ASSESSMENT OF TEMPORAL RESOLUTION ABILITIES IN CHILDREN USING COCHLEAR IMPLANTS

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CERTIFICATE

This is to certify that this dissertation entitled **"Assessment of Temporal Resolution abilities in Children using Cochlear Implants "** is a bonafide work submitted as part of fulfilment of the degree of Master of Science **(Audiology)** of the student with Registration Number **P01II24S023019**. This has been carried out under the guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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CERTIFICATE

This is to certify that this dissertation entitled "**Assessment of Temporal Resolution abilities in Children using 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.

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DECLARATION

This is to certify that this dissertation entitled " **Assessment of Temporal Resolution abilities in Children using Cochlear Implants**" is the result of my own study under the guidance of Dr. Prawin Kumar, Associate Professor of Audiology, All India Institute of Speech and Hearing, Mysuru and has not been submitted earlier to any other university for the award of any other Diploma or Degree.

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ABSTRACT

The present study aimed to investigate gap detection threshold (GDT) in 15 children using cochlear implants (CCI; age range: 6–15 years; post-implant duration: 12–36 months) and compared their performance with 15 typically developing children (TDC; age range: 6–15 years) with normal hearing sensitivity. Each participant underwent gap detection test in a sound-treated environment compliant with ANSI standards. Shapiro-Wilk test showed non-normal distribution of GDT scores hence non-parametric analyses were employed. Between group differences were examined using the Mann–Whitney U test and the comparison between post-implant durations and GDT performance within the CCI group was assessed using Spearman's correlation. Results demonstrated a significant difference between the study groups (Z = −4.749, p = 0 .000). The CCI group performed a mean (M) GDT of 15ms with Standard deviation (SD) of 3.09ms. The Mean GDT in CCI Group was twice that of the TDC group (M = 6.80ms, SD = 1.27ms). Post-implant duration showed no significant association with GDT performance (ρ = −0.058, p = 0 .838), suggesting that accumulated implant experience alone does not meaningfully improve temporal auditory resolution within the observed sample in the current study. Findings indicate that Cochlear implant provides substantial auditory benefit but does not fully restore fine-grained temporal auditory processing similar to TDC with normal hearing. The absence of a significant duration effect with gap detection thresholds implies that targeted auditory rehabilitation rather than passive listening experience may be necessary to address temporal processing deficits in this population. Routine inclusion of gap detection *assessment in children using cochlear implant is recommended to guide individualised intervention and rehabilitation planning.*

Key words: Gap Detection Threshold, Children using Cochlear Implants, Typically Developing Children.

CHAPTER 1

INTRODUCTION

Cochlear implants are medical prosthetic devices recommended for individuals with severe to-profound sensorineural hearing loss in both ears. A Cochlear implant converts incoming acoustic signals into electrical biphasic signals that directly stimulate the auditory nerve and bypass inner ear structures, especially the organ of Corti (NIDCD, 2024). For children born deaf (prelingually deafened children) or who lose their hearing before learning to speak, cochlear implants provide the essential sounds needed for speech and language development (Niparko, 2010). Cochlear implants prove beneficial for those who do not experience significant benefits with conventional hearing aids, due to the extent of their hearing loss (Deep et al., 2019).

As of July 2022, over a million cochlear implants have been implanted worldwide (Zeng, 2022; NIDCD, 2024). Cochlear implants give young recipients the acoustic cues to understand words and build language skills. Early implantation yields the most significant benefits while the brain's auditory pathways remain highly flexible (Kral & Sharma, 2012). Children who receive cochlear implants during this sensitive period can distinguish between different speech sounds, expand their vocabulary rapidly and learn and apply grammar rules in everyday conversation. Early access to sound also supports more natural speech patterns, smoother social interaction, better performance in school, and an overall improved quality of life. Despite all these advantages, implanted children may face challenges like difficulty understanding speech in noise or crowded environments and with complex or fast-paced language (Zaltz et al., 2020). Cochlear implant users reported mixed findings while assessing their temporal resolution abilities.

Auditory temporal processing is the perception of sound or sound alteration within a restricted or defined time domain (Musiek, 2007; Kumar et al., 2016). The key components of temporal processing include temporal resolution, temporal sequencing, temporal integration and temporal masking (Shinn, 2003; Andrade et al., 2023). Temporal resolution means the auditory system's capacity to follow sudden changes in the spectral envelope of sounds. A child must be able to detect this subtle change over time to develop adequate language skills. Gap Detection Threshold (GDT) is a reliable measure of the temporal resolving power of the auditory system. There are several clinical tests of temporal resolution. Random gap detection test (Keith, 2000), where the listener will get a variety of gap durations in noise bursts, the listener has to indicate if he/she heard a gap (or silence) in each case. In the adaptive test of temporal resolution, the listener will get a choice of two noise bursts, and he/she has to indicate which set of tokens contains the gap (Lister et al., 2006). The test is adaptive because the gap will change automatically based on the listener's previous response until a reliable threshold is achieved (Musiek, 2022). Another test widely used in clinical situations is the gap in noise test (Musiek et al, 2007), where the listener will get some white noise signals, each containing one, two or more silent gaps in 6 seconds of a signal. The listener has to respond by pressing the response button every time he/she detects a gap.

The Gap detection test is a critical measure of temporal auditory processing and typically reflects the minimum duration of a silent gap that an individual can detect within a continuous sound. GDTs are usually very low (better) in typically developing children (TDC) with normal hearing ranging from 2 to 5 milliseconds which is indicating of highly refined temporal resolution abilities (Shivaprakash and Manjula, 2003; Musiek et al., 2009). In contrast children using cochlear implants (CCI) perform poorly on the test of gap detection and exhibit significantly higher thresholds that can range from 10 to 25 milliseconds or more and hence reflecting challenges in processing rapid temporal cues due to the limitations of cochlear implant signal encoding (Sharma & Yadav, 2015; Belkasem, 2023).

Studies reveal that typically developing children can easily detect brief gaps, whereas children with cochlear implants tend to require longer gaps to discriminate them reliably. This elevation in GDT among implanted children shows reduced spectral and temporal resolution inherent in prosthetic hearing devices and factors such as age at implantation and auditory experience (Sharma & Yadav, 2015; Belkasem, 2023). Studies have shown that gap detection thresholds in cochlear implant users show improvement over time with auditory experience and rehabilitation although they rarely reach the low thresholds seen in normal-hearing peers (Tuz et al, 2020). These findings underscore the importance of gap detection in measuring auditory temporal processing deficits in paediatric cochlear implant users and guiding intervention and rehabilitation strategies.

Measuring gap detection ability in cochlear implant users provides an understanding of how these children hear and process speech in real life (Grantham et al., 2022). When children have good GDTs, they can better tell vowels and consonants apart which means they can speak and understand words more clearly and make fewer mistakes (Rodvik et al., 2019). Strong GDT skills also help them pick up on the natural flow of speech like changes in pitch, emphasis and rhythm that allow them to grasp the feeling or emotion in conversations (Grantham et al., 2022). Clinicians can personalise training and therapy by regularly checking GDT and helping each child build their optimal communication skills for more confident social interactions and classroom success.

