PSYCHOACOUSTICS AND SPEECH PERCEPTION OUTCOMES IN CHILDREN USING COCHLEAR IMPLANTS: A SYSTEMATIC REVIEW

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This Dissertation is submitted as part

fulfilment for the Degree of Master of Science in Audiology

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September, 2021

CERTIFICATE

This is to certify that this dissertation entitled **'Psychoacoustics and Speech Perception outcomes in Children using Cochlear Implants: A Systematic review'** is a bonafide work submitted as a part for the fulfilment for the degree of Master of Science (Audiology) of the student Registration Number: 19AUD026. This has been carried out under the guidance of the faculty of this institute and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

Mysuru
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DECLARATION

This is to certify that this dissertation entitled **'Psychoacoustics and Speech Perception outcomes in Children using Cochlear Implants: A Systematic review'** is the result of my own study under the guidance of Dr. Prawin Kumar, Department of Audiology, All India Institute of Speech and Hearing, Mysore and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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September 2021

Dedicated to my

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Acknowledgement

*I thank my guide, **Dr. Prawin Kumar**, for guiding and encouraging me at each and every step of my dissertation. I will always be grateful for your guidance. Thank you for being an exemplary mentor.*

*I am thankful to Director **Prof. M. Pushpavathi** for permitting me to take up this project.*

*I thank my **Aama** for being such an amazing and strong person, helping me with each and every decision of my life. I am thankful to my **Aama** and **Baba** for whoever I am and whoever I will be. I thank my brother **Sambriddha** for being such an amazing brother.*

*I thank my **Sanomuwa, Sanobuwa, Thulomami, Mama and Budhi aamai** for constant support in my life.*

*I am grateful and thankful to my **'potkrovlje'** group, Anshuman, Biraj, Dilli, Prateek, Ankit, and Aashish Dai, for making my time in Mysore wonderful.*

*I thank **Saranya** for always being there for me.*

*I thank my **Vidya, Kruthika**, and **Ariya** for all your help, love, and support in these two years.*

*I thank everyone from **Renovators 2.0** who helped me directly or indirectly in the completion of my dissertation and in my journey at AIISH.*

Thank you everyone!!

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Abstract

Cochlear Implant is the most successful implantable hearing devices prosthesis for the restoration of individuals with hearing impairment. Most cochlear implant recipients can detect the speech sounds well within the normal hearing thresholds range and within the speech banana curve, facilitating the transmission of almost all speech sounds in the speech spectrum. The present study aimed to systematically review the findings of published literature regarding speech perception outcomes and psychoacoustic abilities in pediatric cochlear implantees. Different databases were searched, and 18 articles were finally selected for the final qualitative analysis. The current review suggests that the speech perception outcomes have improved significantly after cochlear implantation in children compared to the baseline condition. There is a steady improvement in the speech performance outcome over time. In psychoacoustic tests, older children could perform better in pitch discrimination tasks than younger children. This review helps to establish developmental goals among children with CIs. Clinicians may use these goals to determine whether children have made appropriate progress and whether increased attention should be given to address particular speech perception issues. Limited studies have explored the psychoacoustic abilities in children, and the research gap can be bridged in future studies. However, overall, significant improvement has been shown with time with cochlear implantation in children.

Chapter 1

INTRODUCTION

Cochlear Implant is the most successful implantable hearing devices prosthesis for the restoration of individuals with hearing impairment (Cosetti & Waltzman, 2011). Currently, cochlear implants have been implanted in more than 600,000 individuals worldwide (The Ear Foundation, 2016). Multichannel Cochlear Implants are currently considered as the best treatment option for severe-to-profound sensorineural hearing loss (SNHL) in adults and children if these individuals does not benefit from hearing aids. Before the advent of cochlear implants, individuals with severe to profound SNHL had to rely more on lip-reading, sign language, or amplification fitted in non-invasive mode for communication, which could not make speech sounds audible and intelligible speech for them (Vermeire et al., 2003).

In the auditory system, hair cells of the inner ear are responsible for converting acoustic information to electrical impulses. The auditory nerve transmits the electrical impulse from the inner ear to the auditory cortex via the brainstem and auditory midbrain. Damage to the inner hair cells or the inner ear as a whole is the most common cause for severe-to-profound degree of hearing loss in these individuals (Strenzke et al., 2008). For such individuals, a cochlear implant can restore auditory functions bypassing the inner ear and stimulating the auditory nerve directly through electrical impulses.

A cochlear implant comprises of two parts: an external processor which is responsible for conversion of the acoustic signal to an electrical signal and also the processing of that signal before delivery to the auditory nerve and an internal implant which is a surgically implanted device and transmits the signal generated by an external processor to the auditory nerve through the help of the electrodes. Depending on the pathology and the patient's anatomical variations, various speech coding strategies and mapping parameters are used to maximize speech perception abilities in cochlear implantees (Cosetti & Waltzman, 2011).

Most cochlear implant recipients can detect the speech sounds well within normal hearing thresholds range (below 25 dBHL) and within the speech banana curve facilitating the transmission of almost all speech sound in the speech spectrum (Vermeire et al., 2003). It has resulted in a significant improvement in speech perception abilities and oral language development in individuals with severe-to-profound SNHL (Zwolan, 2008). Despite the development in cochlear implants technology, several factors might be associated with improved speech recognition and auditory performance in children using cochlear implant devices, such as the age of the implantation, deafness due to GJB2 mutation, inner ear anomalies, and meningitis (Black et al., 2011). The technological advances in the cochlear implant also account for the improved speech perception in cochlear implant recipients (Krueger et al., 2008).

Since the cochlear implant's advent 40 years back, the number of children receiving a cochlear implant is increasing exponentially. The increase in the number of cochlear implant beneficiaries might be attributed to the broadening of the eligibility criteria and more studies showing improved outcomes facilitating parents and professionals to opt for CI without a second doubt. Cochlear implants are still comparatively new to the research literature and to the many professionals working with these children. Before 1985, Food and Drug Administration (FDA) approved cochlear implants only for individuals 18 years or older. Currently, the age of implantation has been reduced to 12 months of age; however, we can find plenty of literature that suggests good implant performance with minimal surgery risk even before one year of age (Colletti et al., 2005a; Jöhr et al., 2008; Lesinski-Schiedat et al., 2004a; Miyamoto et al., 2008a, 2008b; Nicholas & Geers, 2013; Roland et al., 2009). The early implantation will maximize the speech perception scores in children tapping the critical period of language development. However, the fast-paced change in the field of pediatric cochlear implantation has caused many professionals to deal with implanted children with reduced implant outcomes confidence. Surgeons, for example, have "no reliable and accurate pre-surgical predictor of performance in cochlear implants." Audiologists and speech-language pathologists are the best professionals to measure and document communication progress overtime properly.

In the early days of introducing cochlear implants, limited data were available about cochlear implants' outcomes. Hence clinicians were also not very well known about the types of consequences observed by cochlear implant recipient, primarily in young children. Although implanted individuals demonstrated improvements with lip reading with single-channel devices, very few patients demonstrated good open-set speech recognition skills without visual cues (Carney et al., 1990). However, the performance of individuals with multichannel cochlear implants has shown a significant amount deal of improvement, which can be almost up to the level of 100% in different settings with the use of the implant (Zwolan, 2008). The significant improvement in cochlear implants might be responsible for the sharp increase in the performance of clients implanted over time. For instance, if we compare the first implant in 1982, using F0F2 coding strategy in Nucleus device, it was a mere 2 % correct mean open-set CNC word recognition (Patrick et al., 2006). However, by 2007, the Nucleus Freedom users demonstrated a mean CNC score of 62% (Zwolan, 2008). Different factors like technological advances in devices, changes in cochlear implant candidacy might be accountable for such steeply increasing performance in last two decades.

