls within the small range for ALD-E &ASR, ns = not significant (p > 0.05).

2) Relationship between Acoustically Evoked Stapedial Threshold with Speech Identification Scores

The second objective was to investigate whether the CI-aided ASR threshold was related to speech identification performance measured with a phonetically balanced (PB) word list. Given that acoustically evoked stapedial threshold and speech identification scores violated normality assumptions, the association between the two variables was explored using Spearman rank-order correlation. The analysis revealed a non-significant negative correlation between CI-aided ASR threshold and speech identification scores ($\rho = -0.278$, $p = 0.200$, n = 23), as shown in Table 4.4.

Table 4.4

Spearman Correlation Between CI-Aided ASR Threshold and SIS Scores (n = 23)

ρ	***p-value***	**Significance**
−0.278	0.200	Not significant

Note: ρ = Spearman's rho; ASR threshold = acoustic stapedial reflex threshold in dB SPL; SIS scores = speech identification scores.

3) Relationship Between CI-Aided LLR Components and Receptive and Expressive language age

The third objective examined the relationship between CI-aided late latency response (LLR) components and language outcomes. Correlation analyses were performed between the LLR latencies (P1, N1, P2, and N2) and receptive (ALD-R) and expressive (ALD-E) language age. Along with correlation analyses of aided LLR amplitude measures (P1-N1 and N1-P2), with receptive (ALD-R) and expressive (ALD-E) language age. As normality assumptions were not met for some variables, Spearman's rank-order correlation was used for analysis.

3.a) Relationship between LLR Latencies with receptive language age (ALD-R) and expressive language age (ALD-E)

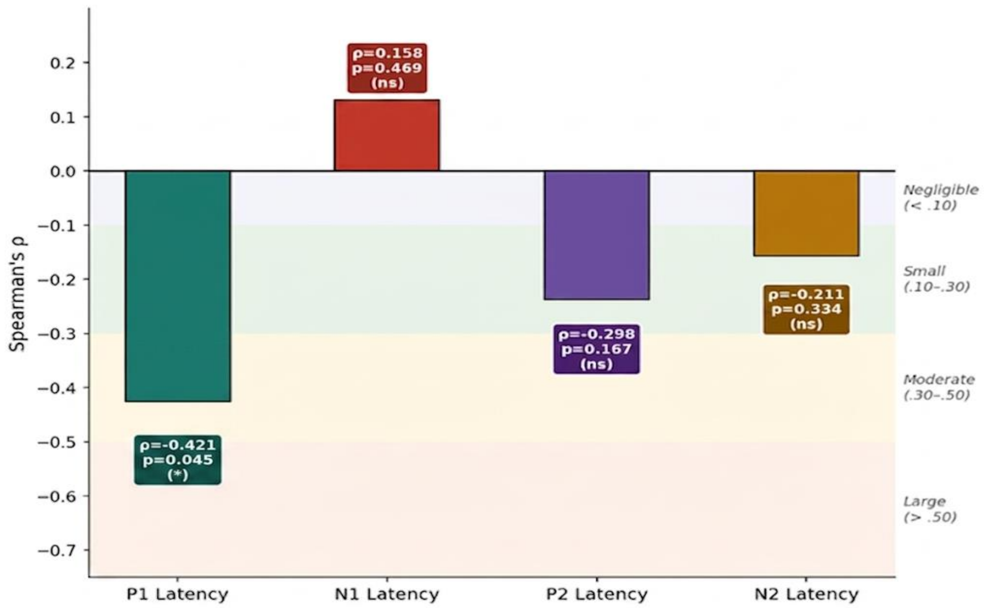
Among all the LLR latency variables, none of them showed a statistically significant relationship with either receptive or expressive language. Negative trends were observed across most latency measures. P1 latency demonstrated the strongest association among the latency variables, showing a negative correlation with ALD-R (ρ = –0.303, *p* = 0.160) and ALD-E (ρ = –0.343, *p* = 0.109). Although these relationships were not statistically significant, participants with longer P1 latencies tended to demonstrate comparatively lower language.

The N1 latency demonstrated a negligible positive correlation with receptive language (ρ = 0.110, p = 0.617) and expressive language ages (ρ = 0.040, p = 0.855), indicating minimal association between N1 latency and language abilities in the present sample.

Similarly, P2 latency showed weak negative correlations with receptive language (ρ = −0.220, p = 0.324) and expressive language age (ρ = −0.154, p = 0.494). N2 latency also demonstrated weak negative correlations with receptive language (ρ = −0.147, p = 0.548) and expressive language ages (ρ = −0.024, p = 0.922). These weak and non-significant findings suggest that later cortical response timing may not strongly reflect language performance in this cohort.

Figure 4.3

Spearman correlation coefficients for CI-aided LLR latency variables (P1, N1, P2, N2) and Receptive Language Age (ALD-R).

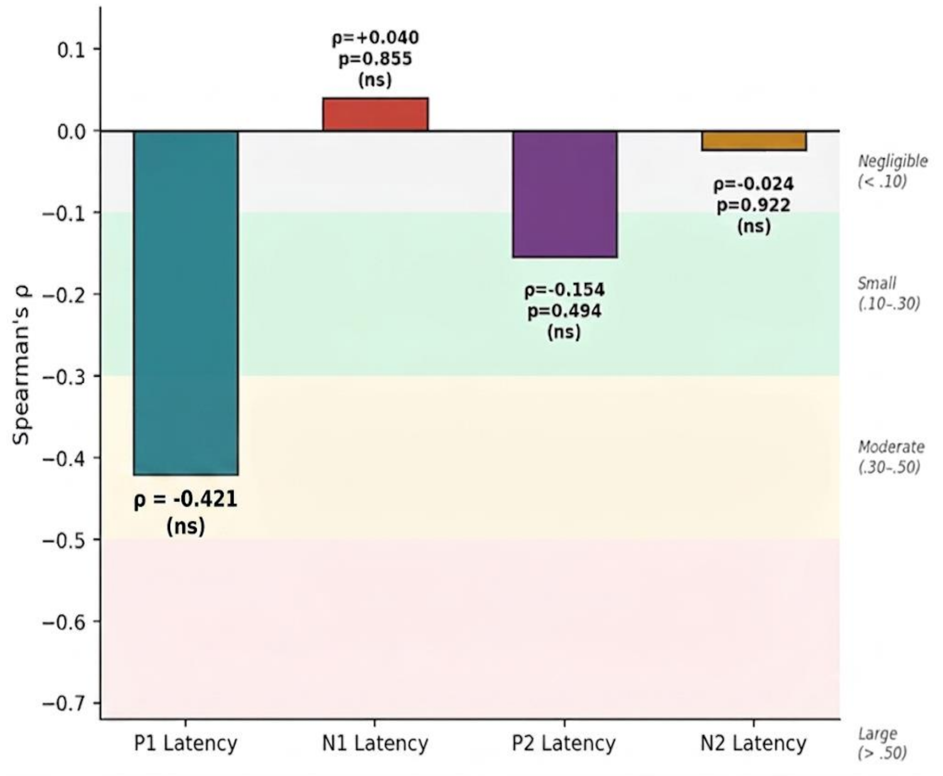


Note: ns = *p>0.05*, effect size bands as per Cohen 1998, n= 23 for all latency variables.

Horizontal bands denote effect size categories (Cohen, 1988). Negative values indicate that longer latencies are associated with lower language age scores. None of the correlations reached statistical significance (all p > 0.05; ns = not significant). The total number of participants for all measures was 23.

Figure 4.4

Spearman correlation coefficients for CI-aided LLR latency variables (P1, N1, P2, N2) and Expressive Language Age (ALD-E).



Note: Horizontal bands denote effect size categories (Cohen, 1988), P1 latency showed the strongest (moderate) negative trend. None of the correlations reached statistical significance (all p > 0.05; ns = not significant), n = 23 for all variables.

3.b) Relationship between LLR Amplitudes with receptive language age (ALD-R) and expressive language age (ALD-E)

Among the amplitudes (P1-N1, N1-P2), the P1-N1 amplitude did not show a statistically significant association with receptive or expressive language. The correlations were weak-to-moderate and negative for receptive language (ρ = −0.281, p = 0.205) and expressive language (ρ = −0.275, p = 0.215). These findings suggest that early cortical response amplitude may not reliably predict language abilities in the present sample

In contrast, N1-P2 amplitude demonstrated statistically significant negative correlations with both receptive and expressive language ages. A negative correlation was observed between N1-P2 amplitude and receptive language (ρ = −0.553, p = 0.011, n = 20; large effect size = 0.55), whereas a moderate negative correlation was found with expressive language (ρ = −0.465, p = 0.039, n = 20; moderate effect size = 0.47). These findings indicate that participants with larger N1-P2 amplitudes tended to exhibit relatively poorer receptive and expressive language performance. These findings suggest that individuals with larger N1-P2 amplitudes were performing relatively poorly on measures of receptive and expressive language.

Table 4.5 summarizes the Spearman rank-order correlation between CI-aided LLR components and receptive and expressive language ages (ALD-R and ALD-E).