Need for the Study

Temporal resolution abilities are crucial for speech perception and speech-language development, with normal hearing individuals detecting gaps of about 3–4ms (Shivaprakash, 2003). Compared to the children with normal hearing, children with sensorineural hearing loss required a higher silence interval of about a 5-ms gap, despite using a procedure that better restored the standard dynamic range of hearing (Brennan et al., 2018). In a similar line, children with cochlear implants reported having poorer gap detection thresholds in comparison to typically developing individuals. This deficit can hinder speech understanding, especially in cochlear implant users with shorter post-implant durations. Temporal processing ability among bimodal CI users is reported to be better than candidates with unilateral CIs (Belkasem, 2023). Paediatric cochlear implant users generally show significantly higher gap detection thresholds ranging from around 10 to 25 milliseconds or more, reflecting challenges in processing rapid temporal cues (Sharma & Yadav, 2015; Carlyon et al., 2025). Despite previous studies reporting poor temporal resolution in cochlear implant users, there is a dearth of literature to establish the temporal resolution abilities among cochlear implant users in paediatric population. Therefore, there is a need to study temporal resolution abilities among children using cochlear implants. A cross-sectional study was done to compare a group of cochlear implant users at various post-implant durations with a control group of normal hearing children, providing an idea of temporal auditory processing development at distinct phases after device switch-on.

Aim of the Study

The present study aimed to measure the Gap Detection Threshold (GDT) among children using cochlear implants and compare with typically developing children.

Objectives of the Study

1. To measure and compare the gap detection thresholds between children using cochlear implants and typically developing children using the gap detection test.
2. To assess the effect of post-implant durations on gap detection thresholds in cochlear implant users.

Hypotheses of the Study

1. There is no difference in gap detection thresholds between CI children and Typically Developing Children.
2. There is no effect of post-implant durations on Gap detection threshold in Cochlear implant users.

CHAPTER 2

REVIEW OF LITERATURE

Temporal processing is defined as “the ability of the auditory system to perceive, analyze, and interpret acoustic changes over time”. It enables individuals to identify timing aspects of sound such as duration, rhythm, sequencing, and rapidity within speech signals. Temporal processing is important for understanding speech, appreciating music and localizing sound sources in listening environments. (Shinn, 2003; Musiek & Chermak, 2007).

Temporal processing is broadly divided into temporal resolution, temporal ordering, temporal integration, and temporal masking. Temporal ordering refers to the perception of the sequence of auditory events whereas temporal integration involves combining auditory information over time. Temporal masking deals with the effect of one sound on the perception of another sound occurring before or after it. Among these, temporal resolution is regarded as one of the most important because it reflects the auditory system's capacity to detect rapid changes in acoustic stimuli. (Phillips, 1999; Bellis, 2003)

Temporal resolution is the minimum amount of time required for an individual to perceive two auditory stimuli as separate events. It is the ability to detect brief silent intervals between sounds. This skill is essential as speech signals contain rapid fluctuations and transient acoustic cues necessary for distinguishing segmentals and suprasegmentals. It contributes significantly to speech perception especially in difficult listening situations such as background noise (Phillips, 1999; Moore, 2012).

Deficits in temporal resolution can negatively affect auditory perception and speech understanding. Individuals with poor temporal resolution abilities may experience difficulty perceiving rapid speech transitions, identifying phonemes accurately and understanding speech in noisy environments. Research has shown that impaired temporal processing may also be associated with language disorders, learning disabilities, auditory processing disorders and hearing impairment. Therefore, assessment of temporal resolution has become an important part of audiological and auditory processing evaluations (Shinn, 2003; Chermak & Musiek, 2007).

Several behavioural and psychoacoustic tests have been developed to evaluate temporal resolution abilities. Commonly used measures include the Gap Detection Test, Random Gap Detection Test, Gaps-in-Noise Test and Auditory Fusion Test-Revised. These tests primarily assess the listener's ability to detect brief silent gaps or rapid acoustic changes within auditory stimuli. Lower gap detection thresholds generally indicate better temporal resolution ability (Keith, 2000; Musiek et al., 2007).

Among the various components of auditory temporal processing, temporal resolution has received considerable attention in both research and clinical audiology because of its strong relationship with speech perception abilities. Speech understanding depends heavily on accurate processing of temporal cues particularly in complex listening situations. Consequently, temporal resolution testing is widely used to investigate auditory function and to identify auditory processing deficits in children and adults (Moore, 2012; Phillips, 1999).

Measures of Temporal Resolution

Random Gap Detection Test (RGDT)

Random Gap Detection Test was developed by Keith (2000) as a clinical tool for assessing temporal resolution abilities in children and adults. Pairs of tones are presented at different frequencies with randomly varying intervals between them. The listener is asked to report whether one or two sounds are heard. The shortest interval at which two sounds are consistently perceived separately is considered the temporal resolution threshold (Keith, 2000).

The RGDT is considered clinically useful because it is easy to administer and requires minimal equipment. The test commonly includes frequencies such as 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz with gap intervals ranging from 0 to 40 milliseconds. The test helps identify deficits in auditory temporal processing that may affect speech understanding and auditory perception. The RGDT is widely used in central auditory processing assessments particularly in paediatric populations because of its simplicity and short administration time (Keith, 2000; Musiek & Chermak, 2007).

Gaps-in-Noise Test (GIN)

Gaps-in-Noise Test is a behavioural measure developed to assess temporal resolution using silent gaps embedded within broadband noise. In this test, segments of noise containing gaps of varying durations are presented to the listener, who is instructed to identify whenever a gap is heard. The test measures both the approximate gap detection threshold and the percentage of correctly identified gaps (Musiek et al., 2005).

The GIN test is considered reliable and clinically efficient for evaluating auditory temporal processing deficits. The GIN test uses more naturalistic broadband noise stimuli which may better reflect everyday listening conditions. It has been widely used in individuals with central auditory nervous system disorders and has shown good sensitivity in identifying temporal processing impairments. GIN is suitable for both research and clinical applications (Musiek et al., 2005; Weihing, Musiek, & Shinn, 2007).

Auditory Fusion Test-Revised (AFT-R)

Auditory Fusion Test-Revised is used to evaluate temporal resolution by measuring auditory fusion thresholds. The test determines the shortest interval at which two auditory stimuli are perceived as separate rather than fused into a single sound. During the procedure, pairs of tones are presented with progressively increasing intervals and the listener reports whether one or two sounds are heard (McCroskey & Kidder, 1980).

The Auditory Fusion Test-Revised is useful for identifying deficits in central auditory processing and temporal acuity. Lower fusion thresholds indicate better temporal resolving ability, whereas higher thresholds suggest reduced temporal processing efficiency. The test has been used in children with learning difficulties, language disorders, and auditory processing disorders. It is considered one of the earlier clinical tools designed specifically for assessing temporal auditory abilities (McCroskey & Kidder, 1980; Katz, 1992).

Temporal Modulation Transfer Function (TMTF)

Temporal Modulation Transfer Function assesses the auditory system's ability to detect amplitude modulation in acoustic signals over time. Modulated stimuli are presented at different modulation frequencies and depths. The listener identifies changes in the modulation pattern. The test reflects sensitivity to temporal envelope cues, which are important for speech perception (Shannon, 1992).