Furthermore, factors like onset age of deafness, the time between onset and receiving the implant, cause, structures of the cochlea, and communication methodology might have caused better CI recipients' performance (Waltzman, 2006). However, the primary factor in determining adult cochlear implant recipient performance is age and hearing loss duration. Those patients who are pre-lingually deaf performed poorly compared to cochlear implant recipients with post-lingually deafened adults (Skinner et al., 1992; Waltzman & Cohen, 1999; Zwolan et al., 1996). Cochlear implant recipients demonstrate a wide range of variability in performance. Some clients may perform better with mean word identification scores of up to 80%, and some average performing clients may score only 58% correct (Dorman & Spahr, 2006). Dorman's study revealed that the "better" performing clients are younger children and whose duration of deafness was shorter (Dorman & Spahr, 2006). However, it is not entirely clear about the role several determinants play in some clients regarding their outcomes or performance with a cochlear implant. With children, even more variables and factors might contribute to performance than those for adults. The reason might be due to differences in age of implantation at different auditory development stages, their mode of communications, and their educational and rehabilitation style. One of the firmly established notions is that implantation's age plays a significant role in the device's outcome. Several authors have reported that congenitally deafened children who get an implant at a young age before two years perform significantly better than later implanted children in speech recognition and spoken language skills (Anderson et al., 2004; Colletti et al., 2005c; Govaerts et al., 2002; Kirk et al., 2000; Lesinski-Schiedat et al., 2004b; Manrique et al., 2004; Miyamoto et al., 2008a; Nicholas & Geers, 2013; Niparko, 2004). Other factors that affect children's performance with cochlear implants include anatomical differences, surgical procedures and competency, devices integrity, additional handicaps, etc. Similarly, oral communication has been more efficient in developing spoken language skills than total or manual communication in implanted children (Geers et al., 2002; Geers et al., 2003; Tobey et al., 2003).

One of the significant factors in postoperative care includes monitoring performance using various suitable speech perception and speech and language measures, leading to the expansion of cochlear implant candidacy. Monitoring with speech perception measures gives us crucial information about the appropriateness of the mapping parameters and the requirement for and success of rehabilitative procedures used with the client, and information about the implant's internal and external components' integrity. The appropriate test for measuring speech perception in implanted children should be selected according to the client's age and vocabulary level. Hence, the tests should be changed as the child grows and his/her language skills develop. Similarly, the tests used to evaluate children's postoperative performance increased in complexity over time, both in terms of complexity of language and the intensity level in which the test is performed. The child's performance should also be assessed using a battery that assesses receptive and expressive skills, vocabulary skills, articulation, intelligibility, and reading skills. A simple performance measure and a more elaborate setting with a higher level of background noise been used to evaluate the child's performance. Clients' speech perception skills with early implantation were limited. Hence the test materials used for assessing speech perception scores were usually presented in quiet and at louder listening levels i.e., 70 dB SPL. Recently implanted clients demonstrate greatly improved speech recognition skills on a variety of test measures. These tests may vary from using just aided audiogram over loudspeakers to test the pure tones levels at early ages to the complicated sentences and word repetition in the presence of background noise like Bamford-Kowal-Bench Speech in Noise Test (BKB-SIN), which uses Bamford- Kowal-Bench sentences recorded in a background of four talker babble.

In the last four decades, there are continuous changes reported in the cochlear implant device's technology. Besides, tremendous research is carried out to report the utility of the CI device and the benefits of the CI recipients. Hence, the present systematic review will explore those studies reported with the expected outcome, psychoacoustic measures, and the impact of technology on speech perception among children using CIs.

Chapter 2

REVIEW OF LITERATURE

Cochlear implants have been one of the most successful prostheses for restoring individuals with severe to profound hearing loss who cannot be managed with hearing aids or other medical intervention (Cosetti & Waltzman, 2011). Since its first advent 40 years back, development and research to improve its performance have been tremendous. Cochlear implantation will allow most of the average postlingually deafened paediatric and adult cochlear implant recipient and very early implanted paediatric CI recipient to achieve near-normal understanding (Vermeire et al., 2003). However, the complex interaction of different factors will determine the outcomes of CI recipients. Studies have identified different factors that may be playing roles in determining the outcomes. These factors can be divided into device-related factors and subjects-related factors.

2.1 Device related factors in CI Outcome

The optimal performance of CI depends on the appropriate implant hardware, including the internal implants, electrodes, or speech processer, and processing of sound fed into the processor. The performance of multi-channel CI is far superior to the performance with initial single-channel cochlear implants and hence been device of choice. Similarly, along with the physical channel, the development of a virtual channel in HiRes 90K can result in 120 virtual channels (Firszt et al., 2009) However, not only the channels but these developments from multipeak (MPEAK) to spectral peak (SPEAK) to continuous interleaved sampling (CIS) have improved the outcomes in CI recipients. The use of virtual channels with current steering technology is superior in obtaining open-set speech identification, music perception, the distinction between instruments, sound quality, and music pleasantness compared to other processing strategies. There are various kinds of electrode designs, and it varies across companies. The choice of electrode design depends upon the anatomy of the cochlea and the choice of surgeon. Theoretically, the perimodiolar electrode design is better because of the smaller distance with the modiolus. However, no such evidence of significant performance in speech identification has been observed (Cosetti & Waltzman, 2011).

Short electrodes, atraumatic cochleostomy, and insertion techniques are used for the preservation of residual hearing (Lenarz et al., 2006, 2009). Significant improvements in speech perception and sound source localization are seen in these patients due to preserved low-frequency hearing. Cochlear implantation in children with partial deafness has shown promising results where speech performance improved from 34 % and 7% to 67% and 47% in quiet and noise. Studies have further shown improved performance with technological advancements (Krueger et al., 2008).

2.2 Subject related factors in CI Outcome

The improvement in the cochlear implant users depends on both device-related factors as well as subject-related factors. Even if the two children are recruited using same implant, different factors like age of implantation, associated disabilities, anatomic abnormalities, preoperative speech and hearing performance, auditory training, mode of communication, and the parental motivation for the therapy affect the outcome of cochlear implantation.

2.2.1 Age of implantation and duration of deafness:

Early diagnosis and rehabilitation have been possible due to new-born hearing screening programs. The children can now be implanted at less than one year of age. The primary motive for implantation in younger ages can be attributed to the studies on the auditory development of normal-hearing infants. Studies have shown that speech perception and production ability develops quite early and is primarily tuned to the native language by 12 months (Kuhl, 1979; Werker & Tees, 1984). Therefore, infants require early auditory input during this critical period. However, numerous contemporary literature suggests significant plasticity even after infancy (Davis et al., 2005; Kraljic & Samuel, 2005; Lively et al., 1993; Norris et al., 2003). For example, Sharma and colleagues, in 2002, using P1 responses in evoked cortical potential, showed that the plasticity and development of the central auditory system exist up to three and half years of age and may extend up to seven years of age in some individuals (Sharma et al., 2002). Similarly, several studies have shown critical changes in speech perception even during the second year of life when children learn how to map acoustic/phonetic cues to words (Dietrich et al., 2007; Rost & McMurray, 2009, 2010). There is also evidence for the continued perceptual organization of speech sounds well into the early years and beyond (Slawinski & Fitzgerald, 1998). Perceptual organization for speech is highly plastic and slow to develop, supporting the notion that it is acceptable to give parents more time to accept the hearing loss and feel comfortable with their decisions regarding implantation.

Studies have shown that the outcome of implantation is significantly better when the implantation happens before one year of age (Colletti et al., 2005b; Dettman et al., 2007; Holt & Svirsky, 2008; Miyamoto et al., 2008b; Roland et al., 2009; Tait et al., 2007; Tajudeen et al., 2010; Waltzman & Roland, 2005). However, in a study by Holt and Svirsky in 2008, authors did not find any difference in speech perception between children implanted before one year of age and those implanted between one to two years of age (Holt & Svirsky, 2008). Similarly, later the child is implanted, lower the speech performance outcome. The decrease performance in later implanted individuals can be attributed to the slow neural plasticity and increasing age. In a study by Arisi and colleagues, the authors found a correlation between the duration of deafness and speech perception outcomes (Arisi et al., 2010).

Hence, we have sufficient evidence to conclude that, although some neural plasticity may occur even during the later ages, earlier implantation will help more critical changes and help us tap the child's critical and sensitive language period. The later the child is implanted, the more deviated might be the listening age of the child; hence, more auditory and speech-language therapy would be required. Hence, earlier implantation will bridge the gap between the listening age and chronological age and help the children with hearing impairment get better integrated with their normal-hearing peers.

2.2.2 Associated disabilities and CI outcomes

The additional disabilities involved in addition to SNHL will play a significant role in the speech performance outcomes of cochlear implant recipients. Waltzman et al. (2000) concluded that cochlear implantation is beneficial for patients with associated disabilities along with severe-to-profound hearing loss. Children with additional disabilities are routinely implanted, with the anticipation of minimizing auditory deprivation and enhancing interaction with the environment and the possibility of language understanding and speech development. Outcomes in children with additional disabilities are variable, and parents must have realistic expectations after cochlear implant surgery. Among all the implanted children, studies have shown that 15% to 45% had additional disabilities like cerebral palsy, developmental disability, visual impairment, autism, and attention deficit hyperactivity disorder (Baldassari et al., 2009; Birman et al., 2012; Edwards, 2007; Filipo et al., 2004; Lesinski et al., 1995; Venail, 2010; Wiley et al., 2006; Wiley et al., 2008). The proportion of children with additional disabilities may have increased over the last two decades as more children are included as cochlear implant candidates, and more premature children survive.

