A SYSTEMATIC REVIEW ON THE EFFECT OF COCHLEAR IMPLANTATION ON COGNITION IN CHILDREN

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This dissertation is submitted in partial fulfillment for Master's degree in Audiology

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AUGUST, 2022

CERTIFICATE

This is to certify that this dissertation entitled "**A systematic review on the effect of cochlear implantation on cognition in children**" is a bonafide work submitted as a part of the fulfillment for the degree of Masters of Science (Audiology) of the student with Registration Number: 20AUD036. 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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CERTIFICATE

This is to certify that this dissertation entitled "**A systematic review on the effect of cochlear implantation on cognition in children**" has been prepared under my supervision and guidance. It has also been 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 "**A systematic review on the effect of cochlear implantation on cognition in children**" is a result of my own study under the guidance of Dr. Geetha. C, Associate Professor in Audiology, All India Institute of Speech and Hearing, Mysuru and has not been and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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Abstract

Aim and objective: *The purpose of the current study was to summarize existing literature on cognitive outcomes in children with cochlear implant using behavioural and electrophysiological methods.* ***Method:*** *The study used a literature search on PubMed, Google Scholar, and Science Direct databases using appropriate keywords. After a thorough full-length review, articles were selected based on the study objectives. The selected articles underwent quality analysis using CASP questionnaire, and 34 articles were finalized for the review.* ***Results:*** *The review gave an insight into cognitive outcomes in children with CI. In all the behavioural non-verbal cognitive tests, children with CI showed cognitive development similar to that of normal hearing children. Cognitive scores showed a modality-specific result. Tasks requiring visual modality such as visual memory was not affected in children with CI even before the implantation. Whereas tasks using the auditory modality showed poorer scores in implanted children. Over the years, implanted children were on par with normal-hearing children in most of the cognitive domains except higher domains such as reasoning. However, in electrophysiological tests, varied results were found.* ***Conclusion:*** *Cochlear implants provide not only a long-term sensory benefit but also help in improving the overall cognition of the children. The studies also focus on the importance of early implantation and suitable rehabilitation for appropriate cognitive development.*

CHAPTER 1

INTRODUCTION

Hearing loss in children results in debilitating effects on their language, psychosocial, developmental, and cognitive skills, restricting learning and literacy (Udholm et al., 2017). The lack of auditory stimulation during the developmental period can inhibit multimodal interactions, which are vital for cognitive functioning. The synaptic network, also known as the connectome, depends on sensory experience for its development. Hearing loss can manifest as a disease involving the connectome, which hinders the development of the synaptic network. Since auditory modality is affected in individuals with hearing loss, other sensory modalities will take over its role, thus exhibiting adverse cognitive deficits (Kral et al., 2016).

Early auditory deprivation can cause the prefrontal cortex to reorganise and possibly slow the maturity of the frontotemporal regions, which might restrict executive abilities, including working memory and planning (Bharadwaj, 2015). Additionally, it may cause disruptions in the brain pathways required for the growth of higher-order cognitive functions such as auditory memory, encoding, serial processing, and learning (Todman & Seedhouse, 1994).

Fortunately, neurosensory restoration has been one of the foci of research in the field of aural rehabilitation. The invention of the cochlear implant (CI) has proven to be the most successful sensory prosthesis for managing severe to profound hearing loss. Since its invention in the 1970s, CI has gone through several upgrades and has been found to provide enormous benefits to its users. CI is a widely accepted form of rehabilitation to restore hearing, especially among the paediatric population diagnosed with severe to profound hearing loss. CI restores the missing function of inner hair cells by transforming the acoustic signal into electrical stimuli for activation of auditory nerve fibers (Lenarz, 2017).

Children with CI improve in auditory perception, speech, language and communication, and overall quality of life (Kim et al., 2010). Despite the known benefits of cochlear implantation, there is well-documented variability in these outcomes (Niparko et al., 2010; Geers & Sedey, 2011). The outcome of cochlear implantation depends upon the age of onset of deafness, etiology of deafness, length of deprivation, age of implantation, family environment, and communication mode (Pisoni, 2012; Geers et al., 2007). In addition to improving speech perception and quality of life, research has demonstrated that cochlear implantation helps hearing-impaired people's cognitive abilities (Volter et al., 2018).

Cognitive skills can be evaluated using subjective scales and checklists or electrophysiological measures such as late cognitive potentials. Both of these methods exhibit certain advantages and disadvantages, which will be discussed below. The current review considered studies done using behavioural and electrophysiological measures to provide better clarity and reliability on the cognitive results.