Table 4.5

Spearman Correlation Between LLR Components and Language Outcomes (n = 19-23)

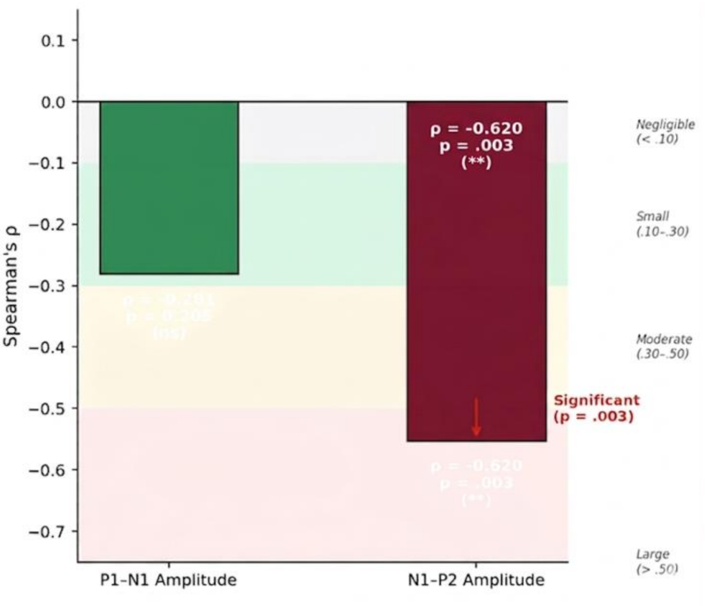
LLR Variable	**ALD-R**			***ALD-E***		
	ρ	***p***	***Effect size***	***ρ***	***p***	***Effect size***
P1 Latency	–0.303	0.160	-	–0.343	0.109	-
N1 Latency	0.110	0.617	-	0.040	0.855	-
P2 Latency	–0.220	0.324	-	–0.154	0.494	-
N2 Latency	–0.147	0.548	-	–0.024	0.922	-

P1-N1 Amplitude	–0.281	0.205	-	–0.275	0.215	-
N1-P2 Amplitude	–0.553*	0.011	Large	–0.465*	0.039	Moderate

**Note:* ρ = Spearman rho; p < 0.05; n varied across analyses due to absent waveform components in certain participants, ALD-R = Receptive Language Age; ALD-E = Expressive Language Age; *= Significant at 0.05.

Figure 4.5

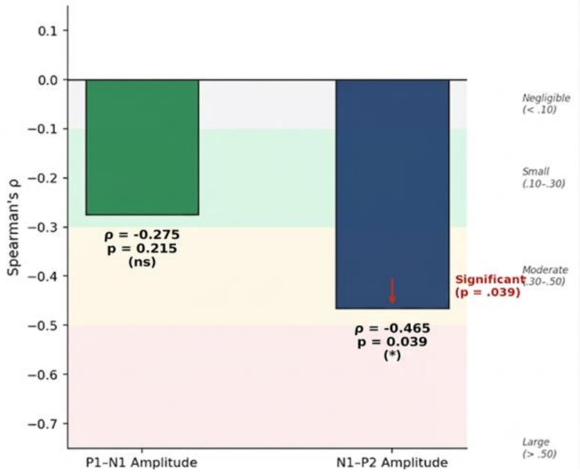
Spearman correlation coefficients for CI-aided LLR amplitude variables (P1-N1 and N1-P2) and Receptive Language Age (ALD-R).



Note: N1-P2 amplitude showed a statistically significant large negative correlation (ρ = −0.553, p = 0.011), Horizontal bands denote effect size categories (Cohen, 1988), * p < 0.05; n = 22 for P1-N1; n = 20 for N1-P2

Figure 4.6

Spearman correlation coefficients for CI-aided LLR amplitude variables (P1-N1 and N1-P2) and Expressive Language Age (ALD-E).



*Note: N*1-P2 amplitude showed a statistically significant moderate negative correlation (ρ = −0.465, p = 0.039). Horizontal bands denote effect size categories (Cohen, 1988), * $p < 0.05$; n = 22 for P1-N1; n = 20 for N1-P2

4) **Relationship Between CI Aided LLR Components and Speech Identification Scores**

The fourth objective examined whether aided LLR components were associated with speech identification performance on the PB word test. Spearman's rank order correlations were computed between each of the six CI-aided LLR measures (P1, N1, P2, and N2) latencies, and (P1-N1, N1-P2) amplitudes and speech identification scores (SIS). Table 4.6 shows the Spearman correlations between each LLR variable and speech identification scores.

Table 4.6

Spearman Correlations Between LLR Components and speech identification scores (n = 19-23)

LLR Variable	*ρ* with SIS	*p*-value	N	Significance	Effect Size

P1 Latency	−0.754**	< 0.001	23	Significant	Large
N1 Latency	−0.387	0.068	23	Not significant	-
P2 Latency	−0.216	0.335	22	Not significant	-
N2 Latency	−0.209	0.390	19	Not significant	-
P1-N1 Amplitude	−0.004	0.985	22	Not significant	-
N1-P2 Amplitude	−0.147	0.535	20	Not significant	-

Note: ρ = Spearman's rho. ** $p < 0.01$, 'n' varied across LLR variables (range: 19–23) due to absent waveform components in certain participants, Effect sizes based on $|\rho|$: negligible < 0.10, small = 0.10–0.29, moderate = 0.30–0.49, large ≥ 0.50 (Cohen, 1988), SIS = Speech Identification Scores.

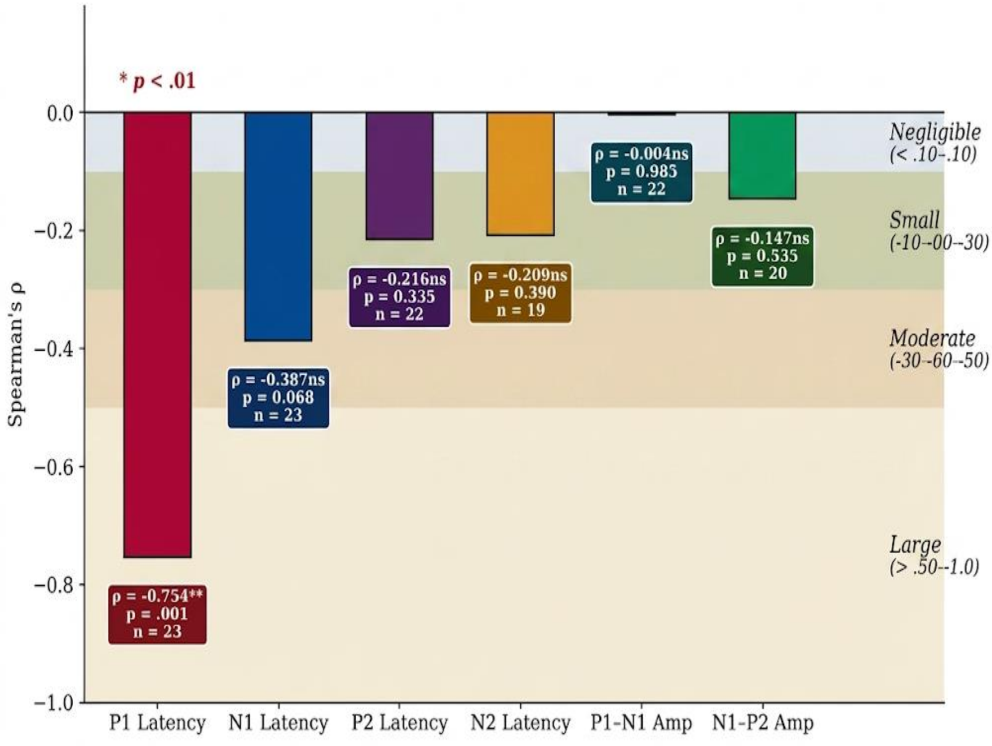
Among all the LLR variables, P1 latency showed a strong and statistically significant negative correlation with speech identification scores (ρ = –0.754, $p < 0.001$, n = 23, effect size: 0.754, large). Participants with longer P1 latencies tended to have lower speech identification scores. The present finding indicates that a delay in cortical auditory maturation was associated with a lower performance in speech perception in the present sample.

A moderate negative correlation was found between N1 latency and speech identification scores (ρ = –0.387, p = 0.068). However, the relationship was not statistically significant.

Other latency variables, P2 and N2 latencies, showed only small and non-significant correlations with speech identification scores. Similarly, amplitude measures of P1-N1 amplitude and N1-P2 amplitude did not correlate significantly with speech identification performance.

Figure 4.7

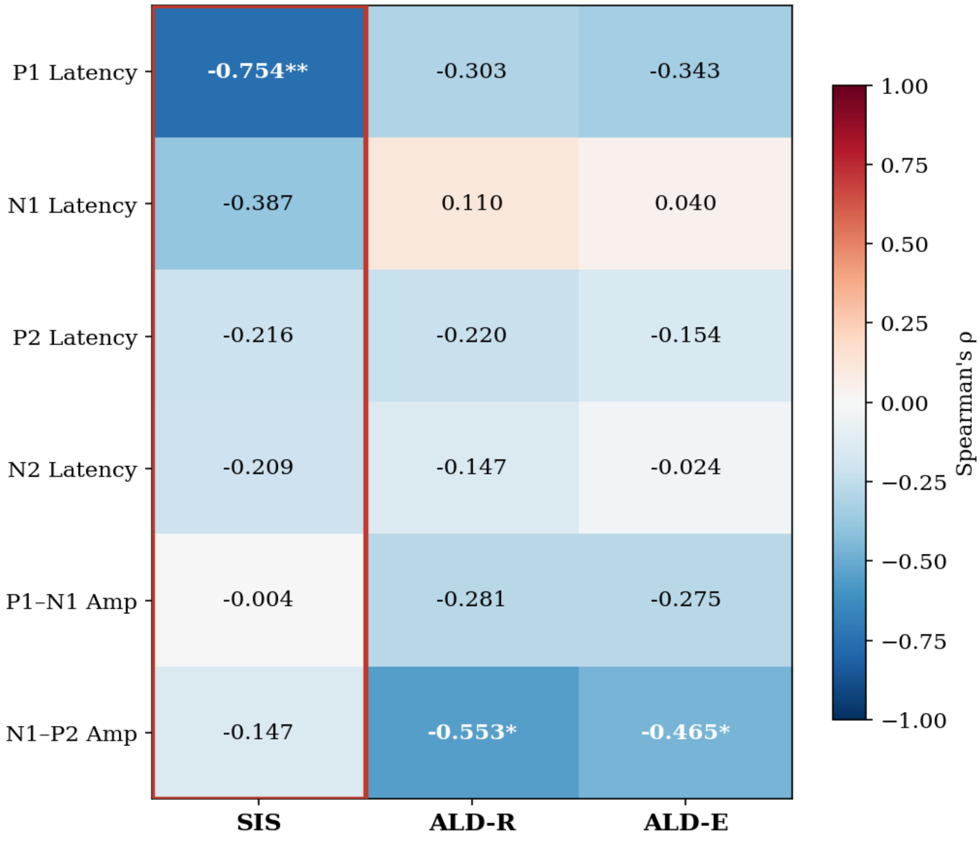
*Spearman Correlation Coefficients Between CI-Aided LLR Components and Speech Identification Scores (SIS). Horizontal background bands denote effect size categories based on Cohen (1988). P1 latency was the only variable to reach statistical significance (**p < 0.01).*