Depending upon the type and severity of the associated condition, the outcome varies as well. Speech perception outcome in this group is comparatively lower than the individuals without additional disabilities (Berrettini et al., 2008). There is a significant difference in statistical and functional outcomes between implanted children with and without developmental disabilities (Baldassari et al., 2009; Birman et al., 2012). Children with additional disabilities perform inferiorly to the children implanted without any other associated disabilities. The median performance lies at two ling sound discrimination with no verbal language for implanted children with additional disabilities, whereas children without developmental delay achieved a median result consistent with a speech in sentences (Birman et al., 2012).

Lesinski et al. (1995) highlighted that cochlear implant children with additional disabilities, the meaning of success should be redefined; for example, hearing environmental sounds makes a difference to the child, even if spoken language is not obtained. Although the speech perception outcome is poor, significant benefits can be seen in the overall quality of life. The additional disabilities play an important role in predicting outcomes post-implantation (Meinzen-Derr et al., 2010, 2011; Wiley et al., 2005) .

As discussed earlier, early implantation means that children are often implanted at 12 months or younger to maximize residual neural plasticity. Learning difficulties and mild neurological deficits can be challenging to diagnose in children younger than two years (Quaranta et al., 2004). So additional disabilities may remain unknown, or the severity not entirely determined at the time of cochlear implant surgery. The incidence of having an additional disability is high, which might not be already known to a full extent during early cochlear implantation and can have impact on speech outcomes. Therefore, before cochlear implantation, it is better to counsel parents to consider this possibility and help to manage their expectations.

2.2.3 Anatomic Abnormalities and CI outcomes

Almost one-fifth of children with SNHL have some radiological anomalies of the temporal bone and are further associated with a wide range of hearing thresholds, progression of hearing loss, and other anomalies (Jackler et al., 1987). The more severe the temporal bone deformity will have the poorer hearing ability. Initially, only mild cochlear dysplasia was considered for cochlear implantation (Phelps, 1992a, 1992b). However, increased experience and increasing literature support in these individuals have led to more children with abnormal cochleovestibular anatomy being considered candidates for CI. One of the study showed that thresholds in five individuals (including a child) with Mondini deformities were in a similar range as patients with normal cochlear structures with substantial variability in performance on speech perception tests. They showed that Mondini deformity was not a contraindication to multichannel cochlear implantation (Munro et al., 1996). Similarly, another study showed that speech perception outcome is similar in children with and without cochleovestibular anomalies (Papsin, 2005). The reason for such findings may be due to significant redundancy in cochlear innervation even in an anomalous cochlea so the input from a 22-channel device can be effectively processed (Papsin, 2005).

Children with incomplete partition generally have progressive hearing loss and can obtain higher speech perception scores. Compared to those, children with common cavity deformity and hypoplastic cochlea demonstrated poorer performance (Papsin, 2005). However, those groups also showed improved speech perception ability with increased duration of cochlear implant use. Narrowed internal auditory canal (IAC) (<2-2.5 mm diameter) generally performs poorer than children with normal and children with anomalous cochleovestibular anatomy, probably due to a lack of cochlear nerve (Bamiou et al., 2001; Lo, 1998; Phelps, 1992b; Shelton et al., 1989). A narrow IAC may contain a facial nerve only and may be predictive of an absent cochleovestibular nerve.

Optimal electrode placement is the primary requirement for maximizing the CI outcomes. There are multiple procedures of CI surgery, although accurate electrode placement is the goal for each of those procedures. Incorrect electrode placement, damaged electrodes can lead to poor outcomes with CI post-implantation. Improper insertion and poor performance can be due to congenital anatomical structures (cochlear malformation including common cavity, Mondini deformity, hyperplastic cochlea) and acquired conditions like cochlear ossification (meningitis, otosclerosis, and other infections) (Cosetti & Waltzman, 2012).

The outcome from the implantation may differ according to different cochleovestibular anomalies and hence should be careful in interpreting the results as a group. The proper insertion technique and placement of electrodes might be challenging, and hence we might get much variability in speech perception outcomes depending upon the type of anomalies.

2.2.4 Preoperative Speech-Language and Hearing function

After approval of cochlear implantation by the FDA in 1990 for severe to profound hearing loss, there has been evolving candidacy, and implants have been possible even for those with more residual hearing and higher auditory function. Different clinics and cochlear implantation centers consider varying audiometric levels as a candidacy criterion. Leigh, Dettman and colleagues in 2016 have shown that children with pure tone average (PTA) between 65 and 85 dB HL benefit more with cochlear implants as compared to the hearing aids and hence be considered for cochlear implantation (Dettman et al., 2016). Similarly, a review by De Kleijn and colleagues in 2018 reported that children who have PTA of less than 80 dB HL benefit more from cochlear implantation (De Kleijn et al., 2018).

Studies have shown that preoperative hearing is a predictor of speech-language and hearing outcomes after cochlear implantation (Adunka et al., 2008; Arisi et al., 2010; Niparko et al., 2010) . Numerous studies have shown positive outcomes in several areas, including improvements in speech, language, and auditory functions when implanted as off-level candidates (Hyde et al., 2010; Nicholas & Geers, 2007; Thoutenhoofd, 2006) .

Several studies have also reported that positive speech-related outcomes after CIs in children with hearing loss are closely associated with the amount of preoperative residual hearing (Chiossi & Hyppolito, 2017; Leigh et al., 2016). In addition, the development of CI technology for preserving residual hearing in low frequencies has led to improved hearing abilities and speech perception in noise, overall natural sound and music quality (Carlson et al., 2015; Carlson, O'Connell, et al., 2018; Carlson, Sladen, et al., 2018; Eshraghi et al., 2017; Skarzynski, 2021; Zanetti et al., 2015). Hence, it might be cumbersome for parents to decide themselves to opt for cochlear implantation or hearing aids as no such clear line occurs for considering for respective management. Since growing literature supports superior findings of speech, language, and auditory function even in moderately-severe to severe hearing loss patients with Cis. The audiologist while counseling needs to facilitate in decision-making process, helping parents to choose appropriate management for their child after knowing all the possible options.

If the speech and language development prior to cochlear implantation are good, they are likely to achieve more benefits after cochlear implantation. They would already have some amount of feedback mechanism, knowledge of language rules, due to which it will be easier for them to adapt to the cochlear implant sounds compared to the children who are hearing any sound for the first time. Those children who already have lost some critical period of speech and language development show poorer outcomes with CIs.

2.2.5 Mode of communication and CI Outcomes

Cochlear Implants recipients who use oral communication before or after surgery have better performance than recipients using total communication (Cullington et al., 2000). The auditory-verbal or auditory oral approach is where the natural conversation takes place. Children with CIs need to be able to understand speech without any visual cues. In total communication, be it before or after the cochlear implant, children would still rely on visual cues and other modalities along with auditory cues. These visual cues will act as distractions during communication, and focus on auditory modality would decrease. Hence in the speech based tasks where visual cues are absent, they tend to perform lesser (poorer). Since most speech performance measures are with auditory cues alone, the recipients with the oral communication approach are likely to perform better than the recipients using the total communication approach. Hence, in the clinical setting, clinician should also encourage the parents to avoid using gestures and lip-reading and focus on the auditory modality alone to facilitate communication.

2.2.6 Auditory training and CI outcome

Auditory abilities are linked to language learning and literacy development in children with normal hearing (Kuhl et al., 2005; Mann & Foy, 2007) and some clinical populations (Corriveau et al., 2007; Witton et al., 1998), including children with CIs (Geers & Hayes, 2011; Tobey et al., 2003). Studies have found that cochlear implanted children have better performance in quiet and have significant difficulty in noise due to different auditory and cognitive factors (Caldwell & Nittrouer, 2013; Pisoni et al., 2011; Pisoni & Cleary, 2003). Understanding speech in noise is crucial for everyday communication and academic success for all children, including children with CIs. The deficits in speech perception in noise implanted children cannot be remediated solely based on implant processing at present and hence require added behavioral intervention (Ingvalson & Wong, 2013).