Temporal modulation detection is considered an important component of auditory temporal processing because many speech cues are carried through fluctuations in the temporal envelope. The TMTF provides information about how effectively the auditory system tracks rapid changes in sound intensity. Poor modulation detection abilities may affect speech recognition especially in noisy environments. The test is widely used in psychoacoustic and auditory perception research to study temporal processing mechanisms (Shannon, 1992; Won, Drennan, & Rubinstein, 2007).

Gap Detection Test (GDT)

Gap Detection Test is one of the most widely used behavioural measures for assessing temporal resolution ability. The test evaluates the minimum duration of silence or "gap" that a listener can detect between two auditory stimuli. Acoustic signals such as pure tones or noise bursts are presented with brief silent intervals inserted between them. The listener is instructed to identify whether one continuous sound or two separate sounds are perceived. The shortest detectable gap is referred to as the gap detection threshold and lower thresholds indicate better temporal resolution ability (Phillips, 1999; Moore, 2012).

Gap detection ability is considered an important indicator of auditory temporal processing because speech perception relies heavily on rapid temporal changes in acoustic signals. Different forms of the test may use broadband noise, narrowband noise or tonal stimuli depending on the purpose of assessment. Research has shown that poor gap detection performance is associated with difficulties in speech perception particularly in noisy listening environments. Therefore, the Gap Detection Test is extensively used in psychoacoustic research and clinical audiology to evaluate temporal acuity (Phillips, 1999; Shinn, 2003).

Auditory Mechanisms Underlying Gap Detection

Gap detection depends on peripheral encoding, neural synchrony in the auditory nerve, brainstem and cortical processing. Any disruption in these systems may elevate thresholds.

Peripheral Encoding

The first stage of temporal processing begins in the outer ear, middle ear and cochlea. Acoustic signals travel through the external and middle ear and reach the cochlea where inner hair cells convert mechanical vibration into neural impulses. The basilar membrane separates frequencies allowing precise representation of sound components (Pickles, 2012). For gap detection the cochlea must accurately represent the offset of the first stimulus and the onset of the second. Temporal precision may deteriorate if cochlear function is reduced due to outer hair cell damage. Sensorineural hearing loss has often been associated with poorer temporal resolution even when sounds are made audible (Moore, 2008).

Intact cochlear processing in typically developing children provides rich spectral and temporal detail. In contrast children using cochlear implants receive electrical stimulation that bypasses hair cells and directly activates the auditory nerve. This restores audibility but the temporal pattern differs from natural hearing (Shannon, 1989; Busby & Clark, 1999).

Auditory Nerve Synchrony

Once sound is transduced in the cochlea, neural firing travels through the auditory nerve. Temporal resolution depends heavily on neural synchrony that means auditory nerve fibers must fire in a coordinated manner that reflects rapid changes in the stimulus. Gap detection requires accurate encoding of silence, stimulus offset and re-onset (Eggermont, 2000). The representation of brief gaps may be blurred due to desynchronized firing or poor neural survival. This issue is particularly relevant in cochlear implant users because spiral ganglion survival varies across individuals. Reduced neural integrity can limit the benefit obtained from electrical stimulation (Shepherd & Hardie, 2001). Studies in CI users have shown that temporal processing ability often differs widely even among children with similar hearing histories suggesting that neural health may be an important factor (Shannon, Fu, & Galvin, 2004).

Brainstem Processing and Cortical Involvement

Signals from the auditory nerve pass through several brainstem nuclei including the cochlear nucleus, superior olivary complex, lateral lemniscus and inferior colliculus. These structures refine timing information and contribute to detection of rapid acoustic events. The inferior colliculus in particular has been strongly linked to gap perception because many neurons in this region respond to stimulus offset and onset cues (Walton, Frisina, & O'Neill, 1998). Brainstem integrity is therefore important for normal gap detection. Delayed maturation or abnormal neural conduction in children may contribute to poorer thresholds seen in younger age groups. Electrophysiological studies using auditory brainstem responses and cortical potentials support the idea that temporal processing continues to mature during childhood (Skoe, Krizman, & Kraus, 2013).

Neurophysiological studies have shown that cortical responses to silent gaps are robust in normal listeners. The latency and amplitude of these responses are associated with behavioural gap detection ability. Children with delayed cortical maturation or auditory deprivation may therefore show poorer performance (Eggermont & Ponton, 2003).

Temporal Resolution in Normal-Hearing Children

Studies consistently show that gap detection ability improves with age in normal-hearing children. Younger children generally demonstrate higher (poorer) gap detection thresholds. They require longer silent intervals to perceive a gap, while older children gradually approach adult-like performance and achieve plateau. This developmental improvement is thought to result from progressive maturation of auditory brainstem pathways, cortical temporal processing mechanisms, increased neural synchrony and improved attentional control (Werner et al., 1992). One of the early studies investigating temporal resolution in children was conducted by Irwin et al. (1985). The researchers evaluated gap detection abilities in normal-hearing children using broadband noise stimuli. The study reported that younger children showed higher gap detection thresholds compared to adults indicating temporal resolution abilities continue to mature with age. The findings suggest developmental change in auditory temporal processing during childhood period (Irwin et al., 1985). Wightman and colleagues examined auditory temporal processing abilities in normal-hearing children using gap detection tasks. Their study demonstrated that children required longer gap durations to detect silent intervals when compared to adults. The researchers concluded that maturation of the central auditory nervous system contributes significantly to the improvement of temporal resolution abilities across development (Wightman et al., 1989). Fitzgibbons and colleague (1994) studied temporal resolution in children with normal hearing by measuring gap detection thresholds under different listening conditions. Their results showed that children exhibited poorer temporal resolution than adults, especially for very brief gaps. They emphasized the importance of temporal auditory maturation for speech perception abilities. (Fitzgibbons and Gordon-Salant, 1994).

Samelli and Schochat (2008) evaluated temporal resolution abilities in normal-hearing children using gap detection measures. Their findings indicated that normal-hearing children generally achieved low gap detection thresholds and hence reflecting efficient temporal auditory processing. The study also highlighted the usefulness of gap detection tasks in paediatric auditory processing assessment (Samelli and Schochat, 2008).

Balen and colleagues investigated gap detection thresholds in normal-hearing Brazilian children using pure-tone and noise stimuli. They found that age had a significant influence on temporal resolution performance with older children demonstrating lower gap detection thresholds. The authors suggested that auditory temporal processing improves progressively throughout childhood (Balen et al., 2009).

Lister and colleagues examined developmental changes in auditory temporal resolution in normal-hearing children and adolescents. The study demonstrated gradual improvement in gap detection thresholds with increasing age, supporting the view that temporal processing abilities continue to mature during late childhood and adolescence (Lister et al., 2011).

Research has also shown that task complexity influences performance. Simpler within-channel gap detection tasks are usually easier than across channel tasks where spectral characteristics before and after the gap differ. Younger children may show greater variability due to immature attention, memory and listening strategies even when peripheral hearing sensitivity is normal (Phillips, Comeau, & Andrus, 2010; Jain, Tanniru, & Kalarikkal, 2025). The age-appropriate gap detection performance in normal-hearing children is considered an indicator of healthy auditory maturation. The temporal resolution plays an important role in speech perception, phoneme discrimination and listening in noise. Poor performance relative to peers requires assessment of auditory processing, language, or attention skills (Eggermont & Ponton, 2003).