Note: ns = not significant (p>.05); **p<0.05; **p<0.01. Effect* size bands based on Cohen (1988); n varies across LLR variables

Figure 4.8

*Spearman Correlation Heatmap between CI-Aided LLR Components and Outcome variables. Colour intensity reflects the magnitude of ρ; red = negative correlation, blue = positive. The red border highlights the SIS column (focus of the current section, 4.6). Significant correlations are marked: * p < 0.05; ** p < 0.01, n = 19-23 across analyses*



Note: Significance Levels. * $p < 0.05$; ** $p < 0.01$, SIS Highlights: The red border highlights correlations for the current section (SIS), n varied across analyses (19–23) due to absent waveform components.

5) Relationship between Acoustically Evoked Stapedial Reflex thresholds and Aided LLR Components

The fifth objective investigated the relationship between CI-aided acoustic stapedial reflex (ASR) threshold and aided late latency response (LLR) components. Spearman rank order correlation was performed between CI-aided ASR threshold and all 6 LLR measures, including P1, N1, P2, and N2 latencies and P1-N1 and N1-P2 amplitudes. Table 4.7 shows the correlations between ASR threshold and LLR variables.

There were no significant correlations between CI-aided ASR threshold and LLR components. P1 latency had the strongest positive correlation with ASR threshold ($\rho = 0.260$, $p = 0.231$), followed by N1 latency ($\rho = 0.196$, $p = 0.371$). However, these associations were not statistically significant. The correlations between ASR threshold and P2 and N2 latencies were weak and non-significant.

Similarly, the LLR amplitude measures were not correlated with CI-aided ASR threshold. P1-N1 amplitude was weakly positively correlated ($\rho = 0.138$, p = 0.539), and N1-P2 amplitude was weakly negatively correlated ($\rho = -0.060$, p = 0.802). Overall, findings indicated that the CI-aided ASR threshold was not significantly related to any of the aided LLR components.

Table 4.7

Spearman Correlations Between CI-Aided ASR Threshold and LLR Components (N = 19–23)

LLR Variable	*ρ with ASR Threshold*	*p-value*	*n*	*Significance*
P1 Latency	0.260	0.231	23	Not significant
N1 Latency	0.196	-0.371	23	Not significant
P2 Latency	0.139	0.537	22	Not significant

N2 Latency	–0.100	0.683	19	Not significant
P1–N1 Amplitude	0.138	0.539	22	Not significant
N1–P2 Amplitude	–0.060	0.802	20	Not significant

Note. ρ = Spearman's rho; 'n' varied across analyses due to absent waveform components in certain participants. CI-aided ASR threshold = Cochlear implant-aided acoustic stapedial reflex threshold.

6) Predictors of Outcomes from Acoustically evoked stapedial reflex thresholds and Aided Late latency measures

6.1 Predicting SIS score from ASR thresholds and Aided LLR measures

As a significant correlation was present between P1 latency and SIS scores, multiple linear regression analysis was performed to further explore this relationship. During the analysis, aided audiogram thresholds, along with SIS, showed significant correlation.

SIS scores as the dependent variable and P1 latency and aided audiogram threshold as the independent variables. The regression model was significant statistically [$F(2, 20) = 16.614$, $p < 0.001$, $R^2 = 0.624$, Adjusted $R^2 = 0.587$], indicating that the two predictors together explained approximately 62% of the variance in speech identification performance.

Both aided audiogram threshold and P1 latency emerged as significant independent predictors of SIS scores. The aided audiogram threshold was a significant negative predictor of SIS scores ($B = -0.497$, $SE = 0.172$, $\beta = -0.462$, $t = -2.889$, $p = 0.009$). This finding is consistent with the principle that increased aided audibility (better thresholds) is directly correlated with improved speech perception in CI users (Niparko et al., 2010).

P1 latency was also a significant negative predictor ($B = -0.097$, $SE = 0.035$, $\beta = -0.446$, $t = -2.793$, $p = 0.011$), consistent with the view of Campbell et al. (2011) that P1 latency is a measurable index of the readiness of the central auditory system to process incoming speech.

These findings suggested that both aided hearing sensitivity and cortical auditory maturation contribute to speech identification performance in paediatric cochlear implant users.

Functional audibility is one of the most consistently reported predictors of speech perception in paediatric CI users, with better aided thresholds associated with higher word recognition scores in multiple cohorts (Geers et al., 2003; Blamey et al., 2013), so the aided audiogram threshold was included. P1 latency was chosen because it reflects the maturational state of the central auditory pathway following implantation (Sharma et al., 2002), and shorter latencies have been specifically linked to better speech perception outcomes in children with cochlear implants (Xiong et al., 2022).

Shorter P1 latencies were similarly associated with better language and perceptual performance (Frånlund et al., 2024), and P1 latency was shown to be a significant predictor of speech outcomes in cochlear-implanted children (Xiong et al., 2022). SIS scores were plotted against P1 latency, indicating a negative trend, such that higher P1 latencies were typically associated with lower speech identification scores, thus providing a preliminary visual basis for the regression analysis.

The standardized beta coefficients for both predictors were comparable in magnitude (–0.462 and –0.446, respectively), suggesting roughly equivalent relative contributions to the prediction of speech identification performance. The regression coefficients are summarized in Table 4.8.

Table 4.8

Predictors of SIS Scores, n=23

Predictor	***B (Unstd.)***	***Std. Error***	***Beta (Std.)***	***t***	***p-value***
Constant	116.468	4.071	—	28.607	0.000
Aided Audiogram	-0.497	0.172	- 0.462	-2.889	0.009
P1 Latency	-0.097	0.035	- 0.446	-2.793	0.011

Note: Dependent variable: SIS Scores = 0.790, $R^2 = 0.624$, Adjusted $R^2 = 0.587$, $F (2, 20) = 16.614$, $p < 0.001$. Unstd. = Unstandardised; Std. = Standardised; SE = Standard Error;

The regression equation obtained was:

SIS = 116.468 - 0.497(CI aided PTA4) - 0.097(P1 latency).

For an example, a participant with an CI aided PTA4 is 25 dB HL and a P1 latency of 120 ms. Inserting these values into the equation:

$$SIS = 116.468 - 0.497(25) - 0.097(120)$$

$$= 116.468 - 12.425 - 11.64$$

Therefore, the SIS = 92.40

Hence, the predicted SIS score for this participant was 92.40%. This example demonstrates that lower aided audiogram thresholds and shorter P1 latencies are associated with better speech identification.

These results show that the extent of aided hearing (as measured by audiogram thresholds) and the maturity of cortical auditory processing (as measured by P1 latency) are important and separate predictors of speech identification ability in paediatric cochlear implant users.

6.2 Predicting of Receptive Language (ALD-R) from ASR thresholds and Aided LLR measures

Spearman correlations were calculated between ALD-R and all other variables in the study. The significant negative correlation was obtained between N1-P2 amplitude and ALD-R (ρ = –0.553, *p* = 0.011, effect size: moderate).

Several other variables showed negative directional trends, including aided audiogram threshold (*ρ* = –0.287), ASR level *(ρ* = –0.359), and P1 latency *(ρ* = –0.303), but none reached significance, likely due to limited statistical power with n = 23.

Table 4.9

Spearman Correlations: All Variables with ALD-R (N = 19–23)

Variable	ρ	***p*-value**	**n**	**Interpretation**
ASR Level	-0.359	0.093	23	Not significant
P1 Latency	–0.303	0.160	23	Not significant
N1 Latency	0.110	0.617	23	Not significant
P2 Latency	-0.220	0.324	22	Not significant
N2 Latency	-0.147	0.548	19	Not significant
P1–N1 Amplitude	–0.281	0.205	22	Not significant
N1–P2 Amplitude	–0.553*	0.011	20	Significant (negative)
SIS Scores	0.345	0.107	23	Not significant

Note. ρ = Spearman's rho. * p <0 .05; ** p <0.01. N varies due to missing LLR waveform data for some participants. ALD-R = Receptive Language Age (ALD – Manipal Manual).

The regression equation obtained was:

$$\text{ALD-R} = 25.358 - 1.938(\text{N1-P2}) + 0.842(\text{ALD-E})$$

For an example, a participant with a midpoint N1-P2 amplitude of 1.06 and an ALD-E of 45.60. Inserting these values into the equation:

$$\text{ALD-R} = 25.358 - 1.938(1.06) + 0.842\,(45.60)$$

$$= 25.358 - 2.05428 + 38.3952$$

Predicted ALD-R = 61.70 (approximately).