Auditory training improves adult CI users' speech-in-noise performance in various conditions, suggesting that adults with post-lingual deafness who have CIs demonstrate perceptual learning (Fu et al., 2004; Ingvalson et al., 2013; Oba et al., 2011; Zhang et al., 2012). Similarly, comparable benefits have been shown in children as well. Mishra and colleagues (2015) demonstrated that implanted children could learn through training to understand speech in noise better (Mishra et al., 2015). Training-induced improvement in auditory perception may facilitate language learning in these children. Studies have found that auditory rehabilitation will facilitate speech performance outcomes and music appreciation after cochlear implant surgery (Fu & Galvin, 2007, 2008; Joshua et al., 2010). Structured auditory training would help the children transition from without cochlear implantation or any hearing impairment phase to the post-implantation hearing phase. The auditory training will help the children and parents learn various strategies and techniques, the basic do's and don'ts to facilitate the speech performance outcomes. Auditory training and speech and language therapy will help the implanted child accelerate speech and language development. Hence this will be one of the primary determinants for speech performance outcomes measures.

2.2.7 Social factors and Parental motivation and expectations

Studies have found that children with higher socioeconomic status have a greater rate of improvement in speech and language (Niparko et al., 2010). It can be attributed to better parental motivation for post implantation habilitation. Mothers have high expectations for the child's outcome after cochlear implantation, along with an intensive rehabilitation process. Similarly, poor communication regarding possible benefits after implants and poor relationships with the professional may add stress for the mother. Maternal satisfaction positively correlated with mothers' expectation of children's social and communication skills results suggested that during the cochlear implant candidates' revaluation and rehabilitation (Zaidman-Zait & Most, 2005).

Parental and family motivation is one of the important step for cochlear implant outcomes. Since the mother plays the primary role in the rehabilitation of the child, the importance of parental involvement is immense (Niparko et al., 2010). It requires a significant commitment from both families and parents to properly rehabilitate the child with cochlear implantation. Professionals should acknowledge parents' high hopes regarding their child's future outcomes. Professionals involved in child rehabilitation should continue to disseminate up-to-date, evidence-based knowledge on the efficacy of cochlear implants.

Different variables, as explained above, affects the speech perception outcomes in children using cochlear implants. It is not easy to quantify each of these variables' roles because of the complex interaction of all these factors. The heterogeneity of data in these studies itself might be contributing to the different results. Hence, we need to be careful about the generalization of the study results to all the CIs patients.

2.3 Aim of the study

The aim of the study is to study the speech perception outcomes in children using cochlear implants. Further, it is also aimed to study the psychoacoustic performance in children using cochlear implants.

2.4 Research Question

The specific research questions of the review were

1. How are the psychoacoustic measures performance and speech perception outcomes among cochlear implantees children?
2. What is the effect of technological advancement on speech perception outcomes in children using Cochlear implants?

Chapter 3

METHODS

The below mentioned method was approved by the institutional level committee to conduct the study. This chapter focuses on the procedures carried out for the study under the following headings.

3.1 Search Engines

3.2 Data extraction (Selection and Coding)

3.1 Search Engines

Studies were selected from the various database searches such as PubMed, Google scholar, Scopus, and Web of science. The search was carried out with appropriate keywords to find articles related to this topic. These keywords included "*Cochlear Implantation*," "*Speech perception test*," "*Children*," "*Severe-to-Profound hearing loss*," and the derivatives of these words were used with the usage of appropriate Boolean operators. Duplicates were found out and removed from the primary sample. The articles were selected based on the title and abstract screening. It was ensured that all the chosen articles are published in peer-reviewed journals. The inclusion criteria for the study were pediatric population up to 10 years of age , specific models of implant or speech processing strategies are mentioned, at least one of speech perception measures, or parental report measures, or psychoacoustical measures are reported and the articles should be published in English only. All the articles which did not meet the above mentioned inclusion criteria were excluded from the study. In addition, the exclusion criteria includes the studies done on adults, single sided deafness or having any cochlear anomalies conditions. Similarly reviews, case reports, animal studies, histopathological studies, studies with insufficient data, studies with duplicated data and studies with heterogeneous group of data and the articles published in language other than English were also excluded from this study.

3.2 Data Extraction (Selection and Coding)

A pre-piloted form was used for the extraction of data from the included studies. The extracted information included the study population, methodology, participant demographics, patient deafness characteristics, data relating to the speech perception tests, including the test conditions, device characteristics, and the outcome of the speech perception tests.

Chapter 4

RESULTS

This chapter deals with the results obtained from the review in terms of extraction of study, quality analysis of the selected articles, and a summary of the selected articles dealing with speech perception outcomes and psychoacoustic performances in children using cochlear implants.

4.1 Extraction of the Study

A total of 18139 articles were identified using database searches, which excluded 6541 duplicates. A total of 11598 articles were selected for the title and abstract screening. From those, 405 articles were further considered for full-text screening. Out of 405 articles, 18 articles that met the inclusion criteria were selected for the study. The summarized content of the included study is provided in the table 4.1. The selection process was validated further by inter-judge selection and discussion in case of any ambiguity arises in finalizing the published manuscript. The detailed Preferred Reporting Items for Systematic Reviews and Meta-Ana**lysis (**PRISMA) flow diagram for selection of studies were used for the present systematic review and same is mentioned below (Figure 4.1).

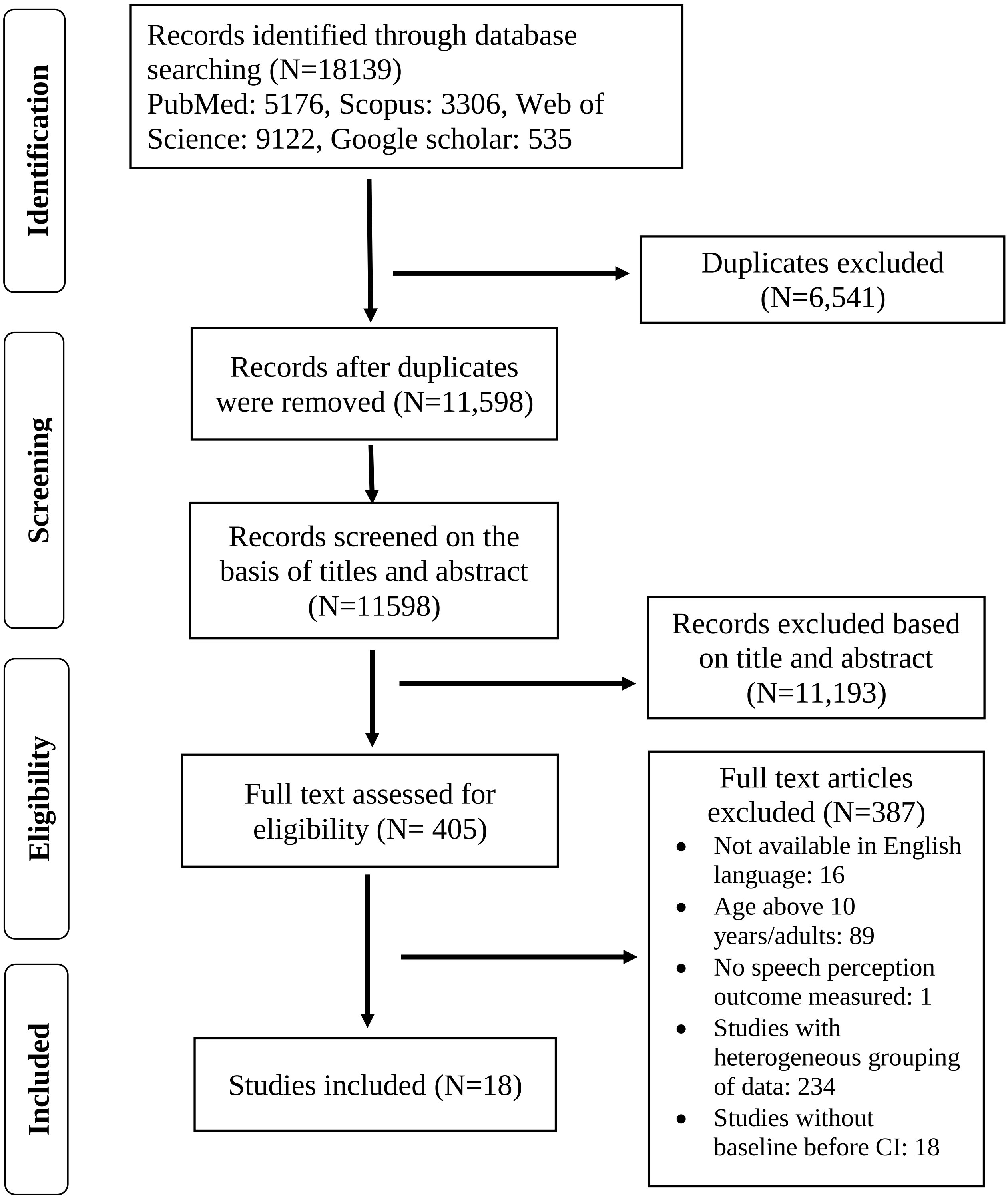

Figure 4.1: Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Flowchart for Selection of the articles