Temporal resolution in Children with hearing loss using Cochlear Implants

One of the earliest and most foundational investigations into temporal gap detection in cochlear implant (CI) users was carried out by Shannon (1989), who studied 17 adult listeners aged 25–78 years. All had profound bilateral sensorineural hearing loss. Ten participants were fitted with the Nucleus 22-electrode device and the remaining seven with the Symbion 6-electrode device. Gap detection thresholds (GDTs) were measured using an adaptive two-interval forced-choice (2AFC) procedure. Results demonstrated that GDT scores ranged from 20–50ms at low stimulation levels and improved substantially to 2–5ms at more comfortable levels. These findings established that temporal resolution measured through gap detection, is not fundamentally impaired by cochlear damage. This work laid foundation for subsequent investigations into temporal processing in children.

In 1998, Chatterjee and colleagues expanded the understanding of temporal processing in CI users by examining within-channel gap detection using dissimilar electrical markers in three CI users. Their findings showed that temporal gap perception was influenced not only by the duration of the silent interval but also by perceptual differences between stimuli. The study highlighted that temporal acuity in CI listeners is closely related to the perceptual organization of electrical stimulation patterns (Chatterjee et al., 1998).

Neural mechanisms underlying gap detection in CI users was initiated by Kirby and Middlebrooks (2011). They conducted an electrophysiological study using six albino guinea pigs as the experimental model. Extracellular spike activity was recorded from the primary auditory cortex (area A1) of awake guinea pigs using multi-electrode recording probes implanted in the right hemisphere. Each animal was bilaterally deafened and implanted with a cochlear device in the left cochlea. Electrical pulse trains at rates of 254, 1,017, and 4,069 pulses per second (pps) were delivered and cortical responses to gaps within these trains were analysed across three response types. Those were Trail-ON (onset of trailing pulse train), Lead-OFF (offset of leading pulse train) and TONIC (reduction in sustained firing). Results demonstrated that cortical neurons encoded temporal gaps through multiple distinct response patterns and that higher pulse rates yielded significantly shorter gap detection thresholds for Trail-ON responses. Median best gap detection thresholds for late-gap stimuli were 5.3, 1.4, and 0.77ms for 254, 1,017, and 4,069pps respectively. The study was significant in establishing that temporal resolution limitations in CI users likely reflect central auditory processing constraints rather than device-related peripheral limitations alone. The finding that intermediate pulse rates around 1,000pps produced cortical response patterns similar to those seen with acoustic stimulation. This finding has direct implications for programming strategies in clinical CI management.

A more clinically oriented paediatric investigation was conducted in 2015 by Sharma and Yadav. This comparative study examined gap detection thresholds in children with cochlear implants and normal-hearing children aged 7–20 years at four frequency-specific conditions 500 Hz, 1,000 Hz, 2,000 Hz, and 4,000 Hz. Gap detection was assessed at multiple frequencies and across different postoperative durations. They found significantly poorer GDTs in CI children compared with normal-hearing peers. The study also observed gradual improvement in temporal resolution with increased CI experience after implantation (Sharma & Yadav, 2015).

Bierer and colleagues (2016) investigated how electrode configurations affected signal and gap-detection thresholds in CI users. This was not exclusively paediatric study but they demonstrated that focused electrode stimulation could improve temporal processing performance compared with broader stimulation modes. These findings contributed to the understanding that electrode interaction and stimulation strategies directly influence temporal resolution outcomes in cochlear implant users (Bierer et al., 2016).

Further paediatric evidence emerged in 2018 through a study evaluating electrically evoked auditory change complexes (eACC) in children with cochlear nerve deficiency using cochlear implants and auditory brainstem implants. The researchers demonstrated that objective electrophysiological responses to temporal gaps could be recorded successfully in implanted children and that these responses were associated with behavioural GDTs in some participants. This study was important because it showed the feasibility of using objective neural measures to assess temporal processing in young children who may not reliably complete behavioural tests (He et al., 2018).

Tuz and colleagues (2020) compared temporal processing performance in children using cochlear implants and normal-hearing children. The study included 30 children using cochlear implants and 10 normal-hearing children aged 9 and 10 years. The cochlear implant group was divided into two subgroups based on age at implantation: Group I comprised 20 children implanted between 13 and 35 months and Group II comprised 10 children implanted between 36 and 45 months of age. Temporal processing was assessed using the Random Gap Detection Test (Keith, 2000), Duration Pattern Test, Frequency Pattern Test, the Mr. Potato Head task and word and sentence recognition tests. Results showed that children using cochlear implants performed significantly worse on all temporal processing tasks compared to normal-hearing children. No significant difference was observed between the two cochlear implant subgroups. A significant association was also found between duration of implant use and temporal ordering performance. These findings support the view that paediatric cochlear implant users show reduced temporal resolution compared to normally hearing peers and that earlier implantation may positively influence temporal processing development (Tuz et al., 2020).

The most comprehensive and recent study on Spectro-temporal resolution in paediatric CI users was provided by Kumar and colleagues (2025) through a systematic review. They screened 193 articles and selected seven high-quality cross-sectional studies covering the period 2004–2024. All seven studies exclusively used the Spectro-Temporal Modulated Ripple Test (SMRT) to assess Spectro-temporal resolution ability in children with cochlear implants (cCI) aged 5–17 years, with overall sample sizes ranging from 12 to 75 participants per study. The review consistently found that cCI demonstrated significantly lower SMRT thresholds (ranging 0.4–7.7 ripples per octave) compared to children with normal hearing (5.2–10.7 ripples per octave), reflecting meaningfully poorer Spectro-temporal resolution. Factors associated with SMRT performance included chronological age, age at implantation, duration of CI use, auditory working memory, auditory short-term memory, and structured auditory training. The review concluded that while the SMRT is a promising non-linguistic tool for assessing auditory function in children, variability in testing protocols, device types, and demographic factors limits direct cross-study comparisons (Kumar et al., 2025).

These findings suggest that while cochlear implantation provides substantial auditory benefit, temporal resolution abilities may remain below those of normal-hearing children, and rehabilitation targeting auditory timing skills may be beneficial.

Factors Affecting Temporal Resolution Abilities

Effect of Duration of CI Use

The duration of cochlear implant (CI) use is an important factor influencing auditory and temporal processing performance. Longer period of implant use demonstrates better perception of timing cues than recent users. This improvement occurs because continued auditory stimulation allows adaptation to the electrical signal provided by the implant and learn to interpret temporal information more efficiently (Sharma et al., 2002).

Neural plasticity plays a significant role in enhancing auditory outcomes. Repeated stimulation of the auditory pathways can promote cortical reorganization and strengthen neural synchrony which are essential for processing rapid changes in sound. As a result, users may show better performance in tasks such as gap detection, temporal modulation detection, and rhythm perception after extended implant experience (Gordon et al., 2011).