6.3 Predictors of Expressive Language (ALD-E) from ASR thresholds and Aided LLR measures

A parallel set of Spearman correlations was computed between ALD-E and all study variables. The pattern closely mirrored that seen for ALD-R. The only significant predictors were ALD-R ($\rho = 0.938$, $p < 0.001$) and N1-P2 amplitude ($\rho = -0.465$, $p = 0.039$)

The significant negative correlation between N1-P2 amplitude and ALD-E ($\rho = -0.465$, $p = 0.039$) mirrors the pattern observed for ALD-R. Directionally consistent negative associations were also observed between ALD-E and ASR level ($\rho = -0.339$), P1 latency ($\rho = -0.343$), and aided audiogram threshold ($\rho = -0.351$), though none reached significance. The near-significant trend for P1 latency ($p = 0.109$) aligns with evidence from Strömbergsson et al. (2024) that P1 latency correlates with broader language outcomes in CI children.

The scatter plot of ALD-E against N1-P2 amplitude showed a generally negative pattern with moderate dispersion. A cluster of data points with comparatively large N1-P2 amplitudes at lower ALD-E values was observed, suggesting that children with the most conspicuously large cortical amplitudes were also those with the most delayed expressive language, a pattern that deserves attention in future follow-up assessments.

Table 4.10

Spearman Correlations: All Variables with ALD-E (n = 19–23)

Variable	*ρ*	***p-value***	**n**	**Interpretation**
ASR Level	-0.339	0.114	23	Not significant
P1 Latency	–0.343	0.109	23	Not significant
N1 Latency	0.040	0.855	23	Not significant
P2 Latency	–0.154	0.494	22	Not significant
N2 Latency	-0.024	0.922	19	Not significant
P1–N1 Amplitude	-0.275	0.215	22	Not significant
N1–P2 Amplitude	–0.465*	0.039	20	Significant
SIS Scores	0.334	0.120	23	Not significant
ALD-R	0.938**	0.000	23	Significant

Note: ρ = Spearman's rho, * $p < .005$; ** $p < 0.01$. n varies due to missing LLR waveform data. ALD-E = Expressive Language Age (ALD—Manipal Manual).

The regression equation obtained was:

$$\text{ALD-E} = -6.281 + 0.803(\text{N1-P2}) + 0.857(\text{ALD-R})$$

For an example, a participant with a midpoint N1-P2 amplitude of 1.06 and an ALD-R of 66. Inserting these values into the equation:

$$\text{ALD-E} = -6.281 + 0.803(1.06) + 0.857(66)$$

$$= -6.281 + 0.85118 + 56.562$$

Predicted ALD-E = 51.13 (approximately).

Figure 4.9

Depicts the overall correlation of outcomes with Acoustically evoked stapedial reflex thresholds and Aided Late latency measures

Note: Heatmap showing Spearman's correlation coefficients (ρ) between objective measures and clinical outcome measures (SIS, ALD-R, and ALD-E). Blue shades represent negative correlations, red shades represent positive correlations, and color intensity indicates the strength of the correlation.

7) Test-retest reliability

Test-retest reliability was assessed by administering the audiological measures. Seven were selected out of 23 participants. The dependent variables for audiological measures were analyzed across two sessions. The test-retest reliability of all the audiological measures was determined using the Spearman rank correlation coefficient as the primary measure; the intraclass correlation coefficient (ICC) and Cronbach's alpha were also computed.

The average-measures intraclass correlation coefficient was 0.798, indicating good reliability for the aggregated measures. Spearman's rank-order correlation analysis was performed separately for each variable pair to determine the degree of association between test and retest scores. Most variables demonstrated good to excellent reliability. ASR threshold levels, P1 latency, SIS scores, ALD showed excellent reliability with correlation coefficients approaching 1.00 ($p < 0.001$), N2 latency and P1-N1 amplitude demonstrated very good reliability; even N1 latency and N1-P2 amplitude showed good reliability. Table 4.11 gives a detailed correlation of all the variables.

Table 4.11

Spearman Test-Retest Correlations for Individual Variables

Variable	**Spearman correlation *ρ***	***p-value***	**Interpretation**
ASR Threshold Level	~1.000	< 0.001	Excellent
P1 Latency	0.991	< 0.001	Excellent
N1 Latency	0.857	0.014	Good
P2 Latency	0.750	0.052	Marginal
N2 Latency	0.893	0.007	Very Good
P1–N1 Amplitude	0.929	0.003	Very Good
N1–P2 Amplitude	0.786	0.036	Good
SIS	0.939	< 0.001	Excellent
ALD-*R*	~1.000	< 0.001	Excellent
ALD-*E*	~1.000	< 0.001	Excellent

Note: Spearman's rho *(ρ)* was used because of the small sample size and non-normal data distribution.

The present study investigated the relationship between acoustically evoked stapedial reflex (ASR) thresholds, aided late latency response (LLR) measures, and speech-language outcomes in paediatric cochlear implant users. The findings revealed that ASR thresholds were not significantly associated with speech identification scores, receptive language age, expressive language age, or aided LLR measures. Although some moderate negative trends were observed, ASR thresholds did not emerge as reliable indicators of speech perception, language development, or cortical auditory processing outcomes in the present sample.

In contrast, aided LLR measures demonstrated meaningful associations with functional outcomes. Among the LLR variables, N1-P2 amplitude was significantly associated with both receptive and expressive language outcomes, while P1 latency showed a strong negative association with speech identification performance. These findings suggest that cortical auditory processing measures may be more sensitive to variations in speech and language abilities than brainstem-level reflex measures in paediatric cochlear implant users.

Regression analyses further highlighted the importance of aided auditory and cortical measures in predicting speech outcomes. CI aided PTA4 and P1 latency together accounted for 62.4% of the variance in speech identification scores, indicating that both peripheral audibility and cortical auditory maturation contribute substantially to speech perception performance. Overall, the findings support the clinical value of aided LLR measures, particularly P1 latency and N1-P2 amplitude, as objective indicators of speech and language outcomes following cochlear implantation.

Table 4.12

Summary of Major Findings

Domain	**Finding**	**Interpretation**
ASR Threshold vs. receptive language age & expressive language age	No significant relationship with ALD-R or ALD-E	ASR thresholds were not associated with receptive or expressive language outcomes

ASR Threshold vs. Speech Identification	No significant relationship with SIS	ASR thresholds were not associated with speech perception performance
ASR Threshold vs. Aided LLR Measures	No significant correlations	ASR thresholds were not related to cortical auditory response measures
LLR Measures and Language Outcomes	N1–P2 amplitude significantly correlated with ALD-R ($\rho = -0.553$) and ALD-E ($\rho = -0.465$)	Larger N1–P2 amplitudes suggested less efficient cortical auditory processing and reduced language performance in the present sample
LLR Measures and Speech Identification	P1 latency significantly correlated with SIS ($\rho = -0.754$)	Longer P1 latencies were associated with poorer speech identification performance
Predictors of SIS	CI-Aided PTA4 and P1 latency	Both peripheral audibility and cortical auditory maturation significantly predicted speech identification scores
Predictors of Language Outcomes	N1–P2 amplitude	N1–P2 amplitude emerged as the primary electrophysiological correlate of receptive and expressive language outcomes
Test–Retest Reliability	Good to excellent reliability across measures	Audiological and language measures demonstrated acceptable measurement stability

The Table 4.12 summarizes the findings of the study; these findings will be discussed in the next chapter.

Chapter 5

DISCUSSION

This study aimed to investigate the relationship between acoustic stapedial reflex (ASR) thresholds and aided late latency responses (LLR) with speech and language outcomes in paediatric cochlear implant (CI) users. The participants underwent audiological assessments i.e., case history, otoscopy, and tympanometry as part of the inclusion criteria. The average chronological age of the participants was 81.10 months (*SD* = 16.08) and the average age at cochlear implantation was 27.74 months (*SD* = 15.19). The audiological measures to evaluate the objectives of the study included objective measures (i.e., acoustic stapedial reflex testing, CI aided LLR testing) and behavioural outcome measures [i.e., CI aided thresholds, Assessment of Language Development - Manipal Manual *(*ALD-MM), Speech Identification Scores].

Niparko et al. (2010) observed rapid language development in comprehension and expression in a large multicentric longitudinal investigation of children who were implanted at a younger age in comparison to those who were implanted later. The researchers found that children who received cochlear implants at about 18 months of age had the most rapid rates of language growth, while children implanted at progressively later ages had correspondingly slower rates of language acquisition. In the present study, the mean age at implantation of approximately 27.74 months falls within the range examined in that study and aligns with the observation that earlier implantation yields better language outcomes.

Ruben (2018) emphasized the importance of the sensitive period for language development, stating that the best results in the development of cortical auditory circuits and therefore, the best results for language are achieved when implantation is ideally done before 12 to 24 months of age. The findings of Hammes et al. (2002) and Ching et al. (2009) revealed that children who received early implantation before 12 months of age could achieve language development comparable to their normal-hearing peers, provided that early implantation was coupled with consistent use of the device and intensive habilitation. The participants of the present study represented a wide range of ages at implantation from at least one year to six years of implant age. This variability in age at implantation likely contributed to some of the inter-individual differences observed in both aided late latency potentials and language outcomes across the sample.

The average CI aided PTA4 was calculated using the pure tone average of four frequencies (PTA4) in the present study, which was 21.58 dB HL (SD = 6.36), and it indicated that the cochlear implant provided sufficient access to speech sounds. Within the group, acoustic stapedial reflex (ASR) thresholds were quite uniform, with an average threshold of 68.95 dB SPL. The homogeneity of ASR thresholds may be due to the consistency of the stimulus presentation protocol that had a synthetic /da/ stimulus, which was presented in the sound field with participants' own CI speech processors. Methodological support for this approach was provided by Franke-Trieger et al. (2021), who showed that free-field ASR measurements can be reliably recorded in CI users and systematically associated with CI MAP parameters, thus validating the free-field paradigm as a meaningful measure of auditory processing in paediatric CI users.