4.2 Quality Analysis

Critical Appraisal Skills Programme (CASP) checklist was used for the analysis of the selected studies (Figure 4.2). It has 12 questions to analyze the article. Most of the studies lack in identification of the confounding factors that might have deviated the results and the accounting of the same while analyzing the results. However, the cochlear implantation group being such a heterogeneous group, and many factors, as already described in earlier chapters, could affect the outcomes. Hence, it is not possible to account for and remove all the confounding factors. Also, some of the studies followed up for only 12 months to 18 months. However, improvement or differences might have been possible if the subjects were followed up for a longer duration. All the studies had shown acceptable results, had good implications for practice and were in line with the other earlier published studies.

Figure 4.2: Quality Assessment of Articles Selected for the Systematic Review

Table 4.1

Study characteristics of the selected articles, Test performed and Outcome

Sl. No.	Author/Year	Patients Demographics	Name of the Implant company	Test Performed	Methods used	Outcomes (++/ NS)
1	Anderson et. al (2004)	37 children Age range: <2 years	MED-EL Combi40/40+	LIP, MTP, MAIS, MUSS	1 year, 2 year and 3 year post implantation	++
2	Baumgartner et. al., (2002)	33 Children 1st Group (<3 years): 10F, 5M 2nd Group (>3 years): 7F,11 M	MED-EL Combi 40/40+	LIP, GASP	Pre-op and post-op after 24 and 36 month	++
3	Gstoettner et. al., (2000)	31 children Age range: 0.7-9.5 years	MED-EL Combi 40, Combi 40+	LIP, MTP, Closed Set MTP, Open set monosyllabic word test, GASP	Compares score Before Cochlear Implant, 24 and 36 months post CI	++
4	Manrique et. al., (2005)	58 children Age range: 1-7 years	Cochlear Nucleus 24 M or 24K or contour	ESP, Disyllabic word recognition test, Open set speech recognition test	Compared ACE vs. SPEAK groups	NS
5	Melo et. al., (2019)	30 children Age range: 1-3 years HiRES: 15 HiRES 120: 15	Advanced Bionics Clarion 1.0, 1.2 CI	ITMAIS, PRISE	Compared the two strategy. Testes at 3, 6 and 12 month post implantation	NS

6	Nikolopoulos et. al., (1999)	133 children Implanted before 8 years of age	Cochlear Nucleus 22	CAP	Follow up till 6 years post implant	++
7	O'Donoghue et. al., (2000)	40 children Mean age: 52 months	Cochlear Nucleus 22	Connected Discourse tracking	Followed up till 5 years	++
8	Osberger & Koch (2004)	21 children Range age: 12-18 months	Advanced Bionics CI and HiRES90K	ITMAIS	Tested 3 and 6 months post implantation HiRes vs CIS, SAS, MPS	++ Hires > CIS, SAS, MPS
9	Osberger et. al., (2000)	58 children Level 1: 36 (mean age: 3.4 years) Level 2: 22 (mean age: 8.6 years)	Advanced Bionics Clarion Multichannel CI, CIS strategy	Monosyllable word identification subtest of ESP test, GASP word test, PBK phoneme test, PBK word test	Tested at 3,6,12 and 18 months post CI. Compared with Pre op HA scores	++
10	Senkal et. al., (2014)	25 children Age range: 12-78 months	Neurelec Digisonic SP	MAIS, MUSS	Pre-op vs Post-op scores at 3, 6, 12 and 18 months.	++
11	Shipgood et. al., (2010)	24 children Age range: 1.6- 4 years	AB HiRes90K using Harmony or Platinum processor. And HiRes Fidelity 120	CAP, SSQ subscales	Preoperative baseline scores compared with 3,6,12,18,24,36,48 and 60 months	++

12	Staller et. al., (1997)	34 Prelingual children Age: 2.8 to 9.5 years	All children used Nucleus 22 implants. Converted from MPEAK strategy to SPEAK strategy. (About 2.4 years of MPEAK experience)	CID ESP Battery, WIPI, BKB sentences	Baseline scores were obtained with MPEAK strategy and after 6 months and 12 months of usage of SPEAK strategy	++
13	Waltzman, & Roland (2005)	18 children. Age: < 12 months	Cochlear Nucleus 24 RCS, CI 24RCA, CI 24 K and ACE strategy	ITMAIS, Age appropriate phoneme, word or sentence recognition tests., GASP, Common phrases test, MLNT, LNT	Baseline taken before surgery and further testing at 3 and 6 months post implantation and then every 6 months till ceiling was obtained.	++
14	Waltzman & Cohen (1998)	11 children Age: 14-23 months	Nucleus 22	ESP test, NUCHIPS, GASP, PBK, Common phrase test, MLNT, LNT	Followed up till 5 years.	++
15	Waltzman et. al., (1997)	38 children Age: <5 years	Multichannel Nucleus Implants. 34 MPEAK, 4 SPEAK strategy. Later 25 more shifted to SPEAK strategy	GASP word and sentence subtest, PBK list, Common phrase test, MLNT, LNT	Followed up till 5 years.	++
16	Wu et.al, (2008)	21 children Age: 6.8 - 10.1 years	Nucleus 24 SPEAK or ACE strategy	CAP, SIR	Follow up at 3,6,9,12,18,2 years, 2.5 years, 3,4,5 years	++

17	Young, et al.,(1999)	43 children	Clarion and Nucleus CI	ESP pattern perception spondee and monosyllables, PBK phones and wordlists, GASP words and sentences	Auditory skills were assessed at 6 months and 12 months after implantation	++ CIS>SPEAK
18	Zakirullah et. al., (2008)	21 children Age (<5 years): 11 5-9 years: 8 11 years: 2	MED-EL Combi 40+ and Tempo speech processor	LIP, MTP-3, MTP-6, MSW-4 and MSW-12, Closed set sentences, OSM, Language specific sentences, GASP, MAIS and MUSS	Pre-op scores were compared with one week, one month, three months, six months and 12 months post switch on.	++

Note: ++ indicates significant improvement; NS indicates no significant improvement)

LIP: Listening Progress Profile, MAIS: Meaningful Auditory Integration Scale, MUSS: Meaningful Use of Speech Scale, MTP: *Monosyllabic Trochee Polysyllabic Word test, GASP: Glendonald Auditory Screening Procedure, ESP: Early Speech Perception Test, NUCHIPS: North western University Children Perception of Speech, PBK: Phonetically Balanced Kindergarten List, BKB: Bamford Kowal Bench test, MLNT: Multisyllabic Lexical Neighborhood Test, LNT: Lexical Neighborhood Test, SIR: Speech Intelligibility Rating, SSQ: Spatial and Qualities of Hearing scale, PRISE: Production Infant Scale Evaluation, CAP: Category of Auditory Performance*

4.3 Speech Perception Scores improvement across timelines in different test measures used

Both questionnaire-based measures and speech perception measures have been performed to measure the outcome of children following cochlear implantation. The results obtained post-implantation in both of these outcome measures are further discussed below.