Longer CI experience is also associated with improvements in everyday communication skills particularly speech perception in noise. As listening experience of implant users increases, the efficiency at using temporal and contextual cues increase for speech perception. Regular mapping adjustments, auditory rehabilitation and consistent device use further contribute to these gains. The degree of benefit may vary depending on duration of deafness, age at implantation and cognitive factors (Blamey et al., 2013).

Effect of Age at Implantation

Age at implantation is one of the strongest predictors of successful auditory outcomes in cochlear implant users. Children implanted at an earlier age generally achieve better speech perception, language development and temporal processing abilities than those implanted later. Early implantation provides access to sound during the critical period of auditory system maturation when the brain is most responsive to sensory input (Nicholas & Geers, 2007).

The auditory cortex undergoes rapid development during early childhood and requires adequate stimulation for normal organization. Prolonged auditory deprivation may lead to reduced neural efficiency and atypical cortical development. This can negatively affect the perception of rapid acoustic changes, speech timing cues and other temporal aspects of hearing (Sharma et al., 2002).

Earlier implanted children often show more age-appropriate speech and language growth because they are able to develop listening skills alongside normal communication milestones. In contrast later implanted individuals may require longer rehabilitation and may not achieve the same level of temporal processing efficiency. An early identification of hearing loss and timely implantation are considered essential for optimal outcomes (Dettman et al., 2007).

Frequency and Stimulus Effects

Temporal processing in cochlear implant users is influenced by the frequency and characteristics of the presented stimulus. Different electrode locations stimulate different regions of the cochlea and these regions may vary in their ability to encode temporal information. Basal electrodes which represent higher frequencies and apical electrodes which represent lower frequencies may show differences in temporal sensitivity depending on neural survival and electrode placement (Garadat & Pfingst, 2011).

The spectral complexity of the signal can further influence performance. Within-channel temporal tasks where the same electrode or frequency region is stimulated before and after a gap are often easier than across channel tasks involving different electrodes. This suggests that both spectral place coding and temporal coding interact in cochlear implant hearing. These findings highlight the importance of stimulus design and processor programming when assessing temporal processing in CCI. Stimulus duration and presentation level also affect temporal resolution performance. Longer duration stimuli usually provide clearer temporal cues thus making gap detection easier for CCI users. With the same understanding, stimuli presented at comfortable loudness levels may improve neural response consistency and lead to better detection of rapid timing changes compared with softer levels (Blankenship et al., 2016).

Temporal Resolution and Speech Perception

Temporal resolution is commonly measured through gap detection tasks. It has a strong relationship with speech perception because speech contains rapid acoustic changes that must be processed accurately. Consonant-vowel transitions, voice onset time and brief pauses between phonemes require the auditory system to detect very short temporal cues. Children with better gap detection thresholds often demonstrate improved speech recognition particularly for fast or degraded speech signals. Poor temporal resolution may cause difficulty distinguishing similar speech sounds such as /ba/, /da/ and /ga/ which depend on rapid spectral and temporal transitions (Shinn, Chermak, & Musiek, 2009). The association becomes even more important in noisy environments where listeners must separate speech from competing sounds. Efficient temporal processing helps listeners use brief dips in background noise to identify speech cues thereby improving speech understanding in classrooms and social settings. Studies have shown that children with auditory processing difficulties or language disorders often have poorer gap detection abilities along with reduced speech-in-noise performance. Thus, temporal resolution is considered an important auditory skill supporting speech perception and communication success (Ziegler et al., 2005; Musiek & Chermak, 2014).

Overall, review of literature suggest that temporal resolution abilities vary between children using cochlear implants in comparison to typically developing children due to several factors such as age of the implantation, duration of auditory deprivation, duration of hearing age, duration of aural rehabilitation etc. Therefore, while estimating the benefits derived using cochlear implants in children, the above factors must be taken into consideration.

CHAPTER 3

METHOD

The present study aimed to measure the Gap Detection Threshold among children using cochlear implants (CCI) and compare with typically developing children (TDC). To achieve the above aim and objective of the study, the following method was adopted.

Research Design

Between-group and within-group comparison study.

Participants

The study included a total of 15 children using cochlear implants (7 females and 8 males) in either ear (Right ear/Left ear) who underwent CI surgery and 15 typically developing children (7 females & 8 males) in the age range of 6–15 years were considered for the study. The mean chronological age of the children using cochlear implants and TDC were 7.8 and 10 years, respectively. The mean hearing age/implant age of the children using cochlear implants was 1.8 years. The CCI and TDC group had to fulfil the subject inclusion criteria to be considered for the study.

Table 3.1

Demographic details of Children using Cochlear Implant (CCI) group

Sl. No	Age (Years)	Gender	Post-Implant duration (Years)	Implant Ear	Speech Processor
1	8	Female	3	Right	CP802
2	6.5	Female	1.5	Right	CP1002
3	7	Male	2	Right	CP802
4	6.5	Male	1.5	Right	CP802
5	8	Male	1	Right	Rondo 3
6	6	Female	1	Right	CP802
7	6	Male	1	Right	CP802
8	14	Female	1	Right	Rondo 3
9	8	Female	2	Right	Naida Q30
10	10	Female	2.5	Right	CP802
11	6	Male	2.5	Right	CP802
12	9	Male	2.5	Right	CP802
13	8	Male	2	Right	CP802
14	8	Male	2	Right	CP802
15	6.5	Female	1.5	Right	CP802

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Inclusion and Exclusion Criteria

Children using Cochlear Implants (CCI)

All participants were using cochlear implants in one ear (either right/left). They had aided audiogram with cochlear implants well within the speech spectrum in the range of 10 to 25 dBHL. They were able to detect Ling's six speech sounds in the range of 20 to 30 dBHL. In addition, CI children were attending regular auditory verbal therapy. The post-implant duration was between 12 months and 36 months. Those children using CIs having any abnormal cochlear anatomy or known global developmental delay were excluded from the study.

Typically Developing Children (TDC)

All the participants in TDC group had hearing sensitivity within normal limits (≤25 dBHL) in both ears. They had either A or As type tympanogram with acoustic reflexes present at 500 Hz and 1000 Hz. Individuals with otological and/or neurological problems were excluded from the study.

Ethical Clearance

Ethical approval for bio-behavioural research is given by the AIISH Institute Review Board (IRB) with a Reference number: SH/IRB/M.4/AUD.15/2025-26. Prior to the involvement of CCI and TDC in the study, written consent was obtained from each child’s parents/caregivers. The procedure and purpose of the study was thoroughly explained to them in detail before the participation in the study. They were given the freedom to withdraw from the study at any moment if they are not willing to be part of the study. Further, guidelines of ethical committee recommendation as per Venkatesan and Basavraj (2009) were followed.

Test Environment

The audiological testing was carried out in a sound-treated audiology setup, compliant with ANSI S3.1 (2013) standards. The audiological assessment was executed in a distraction-free environment for both the groups (TDC & CCI).

Instrumentation

1. Calibrated two-channel GSI 61 Clinical Audiometer fitted with two speakers and headphones, used to obtain aided audiogram and pure tone thresholds respectively.
2. Calibrated GSI-Tympstar Pro was used to assess the middle ear functioning.
3. A personal computer loaded with temporal resolution test was used to estimate the gap detection thresholds.

Test Procedure

Each participant had a thorough, structured case history taken in order to understand more about their medical background. The below mentioned audiological test procedure was followed in the present study.