The average speech identification score (SIS) was 94.74 (*SD* = 6.40; median = 96), thus reflecting generally strong speech identification across the participant group. However, these high scores also showed a prominent ceiling effect as the majority of participants scored near maximum scores on the test. Language outcomes indicated considerably greater variability. For receptive language (ALD-R), the average age was 53.74 months (*SD* = 17.04), and for expressive language (ALD-E), it was 43.34 months (*SD* = 15.75), both of which were below the group's average chronological age of 81.10 months. The average implant age was 27.74 months. These findings indicated that, despite of achieving adequate auditory access and speech recognition through cochlear implantation, majority of participants had not attained age-appropriate language development at the time of testing, i.e., at an average of 27.74 months after implantation. This pattern is in accordance with the findings of Ruben (2018), who emphasized that cochlear implantation alone does not ensure normal language development, as the results depend on a complex interaction of factors including pre-implant auditory deprivation, neural plasticity, consistency of device use and quality of habilitation, richness of the home language environment, and the cognitive profile of the child. The large discrepancy between speech identification scores and language seen in the present study also support this view.

The language outcomes were not normally distributed and exhibited considerable inter-individual variability; hence Spearman rank-order correlation was adopted as the primary statistical method, aligned with the approaches taken by Frånlund et al. (2024) and Sahana and Manjula (2024), who similarly reported substantial inter-individual variability in language outcomes despite comparable auditory access across their respective samples of children with cochlear implants.

Relationship Between Acoustically Evoked Stapedial Reflex Thresholds and Receptive and Expressive language

The first objective of the present study was to examine the relationship between acoustically evoked stapedial reflex thresholds and receptive and expressive language outcomes in children with cochlear implants. Spearman's rank-order correlation analysis revealed non-significant negative correlations between ASR threshold and both receptive language age and expressive language age. Although these correlations did not reach statistical significance, the negative trend consistently indicated that children with higher aided ASR thresholds tended to demonstrate comparatively lower language age.

There are very few studies that have directly explored the relationship between free-field CI-aided ASR thresholds and standardized language outcomes. Thus, making the present study an attempt to investigate this association for additional evidence. Franke-Trieger et al. (2021) had reported that free-field ASR thresholds in cochlear implant users are related to cochlear implant MAP settings and reflect loudness processing through the implant system. Later, Franke-Trieger et al. (2024) suggested that appropriately optimized MAP settings could be validated using ASR measurements and may provide improved auditory input for language learning. However, the relationship between ASR thresholds and language development is indirect and influenced by several additional factors such as age at implantation, duration of implant use, therapy, cognitive abilities, and home language environment. This may explain the absence of statistically significant correlations in the present study.

In the present study, there is a narrow distribution of aided ASR thresholds observed across participants (IQR = 5 dB). Limited variability in a predictor variable could reduce the strength of observable correlations, even if a true relationship may exist in the population. Most children in the present study appeared to have stable cochlear implant MAP settings. Therefore, the reduced spread of ASR thresholds may have limited the ability to detect significant associations with language outcomes. In addition, the relatively small sample size (n = 23) may have further reduced statistical power, despite the presence of modest negative correlations.

Relationship Between Acoustically Evoked Stapedial Reflex Thresholds and Speech Identification Scores

The acoustically evoked stapedial reflex thresholds were not significantly related to speech identification performance, i.e., SIS scores. There was a negative correlation which suggested that higher thresholds for ASR were related to lower speech identification scores, although the relationship was not statistically significant.

These results conform with the findings reported by Franke-Trieger et al. (2024) and Tavartkiladze and Bakhshinyan (2025). They reported non-significant correlations between ASR thresholds and language outcomes and indicated the indirect role of ASR thresholds in speech outcomes. The ceiling effect in SIS scores (mean = 94.74%, median = 96%) likely attenuated any possible correlation with ASR threshold, as the limited range of speech identification scores would decrease the likelihood of identifying a statistically significant association.

Relationship Between CI-Aided LLR Latencies and Receptive and Expressive language

Spearman correlations between the late latency responses (LLR) latency variables (P1, N1, P2, N2) and both receptive and expressive language were non-significant. Among the latency measures, P1 latency showed the strongest, albeit non-significant, negative associations with ALD-R and ALD-E, suggesting that participants with longer P1 latencies tended to demonstrate lower language levels.

There is substantial evidence in the current literature to support P1 latency as a potential biomarker of cortical auditory maturation. Sharma et al. (2002) provided seminal empirical evidence of a sensitive period for central auditory development in CI children. They found that children implanted before the age of approximately 3.5 years showed rapid normalization of P1 latency to the level of age-matched normal hearing peers within six to eight months of CI activation. Children implanted between 3.5 and 7 years of age demonstrated a partial normalization whereas children implanted after 7 years of age showed persistently prolonged P1 latencies even after long-term use of the implant. These results give a biological time line for cortical plasticity correlating with behavioural language outcomes. Building on this foundation, Campbell et al. (2011) indicated P1 as an objective marker of central auditory maturation that can help differentiate children with age-appropriate development from those with delayed cortical auditory pathways and providing clinical utility in guiding intervention strategies.

More recent studies have confirmed these associations. Xiong et al. (2022) found significant correlations between P1 latency and auditory performance and speech recognition measures in implanted children. This relationship is evidence that P1 latency normalization and functional speech outcomes reflect the same underlying process of central auditory maturation driven by restored auditory experience. Similarly, Frånlund et al. (2024) indicated that shorter P1 latencies were significantly associated with better receptive language and suggested that longitudinal tracking of P1 latency may be an objective measure to monitor language development trajectories. On a different note, Sahana and Manjula (2024) did not observe a significant LLR - language association in their paediatric CI sample, that parallels the non-significant latency correlations observed in the present study.

The LLR latencies (P1, N1, P2, and N2) in the study were not statistically significant for language age, but P1 latency showed a moderate negative trend with both receptive and expressive language age. The P1-N1 amplitude did not show significant correlation with ALD-R and ALD-E. Longer latencies tended to be associated with poorer language, but the evidence was not strong enough to confirm a direct latency-language relation in this cohort.

There have been studies on developmental aspect, wherein changes in LLR waveform with maturation has been reported. In infants, toddlers, children, and adults, the P1/N1/P2 complex shows age-related changes in amplitude and latency, with latencies generally shortening as the auditory system matures (Wunderlich & Cone-Wesson, 2006). In a developmental study of speech-evoked CAEPs from 3 months to 8 years, peak latencies decreased with age, and P1 amplitude showed an age-related change, indicating ongoing cortical maturation (Sharma et al., 2015).

The N1-P2 amplitude was significantly negatively correlated with receptive language and expressive language. This suggests that amplitude, not just latency, may have clinically meaningful information. The result may reflect atypical cortical responsivity. In young children who have not yet developed mature cortical inhibitory interneuron networks, the N1-P2 complex may appear with exaggerated amplitude due to the absence of the inhibitory processes that normally sculpt the waveform into the more refined pattern characteristic of older children and adults.

In the adult auditory evoked potential literature, larger cortical amplitudes are generally interpreted as indicative of robust neural synchrony and stronger cortical activation (Picton, 2011). However, in paediatric CI users, the interpretation of LLR amplitude is more complex. Larger peak-to-peak amplitudes in CI children may reflect an immature cortical response profile characterized by broad, poorly differentiated neural activation, rather than efficient and selective auditory processing (Ponton et al., 2000). Under this framework, larger N1-P2 amplitudes in younger or less auditory-mature CI children would be expected to co-occur with less developed language abilities, precisely the pattern observed in the present study.

The P1-N1 amplitude did not demonstrate a statistically significant correlation with either receptive or expressive language outcomes. These findings are consistent with the pattern reported by Sahana and Manjula (2024), they too did not observe significant association between P1-N1 amplitude and language age in their sample of paediatric CI users.

Relationship between aided late latency response components and speech identification scores

Among all the LLR variables tested for a relationship with speech identification scores, the P1 latency was a significant predictor. The P1 latency had a strong negative correlation with SIS scores. This is the strongest finding of the present study and suggests that the longer the P1 latencies, the lower the speech identification scores. None of the other LLR latency or amplitude measures (N1, P2, and N2 latencies; P1-N1 and N1-P2 amplitudes) were significantly related to speech identification performance.

In the current study, a strong association was found between P1 latency and speech identification, which is in close agreement with the findings of Xiong et al. (2022), who reported that P1 latency was significantly correlated with measures of auditory performance and speech recognition in implanted children. He interpreted this relationship as evidence that P1 latency normalization and functional speech outcomes reflect the same underlying process of central auditory maturation driven by restored auditory experience. Campbell et al. (2011) described P1 as an index of cortical readiness for speech processing. They showed that P1 latency can differentiate children with age-appropriate central auditory development from those with delayed development.

Frånlund et al. (2024) described longitudinal monitoring of P1 latency as an objective tool for tracking language development and identifying children who may benefit from augmented intervention. The magnitude of the correlation observed in the present study supports this clinical proposition and P1 latency could be used in monitoring a linguistically diverse, Kannada-speaking population substantially under-represented in the existing literature.

Sharma et al. (2002) established that P1 latency decreases progressively with age and auditory experience, reflecting the maturation of thalamocortical projections to the primary auditory cortex. In the present cohort, children with shorter P1 latencies, presumably those with more mature auditory cortical pathways had clearly demonstrated superior speech identification.

The N1 latency demonstrated a moderate but non-significant negative correlation with speech identification. The N1 is a component that is dependent on cortical inhibitory interneurons (Sharma et al., 2015) that mature relatively late in paediatric CI users, and its emergence and normalization have been associated with advancing auditory and linguistic competence (Ponton et al., 2000). The non-significance of N1 latency in the present sample may reflect the fact that N1 was absent or poorly defined in several participants. The pattern is consistent with Silva et al. (2017), who found that shorter P1 latency was associated with better auditory discrimination skills in CI children but did not have a consistent pattern for N1.