4.3.1 Questionnaire Based measures in cochlear implantees

Questionnaire-based measures are an easy and efficient way to get information about children's speech perception ability from the parents or the caretaker. Out of the 18 studies reviewed, four of the studies have used *Listening Progress Profile* test and have shown that the scores improved to over 95% post-implantation (Anderson et al., 2004; Baumgartner et al., 2002; Gstoettner et al., 2000; Zakirullah et al., 2008). *Meaningful Auditory Integration Scale (MAIS)* **i**s a popular measure to evaluate the meaningful use of sound in everyday situations. Out of the 18 studies, seven studies have used MAIS to assess the speech perception outcomes and the scores post-implantation ranged from 35% to 94% (Anderson et al., 2004; Manrique et al., 2005; Melo et al., 2019, Osberger & Koch, 2004; Senkal et al., 2014; Waltzman & Ronald 2005; Zakirullah et al.,2008). Similarly, *Meaningful Use of Speech Scale (MUSS) a*ssesses the child's use of speech in various contexts. Variable outcomes have been reported in MUSS across the four studies reviewed, with scores ranging from around 35% to 94% after cochlear implantation (Anderson et al., 2004; Manrique et al., 2005; Senkal et al., 2014; Zakirullah et al., 2008). *Category of Auditory Performance (CAP)* is a hierarchical rating scale with eight categories where '0' is no awareness of environmental sounds to a maximum of '7' where the child can use a telephone with a familiar talker. Only three of the 18 studies reviewed have used

CAP to measure children's post-implantation outcomes and have shown steady improvement over time. Nikolopoulas et al. (1999) showed maximum participants being in level '0' and most participants, i.e., 67% reaching level 5 in 1st year, and at six years, 82% of participants reached level 6 and above. In a study by Shipgood et al. (2010), the CAP improved at least a level every three months. Wu et al.'s (2008) study showed that median scores improved from '0' at pre-operative to '7' by three years of age. Among the 18 studies reviewed, only one study has used *Speech Intelligibility Rating (SIR)* and showed that median SIR improved from one preoperatively to five at three years after cochlear implantation (Wu et al., 2008). Similarly, the *Speech, Spatial and Qualities of Hearing scale (SSQ-P)* was used by Shipgood et al. (2010) and found that the scores ranged 3-6 for both unilateral and bilateral implantation (Table 4.2).

Table 4.2

Summary of post implantation results for different questionnaires across studies

Questionnaire	Number of Studies	Total Participants	Results post implantation
LIP	4	122	Range: 95%-100%
MAIS	7	210	Range: 35%-94%
MUSS	4	141	Range: 35%-94%
CAP	3	178	Level 6-7
SIR	1	21	Median: Level 5
SSQ-P	1	24	Range: 3-6

Note: LIP: Listening Progress Profile, MAIS: Meaningful Auditory Integration Scale, MUSS: Meaningful Use of Speech Scale, SSQ: Speech, Spatial and Qualities of Hearing scale, CAP: Category of Auditory Performance, SIR: Speech Intelligibility Rating.

Variable outcomes have been reported across studies in the questionnaire-based measures. Questionnaire-based measures have been frequently used to assess speech perception outcomes, especially in younger children when the speech-based measures are challenging to perform. Significant improvement have been seen in post-implantation conditions in the different questionnaire-based measures in the studies reviewed. However, due to poor reflection of the actual benefits derived with CIs based on Questionnaire based measure and therefore speech perception tests is preferred whenever possible to perform the same.

4.3.2 Speech perception tests in cochlear implantees

Word-based measures are frequently used for assessing the speech recognition scores in both adults and pediatric populations. Various speech-based tests have been used for word recognition scores to track speech perception across different timelines of measurements. The test that has been frequently used across the studies reviewed and have been discussed further (Table 4.3).

The *monosyllabic trochee polysyllabic word test (MTP)* consists of monosyllables, trochee, spondees, and polysyllabic words. Out of the 18 studies reviewed, only two studies have used this test and shown that the scores could reach up to 90% after two years of cochlear implantation (Gstoettner et al., 2000; Zakirullah et al., 2008). *Monosyllable Open Set Test* contains a two checklist with ten words in each list. The reviewed studies showed the improvement in the *Monosyllable Open Set Test* scores with increasing duration after cochlear implantation from around 20% to 85% (Baumgartner et al., 2002; Gstoettner et al., 2000; Osberger et al., 2000; Zakirullah et al., 2008)**.** *Phonetically Balanced Kindergarten List (PBK)* has four lists of 50 words each. Based on the number of phonemes and words correct, scoring is done. Out of the 18 studies, four studies have used PBK test to report speech perception outcomes. Scores were better for the phoneme test ranging from 50-61%, whereas scores ranged from 25-44% in the word-based test (Osberger et al., 2000; Waltzman & Cohen, 1998; Waltzman et al., 1997; Young et al., 1999). *The*

Multisyllabic Lexical Neighbourhood Test (MLNT) and Lexical Neighbourhood Test (LNT) assess multisyllabic and monosyllabic word recognition skills. It has a two-level test designed to control for the lexical property of stimulus words. Out of the 18 studies, three studies have used these measures, and the scores were in the range of 83% to 100% (Waltzman & Roland, 2005; Waltzman et al., 1997; Waltzman & Cohen, 1998). Five of the studies used *Glendonald Auditory Screening Procedure,* and the scores ranged from 25% to 100%, with steady improvement over time (Gstoettner et al., 2000; Baumgartner et al., 2002; Osberger et al., 2000; Waltzman & Cohen 1998; Zakirullah et al., 2008).

Table 4.3

Summary of post implantation results for different speech perception tests across studies

Speech Perception Test	Number of Studies	Total Participants	Results post implantation
MTP	2	52	90%-100%
OSM	4	143	20-85%
PBK	4	130	Phoneme Based: 50-61% Word Based: 25-44%
MLNT	3	67	83-100%
GASP	5	154	25-100%
Closed Set Sentences	1	33	93-98%
Common Phrase Test	2	29	60%-100%
Connected Discourse Tracking	1	40	Median Score: 45

Note: *MTP*: *monosyllabic trochee polysyllabic word test*, *OSM: Monosyllable Open Set Test*, *PBK:* P*honetically Balanced Kindergarten List, MLNT: Multisyllabic Lexical Neighbourhood Test, GASP: Glendonald Auditory Screening Procedure*

Different phrases and sentence-based measures are also used to assess the speech perception ability of children with cochlear implantation. These provide more contextual cues when compared to words based measures. These require a higher level of language acquisition. These are important, especially for older children who achieve ceiling effect in different word-based measures. The ranges of speech perception scores in different tests used in various studies are presented in Table 4.3.

The scores in *Closed Set Sentences* ranged from 93% to 98% after two and three years of implantation (Baumgartner et al. 2002). Similarly, *the Common Phrases Test* scores ranged from 60% to 100 % in the two studies reviewed (Waltzman & Ronald, 2005; Waltzman & Cohen, 1997). *Connected Discourse Tracking* was used by Donoghue, Nikolopolous, and Archbold (2000) in children with cochlear implantation and showed that the mean scores per minute increased from '0' at preoperatively to approximately '45' by five years of age.

4.4 Speech Perception outcomes comparison across Different Processing Strategies

Different studies have compared different processing strategies. In a study by Stellar et al (1997), authors have compared the MPEAK strategy as baseline with 2 years of experience and then converted to SPEAK strategy. They showed that only 20% had open-set speech perception on the baseline, which increased to 93% at 12 months of using SPEAK strategy. Similarly, on BKB sentences, the mean scores of 0% at baseline increased up to 50% by 12 months after the change in strategy. Although the benefit is shown with the SPEAK strategy, the lack of a control group makes us challenging to interpret the results and have direct comparisons. Manrique et al. (2005) have compared the ACE and SPEAK in the group where ACE was found superior in only vowel identification tasks while no such differences were seen in ESP and Disyllabic groups. MAIS and MUSS were significantly better in the ACE group compared to SPEAK. Young et al. (1999) compared the nucleus 22 with

SPEAK strategy and Clarion CIS strategy in different timelines, i.e., 6 and 12 months on various ESP, PBK, and GASP tests. They found that Clarion CIS strategy users were superior in all of the tests in both measurement timelines. Osberger and Koch (2004) compared the HiRES strategy with conventional CIS, SAS, and MPS strategy and found the HiRES strategy was superior in both 3 and 6 months of age. On the other hand, HiRES and HiRES 120 were similar in performance based on mentioned studies.