Pure Tone Audiometry

Pure tone audiometry was performed using a modified version of the Hughson and Westlake method (Carhart & Jerger, 1959). For CCI, aided threshold was measured across octaves and mid-octaves from 250 Hz to 8000 Hz in a free field setup. For TDC, the actual thresholds were obtained for each ear using a calibrated double channel diagnostic audiometer coupled to TDH-39 earphone to estimate air conduction threshold and Radio ear B-71 for bone conduction threshold. Each participant's threshold was measured across octaves from 250 Hz to 8000 Hz.

Immittance Evaluation

Immittance evaluation was done using a calibrated GSI-Tympstar Pro with a 226 Hz probe tone frequency for tympanometry. In addition, both ipsilateral and contralateral acoustic reflexes were obtained at 500 Hz and 1000 Hz. TDC group demonstrated A/As type tympanogram with present acoustic reflexes at 500 Hz and 1000 Hz.

Table 3.2

Pure tone average and tympanometry results of TDC group.

Sl. No	Age (Years)	Gender	Right Ear PTA (dBHL)	Left Ear PTA (dBHL)	RE Tympanometry (Type)	LE Tympanometry (Type)
1	12	Male	12.5	10	A	A
2	12	Female	18.75	15	A	A
3	12	Male	15	13.75	A	A
4	12	Male	10	10	A	A
5	11	Male	15	12.5	A	A
6	11	Male	18.25	15	A	A
7	12	Female	13.75	13.75	A	A
8	11	Female	15	10	A	A
9	8	Female	16.25	15	A	A
10	9	Female	10	10	A	A
11	11	Female	15	13.75	A	A
12	10	Female	20	20	A	A
13	6	Male	15	16.25	A	A
14	6	Male	15	20	As	A
15	7	Male	10	12.5	A	A

Gap Detection Test

The temporal resolution was measured in each group using gap detection test developed by Shivaprakash and Manjula (2003) in sound field condition. Participants were familiarized with the practice items before the actual test. Each stimulus set consisted of three noise bursts of 300ms duration separated by a silence of 750ms. A gap was presented at the centre (50% of the total burst duration of each burst) in one of the three bursts. The stimuli were presented at the most comfortable level. The duration of the gap varies between 20ms to 1ms. The minimum gap identified accurately and consistently was considered as gap detection threshold in each group.

Statistical Analyses

The Shapiro-Wilk test was applied to the GDT Scores of each group, given that the sample size in each group was 15 participants. The Shapiro-Wilk test yielded a statistic of 0.859 ($p = 0.023$) for the CCI group and 0.808 ($p = 0.005$) for the TDC group. Both values fell below the significance threshold of 0.05, which is taken to indicate that the GDT Scores in neither group were normally distributed. As a consequence, non-parametric statistical procedures were more appropriate for all subsequent analyses.

CHAPTER 4

RESULTS

The present study aimed to determine the Gap Detection Threshold (GDT) in children using cochlear implants (CCI) and to compare it with that of typically developing children (TDC). The present study also aimed to investigate the effect of post-implant durations on gap detection thresholds in children using cochlear implants. The gap detection thresholds were measured in milliseconds (ms) for the children using cochlear implants and typically developing children and were subjected to descriptive statistics. The outcomes of descriptive statistics are shown in Table 4.1.

Table 4.1

Descriptive statistics of GDTs for CCI and TDC Groups

Group	**N**	**Mean**	**Median**	**SD**	**Min**	**Max**	**IQR**
CCI	15	15.00	16.00	3.09	10	20	4
TDC	15	6.80	6.00	1.27	5	9	1

Note. CCI =Children using Cochlear Implant group; TDC = Typically Developing Children group; SD = Standard Deviation; Min = Minimum; Max= Maximum; IQR = Interquartile Range; all values expressed in milliseconds (ms).

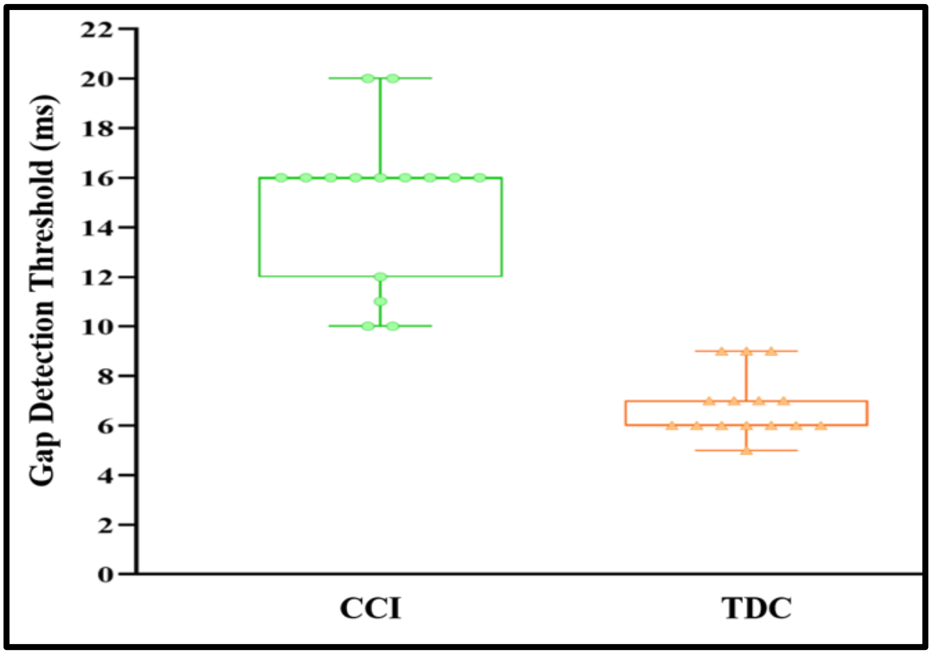

Figure 4.1 *Individual data of GDTs for CCI and TDC Groups*

1. Comparison of Gap Detection Thresholds (GDTs) Between CCI and TDC Groups

Children in the CCI group demonstrated a mean GDT of 15.00ms (Median = 16.00ms, SD = 3.09ms), with individual scores ranging from a minimum of 10ms to a maximum of 20ms as represented in Figure 4.1 and an interquartile range (IQR) of 4ms. In contrast, children in the TDC group showed a considerably lower (better) mean GDT of 6.80ms (Median = 6.00ms, SD = 1.27ms), with scores ranging between 5ms and 9ms and an IQR of only 1ms. The TDC group notably showed narrower distribution and lower central tendency values, suggesting substantially better temporal resolution compared to their peers with cochlear implants. Further, Mann-Whitney U test was performed to evaluate whether there is a difference in GDT scores between the CCI and TDC groups. The results of the Mann Whitney U test is presented in Table 4.2.