No significant correlations were found between LLR amplitude and speech identification scores. This is contrary to the findings of Saravanan et al. (2024). They reported that larger amplitudes resulted in better speech recognition in a direct electrical stimulation paradigm. The aided sound-field paradigm involves signal processing changes that may reduce the sensitivity of amplitude relative to direct electrical stimulation, which may account for the differences in LLR amplitude-speech relationships across studies.

Relationship Between Acoustically Evoked Stapedial reflex and LLR Components

The fifth objective investigated a relationship between acoustically evoked stapedial reflex thresholds and LLRs. These measures reflect various levels in the auditory system. ESRT/ASRT reflects brainstem related loudness-related processing and map adequacy, and aided LLR reflects cortical maturation and higher order processing. They are different physiological levels, so a strong direct relationship is not guaranteed. Tavartkiladze and Bakhshinyan (2025) suggested combining stapedius reflex thresholds with cortical monitoring in CI programming and supporting multimodal assessment.

In the present study, none of the LLR components correlated significantly with ASR threshold. This means that a child can have an ASR threshold that seems acceptable without necessarily showing mature cortical processing, and vice versa. Clinically, that supports a multimodal assessment strategy rather than relying on one objective measure to infer the status of the entire auditory pathway. The study results strengthen the argument that objective peripheral and central measures should be interpreted together, not substituted for one another.

Predictors of Outcomes from Acoustically Evoked Stapedial Reflex Thresholds and Aided Late latency measures

a) Predicting SIS score from ASR thresholds and Aided LLR measures

No significant relationship was observed between Acoustic Stapedial Reflex (ASR) thresholds and Speech Identification Scores (SIS), suggesting that ASR thresholds alone may not be a reliable predictor of speech perception outcomes in paediatric cochlear implant users. A multiple linear regression analysis was conducted with SIS as the dependent variable and CI-aided PTA4 and P1 latency as predictors. The model was statistically significant and approximately 62.4% of the variance in speech identification scores and indicating strong combined predictive utility for these two variables. Both predictors provided independent and significant contributions to the model, and their comparable standardized beta weights (−0.462 for CI-aided PTA4 and −0.446 for P1 latency). According to Cohen's (1988) conventional benchmarks for effect size interpretation (0.10 = small, 0.30 = medium, 0.50 = large), both predictors exhibited moderate-to-large effect sizes. This indicated that peripheral auditory access and central auditory maturation are approximately equal contributors to speech identification in paediatric CI users.

The significant negative contribution of CI-aided PTA4 to speech identification scores is consistent with the reports that increased aided audibility is directly associated with improved speech perception in CI users. Niparko et al. (2010) demonstrated that the quality of auditory access provided through the CI is a primary determinant of speech and language outcomes and forms the foundation upon which all higher-order auditory learning is built. The significant negative contribution of P1 latency aligns with the view of Campbell et al. (2011) that P1 latency is a measurable index of the readiness of the central auditory system to process incoming speech. The finding that P1 latency and aided audiogram threshold together account for over 62% of SIS variance emphasizes the importance of both peripheral input quality and central processing maturity in determining functional speech recognition outcomes, an inference that extends and empirically grounds the multimodal assessment framework advocated by Tavartkiladze and Bakhshinyan (2025).

Prediction of Receptive Language (ALD-R) from ASR thresholds and Aided LLR measures

There was an independent and significant negative contribution of N1-P2 amplitude to the prediction of ALD-R. The N1-P2 amplitude carries unique electrophysiological information about receptive language development but not for expressive language performance. This could be explained by the immaturity of cortical inhibitory processes in younger children. Lamminmäki et al. (2023) reported a close association between maturation of the auditory cortex and language development in children with varying degrees of hearing loss, supporting the inference that atypical LLR amplitude profiles are indicative of a stage of auditory cortical development that is not yet fully conductive to mature language comprehension. In younger children with less mature cortical inhibitory networks, the N1-P2 complex remains ‘exaggerated’ in amplitude, reflecting less efficient cortical refinement of auditory input, which in turn may constrain receptive language development. Other variables including ASR threshold and P1 latency, showed negative trends but did not reach significance. The present findings extend this line of reasoning to the specific context of free-field aided LLR recording in Kannada-speaking paediatric CI users.

b) Prediction of Expressive Language (ALD-E) from ASR thresholds and Aided LLR measures

In the regression and correlation analyses for predicting expressive language age, N1-P2 amplitude again emerged as the only statistically significant LLR-related correlate. The relationship was negative ($\rho = -0.465$, $p = 0.039$), and the effect size was moderate, consistent with the pattern observed for receptive language. This suggests that the same underlying cortical maturation mechanism reflected in the N1-P2 complex is implicated in both domains of language development. The P1 latency showed a near-significant negative trend in the prediction of expressive language and is directionally consistent with the literature reviewed by Frånlund et al. (2024) but was not statistically significant in the present sample, likely due to limited statistical power. The convergent results of N1-P2 amplitude as a significant predictor of both receptive and expressive language in the present study, taken together with its non-significant association with speech identification scores, suggests that this amplitude measure may be particularly sensitive to the higher-order cognitive-linguistic aspects of language processing, rather than to the more peripheral speech perception abilities tapped by the SIS test. This distinction has potential clinical relevance and warrants further investigation with larger, longitudinally followed samples.

Table 5.1

Summary of Findings and Status of Null Hypothesis

<table>
<tr><th>Objective No.</th><th colspan="2">Objectives & Findings</th><th>Status of Null Hypothesis</th></tr>
<tr><td rowspan="4">Objective 1</td><td colspan="3">Comparison of ASR thresholds with Language Outcomes</td></tr>
<tr><td>ASR Threshold & ALD-R</td><td>Not Significant</td><td rowspan="2">Accepted</td></tr>
<tr><td>ASR Threshold & ALD-E</td><td>Not Significant</td></tr>
<tr><td colspan="3">i.e., ASR thresholds not significantly related to language outcomes</td></tr>
<tr><td rowspan="3">Objective 2</td><td colspan="3">Comparison of ASR thresholds with Speech Identification Score (SIS)</td></tr>
<tr><td>ASR Threshold & SIS</td><td>Not Significant</td><td>Accepted</td></tr>
<tr><td colspan="3">i.e., ASR thresholds not significantly associated with SIS</td></tr>
<tr><td rowspan="6">Objective 3</td><td colspan="3">Comparison of CI-Aided LLR components with Language Outcomes</td></tr>
<tr><td>Latencies of P1, N1, P2, N2 & ALD-R</td><td>Not Significant</td><td rowspan="6">Partially Rejected</td></tr>
<tr><td>Latencies of P1, N1, P2, N2 & ALD-E</td><td>Not Significant</td></tr>
<tr><td>P1-N1 Amplitude & ALD-R</td><td>Not Significant</td></tr>
<tr><td>P1-N1 Amplitude & ALD-E</td><td>Not Significant</td></tr>
<tr><td>N1-P2 Amplitude & ALD-R</td><td>Significant</td></tr>
<tr><td></td><td>N1-P2 Amplitude & ALD-E</td><td>Significant</td></tr>
<tr><td></td><td colspan="3">i.e., Only N1-P2 amplitude significantly correlated with both receptive and expressive language outcomes with effect size = 0.55 (large) for ALD-R and effect size = 0.47 (moderate) for ALD-E.</td></tr>
<tr><td>Objective 4</td><td colspan="3">Comparison of CI-Aided LLR components with Speech Identification Scores (SIS)</td></tr>
</table>

	P1 Latency & SIS	Significant	**Partially Rejected**
	N1, P2, N2 Latencies & SIS	Not Significant	
	P1-N1 Amplitude & SIS	Not Significant	
	N1-P2 Amplitude & SIS	Not Significant	
	i.e., P1 latency significantly and negatively correlated with SIS with Effect size = 0.754 (large).		
Objective 5	**Relationship between ASR thresholds and CI-Aided LLR components**		
	ASR Threshold & P1, N1, P2, N2 Latencies	Not Significant	**Accepted**
	ASR Threshold & P1-N1 & N1-P2 Amplitudes	Not Significant	
	i.e., ASR thresholds not significantly related to any LLR components		
Objective 6	**Prediction of Speech and Language Outcomes from Aided LLR measures (Multiple Regression)**		
	Variables	**Prediction formula**	**Partially Reject**
	SIS from CI Aided PTA4 and P1 latency	SIS = 116.468 - 0.497(CI aided PTA4) - 0.097(P1 latency).	
	ALD-R (Receptive Language) from N1-P2 Amplitude	ALD-R = 25.358 - 1.938(N1-P2) + 0.842(ALD-E)	
	ALD-E (Expressive Language) from N1-P2 Amplitude	ALD-E= -6.281+0.803(N1-P2) +0.857(ALD-R)	

	i.e., 1. CI-aided PTA4 and P1 latency predict SIS; *2. N1-P2 amplitude predicts both receptive and expressive language*

The combined results from the six objectives suggest that acoustic stapedial reflex (ASR) thresholds were not significantly related to any of the outcome measures evaluated, including receptive language (ALD-R), expressive language (ALD-E), speech identification scores (SIS), or any component of the cortical late latency response (LLR). Consequently, the null hypotheses 1, 2, and 5 were fully accepted, indicating that ASR thresholds may not be an independent predictor of functional speech and language outcomes in this population.

Aided LLR components had selective relationships with outcome measures, resulting in partial rejection of the null hypotheses 3 and 4. Among the LLR components, only N1-P2 amplitude was significantly correlated with receptive and expressive language outcomes with large and moderate effect sizes respectively. Further, P1 latency was also found to be significantly and negatively correlated with speech identification scores, with a large effect size. This implies that shorter P1 latencies were associated with better speech recognition performance. The other latency and amplitude components (N1, P2, N2 latencies; P1-N1 amplitude) did not reach statistical significance for any outcome.