Out of the 18 studies reviewed, the four studies have used the Med-El implant (Anderson et al., 2004; Baumgartner et al., 2002; Gstoettner et al., 2000; Zakirullah et al.,2008), eight Cochlear (Manrique et al.,2005; Nikolopoulos et al., 1999; Donoghue et al., 2000; Waltzman & Ronald, 2005; Waltzman and Cohen, 1998; Waltzman et al., 1997; Wu et al., 2008; Young et al., 1999), four Advanced Bionics (Melo et al., 2019; Osberger & Koch, 2004; Shipgood et al., 2010; Young et al., 1999), and one Digisonic (Senkal et al., 2014) have reported the speech perception outcomes. All of the studies have shown significant improvement after cochlear implantation as compared to the baseline scores. Hence it is evident that the parental questionnaire task is easier to score higher even in the first year of implantation. As the complexity of the speech perception task increases, the scores become poorer and require more duration to achieve higher open-set speech perception scores. From the present systematic review study, it is not straight forward to conclude that which of the implant is better among the four as just one of the studies by Young et al. (1999) reported the direct comparison between two implant companies, controlling preoperative performance between the groups regarding age, duration of HA use, and communication mode used between the participants. They showed that the scores were higher for the Clarion group with CIS strategy than the Nucleus group with

SPEAK strategy. Hence, probably these companies' products are having alike performance with their CI devices.

4.5 Psychoacoustic Outcomes in children using cochlear implants

One study selected for the review reported the psychoacoustic performance outcomes in children using cochlear implants (Joshua et al., 2009). The limited studies about psychoacoustic performance in children could be attributed to a variety of reasons, mainly being children unable to comprehend the instructions and provide the required attention during the task because of the complex nature of these psychoacoustic tasks including the pitch loudness and duration based task. Joshua et al. (2009) identified the pitch relationship between the two tones in children aged 5 to 15 years. They found that the correct rate for pitch perception varied between 9.5% and 92.5%. Similarly, pitch perception performance was better in children older than six years than those aged less than six years. The duration of musical training positively correlated with the correct rate of pitch perception. However, the effect of pitch-interval size was not significant on pitch perception, and there was no correlation between pitch perception and the age of implantation, gender, or type of cochlear implant.

Chapter 5

DISCUSSION

The present systematic review aimed to study the speech perception outcomes and psychoacoustic performance in children using cochlear implants. The result revealed significant improvement in speech perception measures. The findings from the results are further discussed in this chapter.

5.1 Development of Speech Perception Abilities after Cochlear Implantation

The research articles reviewed in the current study have helped us gain valuable insights into developing different speech perception abilities for various stimuli and conditions. Different tests were used across studies, but although the tests are different, their major areas are mostly similar. However, there is considerable heterogeneity across studies regarding tests used, cochlear implants, processor, age of implantation, and many other factors affecting the ability. We have tried to generate a possible timeline of speech perception abilities based on the studies reviewed. The information presented could provide us with valuable insights on how these abilities develop in children and can serve as a useful clinical tool for identifying the development of auditory perception abilities in children (Table 5.1).

Table 5.1

Development of different auditory skills post implantation

Auditory Skills	**3m**	**6m**	**12m**	**24m**	**36m**	**48m**
Major Improvement in Prelingual auditory skills	✓					
Emerging ability to identify closed set phonemes/words		✓				
Major Improvement in ability to identify closed set phones/words			✓			
Emerging Open set speech perception scores				✓		
Major Improvement in Ability to identify Common phrases					✓	
Development of Intelligible Speech					✓	
Major improvement in Perception over telephones					✓	
Higher Level Open set Speech Perception						✓

Note: ✓ Suggests the time after implantation a child could demonstrate particular skills. (m: Months)

The clinicians and therapists can use the results described in this study to help them identify the children's progress after cochlear implantation. If the progress is slow or a child cannot demonstrate any particular skills, the proper goals and more attention might be required to improve on that particular skill. Similarly, this also can act as a hierarchy to achieve particular skill sets before advancing to another. The studies taken here did not have any children with additional disabilities. We should confirm with the device integrity or breaking down the training into smaller chunks, closely collaborating with the parents for adequate stimulation, using other augmentative devices to enhance the sensory inputs to help with slower progressing children (Bell & Houston, 2014). Careful interpretation of these results is warranted before use with any particular child due to individual differences in performance.

5.2 Questionnaires and Speech Perception Measures to assess the Cochlear Implant Outcome

Cochlear implant outcomes can be measured in various ways, from using questionnaire-based measures to speech perception tests. Audiometric techniques should be used to examine the children to measure the outcomes of cochlear implantation accurately, but these measurements do not tell the whole picture about the effects of implantation all by itself. Because children can learn to use the sensations provided by their implants in various ways, audiometric measures do not directly tell us about the child's use of the implant in everyday life; this is why they are frequently supplemented by language development and educational achievement measures. Especially, young children cannot provide reliable information regarding speech perception tasks. The work becomes more challenging as the young children typically perform worse on auditory tests and scales in the first few months following implantation and may outperform their older implanted counterparts at later intervals, such as two years after implantation. The use of validated instruments, such as the Bamford–Kowal–Bench (BKB), or similar speech discrimination tools, open set speech perception tools or language developmental scales, such as the Reynell scales, would be the gold standard for assessing the benefits of early implantation. On the other hand, these metrics can only be used in long-term follow-up intervals after cochlear implantation.

The results of the current review highlight that the use of questionnaire-based measures are often used to measure the outcomes. Categories of auditory performance, listening progress profile, infant-toddler meaningful auditory integration scale, meaningful use of speech scale have been widely used in assessing the progress of auditory performance in very young children. The parental questionnaire has been widely used for the younger groups of children, as presented in the current review. The information obtained from the parents is beneficial because of various reasons. Parents are frequently the ones who determine whether or not their children need a cochlear implant. Therefore a questionnaire that highlights parents' perspectives would be a valuable approach to get an overview of the process and outcomes. Second, parents may offer reliable information about the child's functioning and an evaluative viewpoint on the implantation process, additional treatments that may be required, and the advantages and limits that may be encountered. A questionnaire of parents' views can be used as a single method which can be used to get information across a child's age levels. Finally, parents can also comment on outcomes across various situations (school, everyday life & the family). Hence, parents are the most comprehensive description of the outcomes of pediatric cochlear implants that can be obtained from a single source. However, it must be recognized questionnaire-based measures should not be used as a single source of information. The outcome measures using the questionnaires or parental views are usually considered "soft" measures because of several limitations. The parental questionnaires-based outcomes are subjective and indirect. Similarly, these also have inadequate reliability and validity. The studies reviewed have shown that these can easily reach a plateau, often reaching more than 90% score or the maximum level within a few years after implantation (Table 4.2). Hence the results from these measures should be complemented by other objective tools to get an overall idea of the outcomes of the cochlear implantation.

Different speech perception test has been used for assessing the cochlear implant outcomes in children. Although the outcome is similar across studies in the questionnaire-based measures, speech perception outcome measures in the studies reviewed are very diverse. The current review suggests that congenitally deaf children achieve a significant and usable open-set speech perception following cochlear implantation at an early age. However, the results across the studies are different in the same tests. For example, the monosyllable open sets test scores range from 20% to 85% in four of the reviewed studies. Similarly, five of the studies using GASP showed varying ranges from 25 to 100% (Table 4.3). The differences in the result can be due to various factors already discussed in the review chapters, such as differences in the age of implantation, device-related factors, and the duration of use. All the different factors could play a role in the outcome of cochlear implantation. In spite of that, the overall speech perception outcomes in the cochlear implanted children are promising.

5.3 Speech perception with different processing strategy

Since the arrival of cochlear implants, we have seen many technological advancements along the way in cochlear implant hardware and software. The speech processor of the cochlear implant is responsible for analysing the incoming sound into small time frames and processing it by amplifying, filtering, compressing, and coding the signal, which is then sent to cochlear implant electrodes. The speech processor should analyse speech in the same way the cochlea does to represent speech signals accurately. This task is executed by different speech processing strategies which consist of rules to code frequency, intensity, and time factors applied to the incoming signal and then sent to different processing channels and later to the electrode contacts. The frequency information is provided by electrode contacts and the stimulation rate, known popularly as place coding and rate coding, whereas the intensity information is derived from the current level presented in these strategies.