Table 4.2

Mann-Whitney U Test Results for GDTs between groups (CCI vs. TDC Groups)

Group	N	Mean Rank	Sum of Ranks	Mann-Whitney U	p-value	r
CCI	15	23.00	345.00	0.000	0.000	0.867
TDC	15	8.00	120.00	-	-	

Note. CCI = Cochlear Implant group; TDC = Typically Developing Children group; GDTs = Gap Detection Thresholds; N: No. of participants; p-value: Level of significance; r: Effect Size

The Mann-Whitney U test revealed a highly significant difference in GDT scores between the two groups ($Z = -4.749$, $p = 0.000$, $r = 0.867$). The mean rank assigned to the CCI group (Mean Rank = 23.00, Sum of Ranks = 345.00) was substantially higher than that of the TDC group (Mean Rank = 8.00, Sum of Ranks = 120.00), indicating that GDT scores in the CCI group were consistently higher (poorer) than those of their typically developing peers. The U value of zero is particularly important since it indicates a complete absence of any overlap between the two rank distributions, such that every child in the CCI group had a higher GDT than every child in the TDC group. This outcome led to the rejection of the first null hypothesis, which had postulated no significant difference in gap detection thresholds between the two groups.

2. Effect of Post-Implant Duration on Gap Detection Threshold

The second objective of the current study was to investigate whether the gap detection performance of a child was influenced by the duration of time they had been using a cochlear implant. The post-implant duration was documented in years for all 15 participants in the CI cohort. To investigate any correlation between the duration of implant use and GDT scores, a Spearman rank-order correlation was calculated. Spearman's rho (ρ) was chosen over Pearson's r due to the non-normal distribution of GDT data and its lack of parametric assumptions about the data. The Spearman correlation between post-implant duration and GDT was extremely small and negative ($\rho = -0.058$, $p = 0.838$, $N = 15$) as shown in Table 4.3. The correlation coefficient of −0.058 was negligible in magnitude and did not reach statistical significance ($p = 0.838$). The second null hypothesis that post-implant duration would have no significant effect on GDT performance was retained. These results suggest that the duration of cochlear implant use within the range observed in the current sample does not meaningfully predict gap detection ability.

Table 4.3

Spearman Rank-Order Correlation Between Post-Implant Duration and GDT in the CI Group

Variable	**r_s**	**N**	**p (two-tailed)**
Post-implant duration (years) × GDT (ms)	−0.058	15	0.838

Note. r_s = Spearman's rho; GDT = Gap Detection Threshold.

Overall, the findings of this study can be summarized into two observations. First, there was a statistically significant and clinically meaningful difference in gap detection thresholds between children with cochlear implants and typically developing children. The CCI group demonstrated GDTs approximately twice as large as those of the TDC group. The Mann-Whitney U test confirmed this difference to be highly significant ($p = .000$), and the complete separation of rank distributions ($U = 0.000$) underlines the robustness of this finding. This outcome indicates that participants in the CCI group experienced significantly reduced temporal auditory resolution relative to participants in the TDC group.

The second observation is the post-implant duration did not significantly predict gap detection performance within the CCI group. The Spearman correlation between implant age and GDT was negligible ($\rho = -.058$) and statistically not significant ($p = .838$). This analysis suggests that longer experience with a cochlear implant did not confer a measurable advantage in temporal auditory processing as assessed by the gap detection test under the current study conditions.

CHAPTER 5

DISCUSSION

The present study investigates temporal resolution in children using cochlear implants in comparison to typically developing children with normal hearing. This study utilizes gap detection threshold as the primary psychophysical measure. A secondary aim was to determine whether the duration of implant use had any meaningful relationship to their GDT performance. The results revealed that children using cochlear implants demonstrated significantly poorer temporal resolution than their normally hearing peers, while duration of implant use failed to emerge as a significant predictor of gap detection ability. The findings from analyses are interpreted in the following sections in relation to the established literature and their clinical significance.

1. Gap Detection Thresholds in Children Using Cochlear Implants Versus Typically Developing Children

The most prominent finding of the present study was the marked and statistically significant difference in GDTs between the two groups. Children using cochlear implants required a mean silent interval of 15.00ms to reliably detect a gap in an ongoing sound, whereas typically developing children performed this task with a mean threshold of only 6.80ms.

These findings are consistent with literature documenting elevated GDTs in cochlear implant users. In one of the earlier studies by Fitzgibbons and Wightman (1982) demonstrated that cochlear-impaired listeners exhibited significantly poorer gap detection performance than normal-hearing controls even when stimuli were equated for sensation level. It established a foundational expectation that cochlear damage disrupts temporal processing in ways that cannot be attributed simply to reduced audibility. The present findings extend this logic to the paediatric cochlear implant population.

Busby, Tong, and Clark (1992) provided earliest psychophysical data specifically from cochlear implant users, including gap detection thresholds collected alongside measures of duration difference limens, repetition rate discrimination, and electrode position identification. In their sample of early-deafened patients, GDTs ranged quite broadly across individuals, and for some patients the thresholds were considerably elevated relative to what would be expected from postlingually deafened. The mean GDTs of 15.00ms obtained in the present CCI sample falls within the upper range of values that Busby et al. documented, suggesting that the paediatric users in the current study may face temporal processing limitations that resemble those seen in early-deafened adults.

Wei et al. (2007) measured GDTs in a group of Mandarin-speaking cochlear implant users alongside frequency discrimination and tone recognition tasks, reporting a mean GDT of approximately 30ms with a range stretching from 4ms to 128ms. Their prelingually deafened subgroup tended to show higher thresholds than the post-lingually deafened group. The pattern visible in the present data given that the CCI participants had early and in most cases congenital or prelingual hearing loss. The range of 10ms to 20ms observed in the current CCI sample is narrower, possibly because the present study included a more homogeneous sample in terms of age, device type, and implant experience.

In one of the studies with a paediatric CI population was reported by Sharma and Yadav (2015), who measured GDTs at four frequencies (500 Hz, 1 kHz, 2 kHz, and 4 kHz) in children with cochlear implants and to compared with normally hearing children. Their normally hearing group returned mean thresholds ranging from approximately 3.4ms at 1 kHz to 4.8ms at 4 kHz, values that are closely aligned with the 6.80ms mean observed for the TDC group in the present study, with the remaining difference attributable to procedural factors including the use of narrowband rather than broadband noise marker and the younger age range of the present sample. The CI children in Sharma and Yadav's study showed thresholds that varied dramatically with post-implant duration: those tested only two months after surgery had mean GDTs exceeding 19ms at 500 Hz and reaching 23ms at 4 kHz, values strikingly similar to the mean of 15ms found here despite the difference in stimuli and frequency conditions. Taken together, the two datasets reinforce a consistent picture in which electrically stimulated hearing, regardless of the frequency band tested, yields temporal resolution that falls far below the performance of normally hearing age-matched children

In one of the study by Kumar, Chinnaraj, and Jain (2025) reported poor spectro-temporal resolution in children with cochlear implants could be due to technical constraints such as limited electrode coverage, current spread between adjacent sites, and the low-pass filtering of temporal fine-structure cues inherent to contemporary signal processing strategies. The poor temporal resolution abilities among children using cochlear implant could be because of channel-to-place mismatch that occurs due to variable insertion depths and an inability of the electrode array to encompass the full length of the cochlea (Baskent & Shannon, 2005).