The multiple regression analysis (Objective 6) further supported these findings, explaining 62.4% of the variance in SIS with a model that included CI-aided PTA4 and P1 latency as significant predictors. Regression analysis revealed N1-P2 amplitude as the only significant predictor of receptive and expressive language outcomes.

Chapter 6

SUMMARY & CONCLUSIONS

The present study examined the relationships between acoustically evoked stapedial reflex (ASR) thresholds, CI-aided late latency responses (LLR) with speech and language outcomes in 23 paediatric cochlear implant users. The average chronological age of the participants was 81.10 months and the average age at implantation of 27.74 months. The objective measures included sound-field ASR testing and aided LLR recording, while behavioural outcome measures consisted of CI aided audiogram thresholds, speech identification scores (SIS), receptive (ALD-R) and expressive (ALD-E) language age as estimated using the ALD-MM tool.

The ASR thresholds showed negative trends that were not significant for language outcomes and SIS. The most robust finding of the study was the significant negative correlation of P1 latency with SIS. Only N1-P2 amplitude was significantly related to both receptive and expressive language outcomes. There were no significant relationships between ASR thresholds and any component of LLR, confirming that peripheral and central auditory measures reflect different dimensions of auditory functioning. Multiple regression analyses showed that the CI aided audiogram threshold and P1 latency explained approximately 62.4% of the variance in SIS, whereas the N1-P2 amplitude was an independent predictor of both receptive and expressive language domains.

Based on the findings of the present study, the following inferences are drawn:

1. ASR thresholds did not significantly predict speech identification scores or language outcomes in paediatric CI users. The restricted range of ASR thresholds and ceiling effects in SIS likely limited the detectability of these associations. The negative

directional trends observed in the study warrant further investigation with larger and more diverse samples.

2. The P1 latency of the aided LLR is the strongest electrophysiological predictor of speech identification performance, with shorter P1 latencies reflecting more mature thalamocortical auditory pathways and significantly better speech recognition. This reaffirms P1 latency as a clinically meaningful biomarker of central auditory maturation in paediatric CI users.

3. The N1-P2 amplitude of the aided LLR emerged as a significant electrophysiological correlate of both receptive and expressive language outcomes, with large and moderate effect sizes respectively. It was confirmed that N1-P2 was an independent predictor of language outcome in the regression model. N1-P2 amplitude was not significantly associated with speech identification performance. These findings indicate that N1-P2 amplitude may serve as a clinically valuable biomarker of language-relevant cortical maturation in paediatric CI users.

Future Directions

Future research should focus on studies with larger sample sizes to improve statistical power and enable control of other covariates such as age at implantation, duration of CI use, etiology and cognitive abilities. Longitudinal designs are particularly needed to track the maturation of P1 latency and N1-P2 amplitude over time, and to determine whether these measures can be used as early prognostic indicators of speech and language outcomes in individual CI users.

Further, translating the present correlated findings into clinically actionable protocols would be studying the relationship between ASR thresholds and CI MAP parameters across a broader range of programming settings and intervention studies that test whether LLR-guided habilitation improves language outcomes.

Clinical Implications

The current findings have several direct clinical implications. First, the P1 latency of LLR should be adopted as a routine objective monitoring tool in paediatric CI clinics. It is a non-behavioural index of cortical auditory readiness, strongly associated with SIS and can be used at all post-implant follow-ups, even in very young or minimally cooperative children. Serial P1 latency measurements may help detect children with delayed central auditory maturation and initiate timely intervention.

Second, the LLR amplitudes could be routinely considered in addition to latency when interpreting aided LLR in clinical settings. The strong correlation with the receptive and expressive language results may indicate that the relatively large amplitudes are markers of incomplete maturation of cortical inhibition, which may limit the language development. Such children should be monitored more closely and receive more intensive habilitation and other forms of communication.

Third, as ASR thresholds and LLR measures reflect different aspects of auditory functioning, a multimodal assessment approach that includes both peripheral and cortical objective measures is warranted. Reliance on either measure in isolation risks missing clinically significant information about MAP adequacy or cortical maturation as neither measure alone adequately characterizes the full auditory pathway.

Fourth, the gap between speech perception and language outcomes in this sample highlights the need for standardized language monitoring as a routine part of pediatric CI follow-up. High SIS scores should not be interpreted as evidence that language development is on track. Children with poor language in the presence of good speech identification should be referred for intensive speech-language habilitation, family counselling, and, if indicated, cognitive assessment. Clinicians working in India and similar linguistically diverse settings should also be cautious about using normative LLR data from the West and should focus on longitudinal intra-individual tracking rather than cross-sectional comparisons with external norms until region-specific standards are developed.

References

American National Standards Institute. (2013). *ANSI S3.1-1999 (R2013): Maximum permissible ambient noise levels for audiometric test rooms.* ANSI.

Andrade, K. C. L., Filho, O. A. C., Bento, R. F., & Bevilacqua, M. C. (2014). A literature review of electrically evoked stapedial reflex: Parameter measures and clinical applications. *Cochlear Implants International*, *15*(1), 1–8.

Bakhos, D., Galvin, J., Loundon, N., Nguyen, D. Q., Lescanne, E., & Robier, A. (2014). Cortical auditory evoked potentials in hearing-impaired children fitted with hearing aids. *European Annals of Otorhinolaryngology, Head and Neck Diseases, 131*(4), 233–238.

Battmer, R. D., Laszig, R., & Lehnhardt, E. (1990). Electrically elicited Lazarev reflex in cochlear implant patients. *Ear and Hearing*, *11*(5), 370–374.

Blamey, P., Artieres, F., Baskent, D., Bergeron, F., Beynon, A., Burke, E., Dillier, N., Dowell, R., Fraysse, B., Gallego, S., Govaerts, P. J., Green, K., Huber, A. M., Kleine-Punte, A., Maat, B., Marx, M., Mawman, D., Mosnier, I., O'Connor, A. F., & Lazard, D. S. (2013). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants: An update with 2251 patients. *Audiology and Neurotology, 18*(1), 36–47.

Boons, T., Brokx, J. P. L., Dhooge, I., Frijns, J. H. M., Peeraer, L., Vermeulen, A., Wouters, J., & van Wieringen, A. (2012). Predictors of spoken language development following pediatric cochlear implantation. *Ear and Hearing, 33*(5), 617–639.

Bresnihan, M., McDermott, A., & O’Donoghue, G. (2001). The stapedius reflex in cochlear implantation: Its use in programming in children. *American Journal of Otology, 22*(1), 40–44.

Campbell, J., Cardon, G., & Sharma, A. (2011). Clinical application of the P1 cortical auditory evoked potential biomarker in children with sensorineural hearing loss and auditory neuropathy spectrum disorder. *Seminars in Hearing, 32*(2), 147–155.

Chai, B., Holland, M. L., Camposeo, E. L., King, K., & Schvartz-Leyzac, K. C. (2024). Patient and device factors contributing to electrically evoked stapedial reflex thresholds in cochlear implanted adults. *Audiology and Neurotology, 29*(4), 263–270.

Ching, T. Y. C., Dillon, H., Day, J., Crowe, K., Close, L., Chisholm, K., & Hopkins, T. (2009). Early language outcomes of children with cochlear implants. *Cochlear Implants International, 10*(Suppl. 1), 28–32.

Cinar, B. C., Tahir, E., Ozgur, A., Kaya, S., & Sennaroglu, L. (2011). Electrically evoked stapedius reflex testing in Nucleus cochlear implant users. *Cochlear Implants International, 12*(Suppl. 2), S79–S82.

Ciprut, A., & Adigul, S. (2020). Comparison of electrically evoked stapedial reflex thresholds and maximum comfort levels in cochlear implant users. *Journal of the American Academy of Audiology, 31*(10), 737–744.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Lawrence Erlbaum Associates.

Creswell, J. W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches* (4th ed.). SAGE Publications.

Field, A. (2018). *Discovering statistics using IBM SPSS statistics* (5th ed.). SAGE Publications.

Franke-Trieger, A., Mattheus, W., Seebacher, J., Zahnert, T., & Neudert, M. (2021). Acoustic stapedial reflex in cochlear implant users measured in the free-field: A comparison with normal hearing listeners. *Audiology and Neurotology, 26*(5), 345–355.

Franke-Trieger, A., Mattheus, W., Seebacher, J., Zelger, O., Zahnert, T., & Neudert, M. (2024). Free-field acoustic stapedial reflex thresholds as indicators of MAP quality in cochlear implant users. *Ear and Hearing, 45*(1), 71–80.

Frånlund, K., Lindehammar, H., Mäki-Torkko, E., & Hergils, L. (2024). Cortical auditory evoked potentials (P1 latency) in children with cochlear implants in relation to clinical language tests. *International Journal of Audiology, 63*(10), 802–808.

Geers, A., Brenner, C., & Davidson, L. (2003). Factors associated with development of speech perception skills in children implanted by age five. *Ear and Hearing, 24*(Suppl. 1), 24S–35S.

Gordon, K. A., Papsin, B. C., & Harrison, R. V. (2004). Programming cochlear implant transition levels with the electrically evoked stapedius reflex threshold. *International Journal of Audiology, 43*(5), 285–291.

Hammes, D. M., Novak, M. A., Rotz, L. A., Willis, M., Edmondson, D. M., & Thomas, J. F. (2002). Early identification and cochlear implantation: Critical factors for spoken language development. *Annals of Otology, Rhinology, and Laryngology, 111*(5 Suppl. 189), 74–78.

Jerger, J., Jenkins, H., Fifer, R., & Mecklenburg, D. (1986). Stapedius reflex to electrical stimulation in a patient with a cochlear implant. *Annals of Otology, Rhinology, and Laryngology, 95*(2), 151–157.