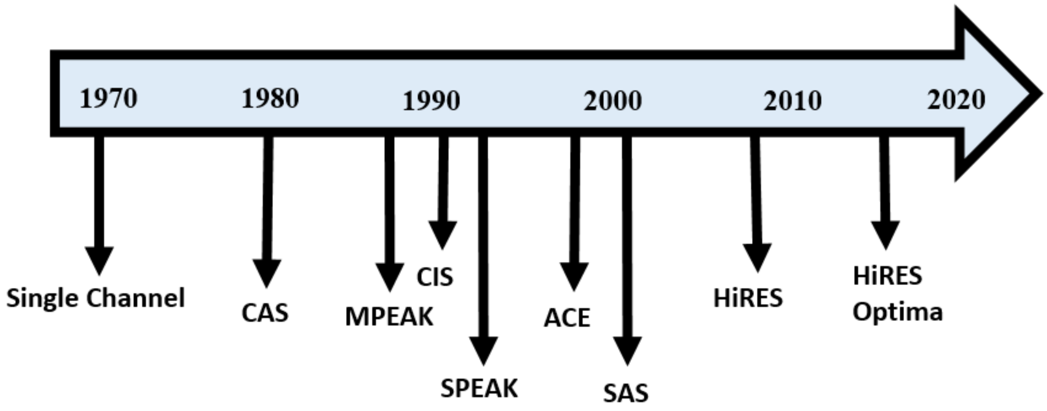

Figure 5.1 Development of speech processing strategy over time

(Note: CAS: Continuous Analog Stimulation. SAS: Simultaneous Analog Stimulation, MPEAK: Multipeak; CIS: Continuous Interleaved Sampling, SPEAK: Spectral Peak, ACE: Advanced Combination Encoder, HiRES: HiResolution; (Information from: Wolfe & Schafer, (2014))

Continuous Analog Stimulation (CAS) and Simultaneous Analog Stimulation (SAS) are the processing strategies of the earliest multichannel cochlear implants. Simultaneous strategies have more chances of channel interaction, whereas sequential strategies like CIS, ACE and all others (except CAS & SAS) have lesser chances of channel interaction. The MPEAK strategy is a feature extraction technique where SPEAK and CIS are peak picking and envelope-based strategy. The ACE is hybrid technology and utilizes the benefits of both CIS and SPEAK strategies. The SPEAK strategy uses 22 channels with 6-10 maxima; hence place coding is superior, whereas the rate is limited to only 200 to 300 PPS.

In contrast, CIS uses only limited channels and maxima of 4-12 but uses a high stimulation rate of 900-3500 PPS. Similarly, ACE has both benefits, i.e., it uses 22 spectral channels, maxima of up to eight, and the rate can be increased up to 3500 PPS. HiRES and Hires120 are close variation of CIS strategy with a high stimulation rate and 16 spectral channels. It uses Fast Fourier transform rather than envelope extraction techniques.

In the articles reviewed, the MPEAK strategy was inferior to SPEAK strategy, and ACE was superior to both (Stellar et al., 1997; Manrique et al., 2005). Similarly, in another set of studies, HIRES was superior to both CIS and SPEAK strategy and CIS strategy being superior to SPEAK strategy (Young et al., 1999; Osberger & Koch, 2004). Hence technological advancement with strategy has been shown to improve speech perception. Several other studies have also shown similar results as shown here in adult cochlear implant recipients (Kiefer et al., 1996; Kiefer et al., 2001; Koch et al., 2004; McDermott et al., 1992; Skinner et al., 1994).

Similarly, there has been a tremendous amount of development in technology from the various types of electrode placement, length of electrodes, different types of pre-processing strategies in different companies. However, most of the studies for actual comparison between those parameters involve the postlingually deafened adult cochlear implant recipient measure of ease of recording the responses. Many factors, as already discussed above, might affect the CI outcomes in children. Comparing the outcomes in those children would be a difficult task because of variables that cannot be controlled. We can undoubtedly generalize the findings from the adult population to the young cochlear implanted children to understand the role of those technologies in improving speech perception outcomes.

5.4 Performance in psychoacoustic measures

Different studies have suggested a relationship between speech recognition abilities and psychoacoustic abilities in normal-hearing and hearing impaired listeners. The correlation between speech perception and psychoacoustic ability is majorly obtained due to loss of audibility in hearing impaired individuals (Dubno & Schaefer, 1992; Plomp & Dreschler, 1980). Other than audibility, studies also have demonstrated a correlation between speech perception and measures of temporal processing (Boothroyd et al., 1996; Thibodeau & Van Tasell, 1987; van Rooij & Plomp, 1990). Different studies in adults have examined the speech reception with psychoacoustic abilities. Studies have concluded that gap detection (Busby & Clark, 1999; Shannon, 1989), forward masking recovery time (Shannon, 1990), and electrode discrimination (Zwolan et al., 1997) are poor predictors of speech perception ability in adults with cochlear implants.

Similarly, Fu, Shannon, and Wang (1998) demonstrated that speech perception is more correlated with the spectral resolution even though speech recognition in quiet is marginally dependent on it. Similarly, another study reported that variation in electrical stimulation comfort level across electrodes had poor speech recognition (Xu et al., 2005). Hence, it is crucial to understand the relationship between psychoacoustic measures and speech perception ability in individuals with cochlear implants, especially among children.

In the only study reported in current document, there is observation of variation in pitch perception among the cochlear implant listener (Joshua et al., 2010). The pitch discrimination scores differed markedly between 9.5% to 92.5% in implanted children in another study. Similarly, older children were able to perform better in the pitch discrimination tasks than younger children. The poor pitch perception could be attributed to channel setting of sound frequency and tone perception changes caused by the cochlear implant (Nardo et al., 2007; Reiss et al., 2007). Another likely explanation is abnormal frequency coding resolution that results from the disorganization of tonotopic maps in the auditory cortex of prelingually deafened children (Huffman & Cramer, 2007). Also, it can be attributable to an ability to better understand test instruction by older children, familiarity due to longer duration of cochlear implant use, and plasticity effect. Limited studies have explored the psychoacoustic abilities in children, and the research gap can be bridged in future studies. Similarly, although the very young child might be unable to perceive the instruction, the testing could be done in early implanted children who have higher open-set speech perception scores. The knowledge about the various psychoacoustic ability in the cochlear implant population can help researcher improve the processing strategies for cochlear implants, and this would be an exciting topic to explore in the future further.

Chapter 7

SUMMARY AND CONCLUSION

Cochlear Implants are currently considered the best treatment option for severe-to-profound sensorineural hearing loss (SNHL) in adults and children if these individuals do not benefit from hearing aids. Most cochlear implant recipients can detect the speech sounds well within the normal hearing thresholds range (below 25 dBHL), and within the speech, banana curve facilitating the transmission of almost all speech sounds in the speech spectrum. It has significantly improved speech perception abilities and oral language development in individuals with severe-to-profound SNHL. Different factors affect the speech perception outcomes. The optimal performance of CI depends on the appropriate implant hardware, including the internal implants, electrodes, or speech processer, and the processing of sound fed into the processor. The improvement in the cochlear implant users depends on both device-related factors as well as subject-related factors. Even if the same implant is implanted in many children, different factors like age of implantation, associated disabilities, anatomic abnormalities, preoperative speech and hearing performance, auditory training, mode of communication, and the parental motivation for the therapy affect the outcome of cochlear implantation.

The main purpose of the present review was to study the speech performance outcomes and psychoacoustic performance in children using cochlear implants. The review of the literature suggests that the speech perception outcomes have improved significantly after cochlear implantation in children as compared to the baseline condition. Similarly, as highlighted in the study, different speech based tests can be used for the assessment of the outcomes in CI children ranging from the questionnaire-based study to the speech perception tests. The studies suggest that the ability to identify closed-set phonemes/words occurs around six months after implantation, while higher-level open-set speech perception is achieved after around four years of implantation. Hence, there is a steady improvement in the speech performance outcome over time. However, there might be individual differences among the child, and the factors mentioned earlier could play a significant role in deviating the performance after cochlear implantation.

Similarly, in the reviewed articles, the technological advancement in the cochlear implant processing strategy has also been shown to improve the outcomes after cochlear implantation. Similarly, older children were able to perform better in the pitch discrimination tasks than younger children. This review helps to establish developmental goals among children with CIs. Clinicians may use these goals to determine whether children have made appropriate progress and whether increased attention should be given to address particular speech perception issues. Limited studies have explored the psychoacoustic abilities in children, and the research gap can be bridged in future studies.

Similarly, the direct comparison between the different companies of cochlear implants could not be made due to the lack of controlled studies comparing outcomes between those. Similarly, much heterogeneity occurs between the studies to make the comparison difficult. However, overall, significant improvement has been shown with time with cochlear implantation in children.

Implication of the Study

1. The present systematic review helped in understanding the gap in literature in terms of speech perception outcome in paediatric cochlear implantees.
2. It also helped in understanding the limited research conducted in the area of psychoacoustic measures in paediatric cochlear implantees
3. Add information to the literature.

Future directions

1. Systematic review of literature about speech perception outcomes in adults with cochlear implantees can be explored.
2. Systematic review of literature about psychoacoustic measures in adults with cochlear implantees can be explored.

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