2. Effect of Post-Implant Duration on Gap Detection Threshold

The second finding of the present study was absence of any significant relationship between post-implant duration and GDTs ($\rho = -0.058$, $p = 0.838$). One possibility for this finding is that the neural substrates underlying gap detection are shaped primarily by events that occur before or very soon after implantation such as the duration and timing of auditory deprivation, the age at which the cochlea began to receive input, and the integrity of the auditory nerve at the time of implantation. This is consistent with the observation in the literature that duration of deafness prior to implantation, rather than duration of implant use, is more robustly associated with psychophysical performance in cochlear implant populations.

Cosentino et al. (2016) reported a statistically significant positive correlation between duration of deafness and GDT in their adult sample, a finding that persisted after including two additional participants, suggesting that longer periods of auditory deprivation leave a measurable mark on temporal processing capacity even after implantation. In the present study, the duration of pre-implant deafness was not recorded as a separate variable. It would have demonstrated a stronger relationship with GDTs than post-implant duration did.

A second possibility, the developmental trajectory of gap detection ability in children with cochlear implants. In normally hearing children gap detection thresholds decrease across childhood as the auditory system matures, reaching adult-like performance levels somewhere around mid-to-late childhood depending on the stimulus conditions used. Another study by Kumar et al. (2025) observed that spectral resolution as measured by the spectro-temporal modulated ripple test, continues to improve in children with cochlear implants until implant age of approximately 13.7 years, whereas in normally hearing children the same abilities mature by around age 8.

A third possibility, which cannot be ruled out with the current design, is that post-implant duration does have a genuine effect on temporal processing, but that this effect is moderated by other variables, such as the type and brand of cochlear implant device, the speech coding strategy used, the extent of auditory rehabilitation, the amount of spoken language exposure in daily life, or individual differences in auditory plasticity and cognitive abilities. Kumar and colleagues reported cognitive factors including auditory working memory and auditory short-term memory as significant correlates of spectro-temporal resolution performance in children with cochlear implants (Kumar et al., 2025). Similarly, Fu (2002) demonstrated in adult cochlear implant users that mean modulation detection thresholds, measured across the full dynamic range of electrical stimulation, were very strongly correlated with phoneme recognition, suggesting that the fidelity of temporal envelope processing represents a key individual-differences variable. If individual differences in cognitive and perceptual processing are themselves more important than years of implant use in determining GDT outcomes, a simple bivariate correlation between post-implant duration and GDT may fail to capture the true structure of the data.

Gap detection thresholds have a functional relationship to the perception of speech sounds in which silent intervals serve as primary cues to phonemic identity. In English, the distinction between voiced and voiceless stop consonants in intervocalic position relies partly on the duration of the closure interval, and the perceptual boundary between phonemes.

Sagi et al. (2009) showed that the ability to identify gaps of varying duration was significantly correlated with CNC word recognition in their cochlear implant sample. listeners who can finely discriminate gap durations are better positioned to use the temporal gap cues that differentiate consonant categories. This advantage accumulates into better open-set word recognition. For the children in the present study, mean GDTs of 15ms are sufficiently elevated that they may already struggle to reliably detect the shorter gap durations that characterize voiced stop closures in running speech, particularly under adverse listening conditions such as background noise or fast speech rates.

Wei et al. (2007) study on Mandarin-speaking implant users found that gap detection was correlated with tone recognition primarily in noise. Frequency discrimination showed stronger correlations in quiet conditions. This difference suggests that gap detection ability may become especially diagnostic of speech understanding capacity when the listening environment is challenging such as classrooms. The elevated GDTs documented in the present CCI sample suggest that these children may face particular disadvantages in precisely those noisy listening situations where temporal gap cues become most important as a supplement or alternative to degraded spectral information.

CHAPTER 6

SUMMARY AND CONCLUSION

The present study aimed to investigate temporal auditory resolution in children using cochlear implants in comparison with typically developing children. Temporal resolution often assessed through the gap detection test. GDT reflects the auditory system's ability to detect brief silent intervals embedded within continuous sound. This capacity is considered key to speech perception in challenging listening environments.

A total of 30 children participated in the study and they were equally distributed into two groups of fifteen children each. The CCI group comprised children who had received cochlear implants and were actively using them, while the TDC group consisted of children with no known hearing or developmental concerns. All participants were administered a standardised gap detection test and their gap detection thresholds were recorded in milliseconds. In addition to comparing the two groups this study also explored whether the duration of cochlear implant use referred to as post-implant duration had any effect on the GDT performance within the CCI group.

The descriptive statistics revealed a clear contrast between the two groups. Children in the CCI group produced a mean GDT of 15.00ms (SD = 3.09ms) whereas those in the TDC group achieved a considerably lower mean GDT of 6.80ms (SD = 1.27ms). The TDC group displayed a much narrower distribution of scores that reflect greater consistency in temporal processing ability. Whereas CCI group showed greater variability which is consistent with the known heterogeneity of outcomes in cochlear implant users. The Mann-Whitney U test yielded a Z score of −4.749 with $p = .000$ indicating a highly significant difference between the two groups. This finding led to the rejection of the first null hypothesis which had posited no significant difference in temporal resolution between the two groups.

Regarding the second research question, the Spearman correlation between post-implant duration and GDT in the CCI group was negligible and non-significant ($\rho = -0.058$, $p = 0.838$). The direction of the coefficient was negative suggesting a very slight tendency for longer implant users to have marginally better thresholds. Hence the second null hypothesis was retained and it was concluded that post-implant duration as within the range of experience represented in the current sample did not predict gap detection performance in a reliable or clinically meaningful way.

The current study conclusions must be interpreted within the scope of the study's design and sample. The relatively modest sample size while adequate for the statistical approach adopted in the study but it limits the extent to which these findings can be generalised to the broader population of cochlear implant users. Furthermore, the range of post-implant durations represented in the sample may not have been wide enough to detect a clear relationship. It is also important to note that the gap detection test which is widely used as a measure of temporal resolution but captures only one dimension of auditory processing.

The contribution of current study to the existing knowledge is meaningful. It provides quantitative evidence that children using cochlear implants demonstrate significantly reduced temporal resolution relative to their typically hearing peers and that this gap is not appreciably bridged by longer implant experience. These findings have practical implications for audiological rehabilitation. Clinicians working with cochlear implant users should incorporate specific auditory training activities that must target temporal processing. Findings support the continued development of cochlear implant technology aimed at improving the fidelity of temporal cues delivered to implant users.

Clinical Implications

The findings of present study have several implications for clinical practice with paediatric cochlear implant users. They provide support for the routine inclusion of temporal resolution assessment as part of comprehensive audiological evaluation in children with cochlear implants. Standard clinical test batteries for this population typically emphasize speech recognition measures such as word and sentence identification in quiet and noise, but these outcomes aggregate the contributions of multiple perceptual abilities and may fail to identify specific processing limitations that could be addressed through targeted intervention. Gap detection testing can be completed quickly and does not require linguistic knowledge beyond an understanding of whether a sound is heard as continuous or interrupted. It offers a sensitive and non-linguistic index of temporal auditory function that is feasible for use even with younger children.

Future Directions

1. Future research would benefit from exploring temporal resolution across a larger and more heterogeneous sample of cochlear implant users and exploring a broader range of post-implant durations, including device types.
2. Longitudinal designs that track individual children over several years would be particularly valuable in clarifying whether and when temporal processing improvements emerge.

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