King, A. M. (2009). The national protocol for paediatric amplification in Australia. *International Journal of Audiology, 49*(Suppl. 1), S64–S69.

Lakkanna, S., Nayak, R., & D’Souza, C. (2021). *Assessment of Language Development—Manipal Manual (ALD-MM).* Department of Audiology and Speech Language Pathology, Kasturba Medical College, Manipal Academy of Higher Education.

Lamminmäki, S., Parkkonen, L., Hari, R., & Alho, K. (2023). Maturation of auditory cortex is linked to language development in children with hearing loss. *Developmental Cognitive Neuroscience*, *63*, 101289.

Mertens, G., Hofkens, A., Van de Heyning, P., Van Rompaey, V., Boudewyns, A., Di Gregorio, M. F., Eikelboom, R. H., Marino, R., Kurz, A., Kühn, H., Shehata-Dieler, W., Lorens, A., Pulibalathingal, S., Rajeswaran, R., Tavora-Vieira, D., Bellekom, S. R., Topsakal, V., & HEARRING Members. (2021). Minimal outcome measurements in pediatric cochlear implant users: A consensus paper. *B-ENT*, *17*(2), 110–120.

Mostafa, B. E., Shafik, A. G., El-Daly, A. A., & El-Makhzangy, A. M. (2013). Cortical auditory evoked potentials in cochlear implanted children: Relationship to implantation age and speech perception. *Otolaryngology–Head and Neck Surgery*, *149*(2 Suppl.), P245.

Niparko, J. K., Tobey, E. A., Thal, D. J., Eisenberg, L. S., Wang, N. Y., Quittner, A. L., & Fink, N. E. (2010). Spoken language development in children following cochlear implantation. *JAMA*, *303*(15), 1498–1506.

Picton, T. W. (2011). *Human auditory evoked potentials.* Plural Publishing.

Pimperton, H., Blythe, H., Kreppner, J., Mahon, M., Peacock, J. L., Stevenson, J., Terlektsi, E., Worsfold, S., Yuen, H. M., & Kennedy, C. R. (2020). The impact of universal newborn hearing screening on long-term literacy outcomes: A prospective cohort study. *Archives of Disease in Childhood*, *105*(2), 137–144.

Pimperton, H., & Kennedy, C. R. (2012). The impact of early identification of permanent childhood hearing impairment on speech and language outcomes. *Archives of Disease in Childhood, 97*(7), 648–653.

Pimperton, H., Kreppner, J., Mahon, M., Peacock, J., Stevenson, J., Terlektsi, E., Worsfold, S., Yuen, H. M., & Kennedy, C. R. (2021). Speech perception and language outcomes for infants receiving cochlear implants before or after 9 months of age: Use of category-based aggregation of data in an unselected pediatric cohort. *Journal of Speech, Language, and Hearing Research, 64*(5), 1682–1697.

Ponton, C. W., Eggermont, J. J., Kwong, B., & Don, M. (2000). Maturation of human central auditory system activity: Evidence from multi-channel evoked potentials. *Clinical Neurophysiology, 111*(2), 220–236.

Ruben, R. J. (2018). Language development in the pediatric cochlear implant patient. *The Laryngoscope, 128*(4), E111–E119.

Sahana, P. (2025). *Effect of bimodal hearing device on speech identification in noise, localization, emotion perception, and late latency responses in children* [Doctoral thesis, University of Mysore]. All India Institute of Speech and Hearing.

Sahana, P., & Manjula, P. (2024). Aided late latency responses and language age in paediatric cochlear implant users: Is there a relationship? *Journal of Hearing Science, 14*(1),29–38.

Saravanan, P., Devi, N., & Geetha, C. (2024). Electrically evoked late latency response using single electrode stimulation and its relation to speech perception among paediatric cochlear implant users. *Frontiers in Human Neuroscience, 18*, 1441854.

Scheperle, R. A., & Abbas, P. J. (2015). Peripheral and central contributions to cortical responses in cochlear implant users. *Ear and Hearing, 36*(4), 430–440.

Sharma, A., Dorman, M. F., & Kral, A. (2005). The influence of a sensitive period on central auditory development in children with unilateral and bilateral cochlear implants. *Hearing Research, 203*(1–2), 134–143.

Sharma, A., Dorman, M. F., & Spahr, A. J. (2002). A sensitive period for the development of the central auditory system in children with cochlear implants: Implications for age of implantation. *Ear and Hearing, 23*(6), 532–539.

Sharma, A., Gilley, P. M., Dorman, M. F., & Baldwin, R. (2015). Deprivation-induced cortical reorganization in children with cochlear implants. *International Journal of Audiology, 46*(9), 494–499.

Silva, L. A. F., Couto, M. I. V., Frizzo, A. C. F., & Alvarenga, K. F. (2013). Long-latency auditory evoked potentials in cochlear implanted children: A systematic review. *International Archives of Otorhinolaryngology, 17*(2), 199–206.

Silva, L. A. F., Couto, M. I. V., Frizzo, A. C. F., & Alvarenga, K. F. (2014). Cortical auditory maturation following cochlear implant activation: A longitudinal study. *Brazilian Journal of Otorhinolaryngology, 80*(6), 463–470.

Silva, L. A. F., Couto, M. I. V., Frizzo, A. C. F., & Alvarenga, K. F. (2015). Longitudinal changes in electrophysiological and behavioural measures after cochlear implantation: A case study. *CoDAS, 27*(5), 504–508.

Silva, L. A. F., Couto, M. I. V., Frizzo, A. C. F., & Alvarenga, K. F. (2017). P1 latency and auditory discrimination in cochlear implant children: Relationship with implantation age and duration of device use. *Brazilian Journal of Otorhinolaryngology, 83*(3), 337–344.

Stephan, K., & Welzl-Müller, K. (2000). Stapedius reflex and loudness scaling in patients with cochlear implants. *Audiology, 39*(3), 146–152.

Stephan, K., Welzl-Müller, K., & Stiglbrunner, H. (1988). Acoustic reflex in patients with cochlear prostheses. *American Journal of Otology*, *9*(3), 244–247.

Swapna, N., Jayaram, M., Prema, K. S., & Geetha, Y. V. (2010). *Assessment Checklist for Speech-Language Skills (ACSLS).* All India Institute of Speech and Hearing, Mysuru, India.

Tavartkiladze, G. A., & Bakhshinyan, V. V. (2025). Objective measures at different stages of cochlear implantation: A data analysis. *Medical Research Archives*, *13*(1).

Vandana, H. S. (1998). *Development of speech identification test for Kannada speaking children* [Master's dissertation, University of Mysore]. All India Institute of Speech and Hearing.

Venkatesan, S., & Basavaraj, V. (2009). *Ethical guidelines in bio-behavioural research.* All India Institute of Speech and Hearing.

Wolfe, J., Neumann, S., Marsh, M., Schafer, E., Smith, D. R., Woodruff, B., & John, A. (2018). Effects of loudness normalization and a novel compression scheme on speech recognition and subjective satisfaction with cochlear implants. *Journal of the American Academy of Audiology, 29*(3), 229–240.

Wunderlich, J. L., Cone-Wesson, B. K., & Shepherd, R. (2006). Maturation of the cortical auditory evoked potential in infants and young children. *Hearing Research, 212*(1–2), 185–202.

Xiong, S., Jiang, L., Wang, Y., Pan, T., & Ma, F. (2022). The role of the P1 latency in auditory and speech performance evaluation in cochlear implanted children. *Neural Plasticity, 2022*, 6894794.

Young, N. M., & Kirk, K. I. (Eds.). (2016). *Pediatric cochlear implantation: Learning and the brain.* Springer.

Appendix

All India Institute of Speech and Hearing

(An autonomous Institute under the
Ministry of Health and Family Welfare, Govt. of India)
Center of Excellence - Assessed & Accredited by NAAC with 'A' Grade
ISO 9001:2015 Implemented Institute
Manasagangothri, Mysuru-570006

ಅಖಿಲ ಭಾರತ ವಾಕ್ ಮತ್ತು ಶ್ರವಣ ಸಂಸ್ಥೆ
ಮಾನಸಗಂಗೋತ್ರಿ, ಮೈಸೂರು-570006

अखिल भारतीय वाक् श्रवण संस्थान
मानसगंगोत्री, मैसूरु - 570 006

INSTITUTE REVIEW BOARD (IRB) APPROVAL FOR BIO-BEHAVIOURAL RESEARCH PROPOSAL INVOLVING HUMAN SUBJECTS AT AIISH

AIISH Institute Review Board (IRB)

Ref: SH/IRB/M.4/AUD.10/2025-26 | **Date: 06.01.2026**

Title of the Dissertation	: Investigating the relationship among Acoustic Stapedial Reflex Thresholds, Aided Late Latency responses, and outcomes in Paediatric Cochlear Implantees
Name of the Investigator	: Ms. Simran Banga
Guide	: Dr. Manjula P
Co-Guide (if any)	: Nil
Proposed Duration of the Project	: 08 months
Source of funding	: Non-funded Master's dissertation
Estimated budget	: Nil
Reference Number of the Project	: Nil
Date on which the IRB meeting was held	: 02.01.2026

A clear statement of the decision reached IRB meeting
(In the vent of the proposal is not approved, a statement
of reasons for the same must be indicated) : **APPROVED**

Advice & suggestions (if any) : Assent should be taken from the participant

Signature & Name of the Member Secretary-IRB
Dr. Animesh Barman
Professor of Audiology
All India Institute of Speech and Hearing, Mysore-570006

सदस्य सचिव / Member Secretary
संस्थागत समीक्षा बोर्ड
Institutional Review Board
अखिल भारतीय वाक् श्रवण संस्थान
All India Institute of Speech and Hearing
मानसगंगोत्री / Manasagangothri
मैसूरु / Mysuru-570 006