1.1 Behavioural assessment of cognition

Cognition is a vast domain with several measures to assess it. The Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2013) classifies cognition into its six principle domains - complex attention, executive function, learning and memory, language, perceptual-motor function, and social cognition.

Complex attention is the capability to pay attention to numerous things at once and to selectively pay attention to certain things while ignoring others. Individual’s capacity to organise the actions in response to external events is known as perceptual-motor control. In other words, an individual has the capacity to engage with the world around us via the use of both our motor and sensory faculties, such as vision and touch. With the help of social cognition, one can understand and anticipate own conduct as well as the behaviour of others in social circumstances (5th ed.; DSM–5; American Psychiatric Association, 2013)

Intelligence can be defined as a general mental ability that integrates cognitive functions such as perception, attention, memory, language, or planning (Colom, 2010). There are several standardized tests to assess intelligence in children, such as Wechsler Intelligence Scale for Children (WISC-V; Wechsler, 2014), the Universal non-verbal intelligence test (UNIT-2 Bracken & McCallum, 2015), and the Stanford-Binet intelligence scale – fourth edition (Thorndike, Hagen & Sattler, 1986). WISC-IV also has an Indian population-specific adaptation and norms (Wechsler Intelligence Scale for Children–Fourth Edition, India).

Short-term memory (STM) capacity, also called immediate memory capacity, is the amount of information that can be retained at any given time in one's mind. Working memory capacity or span (WM) involves an active system where information is held in the mind, internalized, assembled, manipulated, or transformed somehow, and then recalled or used in its new format (Bharadwaj, 2015). Some of the commonly used tests to assess memory and learning are: Woodcock Johnson III Tests of Cognitive Abilities, Normative Update (Woodcock, 2007), The Kaufman Assessment Battery for Children II (KABC-II). The Mullen Scales of Early Learning (MSEL; Mullen, 1995) and the Bayley Scales of Infant Development-Second Edition (BSID-II; Bayley, 1993). Leiter International Performance Scale, Third Edition (Leiter-3; Roid & Miller, 1997) is another widely used non-verbal cognitive test that includes non-verbal memory and attention skills. This test is designed to be culturally fair and thus, the outcomes do not vary depending on the participant's ethnic or social background (Khan et al., 2005). Apart from these tests, there are different methods used to assess memory abilities. One among them is forward and backward digit span, used as a measure of working memory in children with CI.

Cognitive batteries that have been developed and standardized for Indian population, particularly for children, is the NIMHANS neuropsychological battery for children (Kar et al., 2004). It has been validated for children aged 5-15 years. Porrselvi, A. P., & Shankar, V. (2017) stressed the lack of scalable cognitive batteries available for children in India. Bhavani et al. (2021) recently developed a machine learning-derived algorithm to assess cognition in preschool children known as DEEP (DEvelopmental Assessment on an E-Platform). It comprises gamified age-appropriate neuropsychological tasks based on BSID-III.

1.2 Electrophysiological assessment of cognition

Auditory evoked event-related potentials (ERP) were developed with the main objective of better feasibility for hearing assessment among younger populations such as infants and children (Davis, 1976). The P3 or the P300 component is a late ERP being utilized as a measurement tool for the evaluation of cognitive capability among the hearing impaired and normal hearing population (Brown et al., 1983). It uses an oddball paradigm where occasional target stimuli have to be detected in a train of irrelevant non-target stimuli. Irrespective of the stimulus mode (visual, auditory, or somatosensory), a positive deflection P300 will be seen for the target stimuli compared to non-target or irrelevant stimuli. It is the third positive wave of the cortical auditory evoked potential generated by the oddball paradigm, and it typically appears 300 milliseconds after the stimulus is presented. This deflection is seen when a person separates the target stimulus from the often-occurring sequence of inputs. P300 potential, an objective measurement of cognitive process induced by auditory stimulation, is an excellent measure of attention and memory operations (Goldstein et al., 2002; Polich, 2007).

It reflects cortical processes involved in stimulus assessment and categorization, decision-making skills, and memory operations. The neural generators of P300 are located in the frontal lobe, temporo-parietal junction, and hippocampus. Electrical activity resulting from the interaction between the frontal lobe and hippocampal/temporal-parietal function is reflected in the P300 wave (Huang et al., 2015). A cortical source analysis done by Ghiselli et al. (2020) found higher activation in frontal areas (Broca's area 10, 11, and 25) and cingulate cortex (Broca's area 32) in the same time window as that of P300.

For the cochlear implant recipients, who find it challenging to give consistent behavioural reactions, the P300 could be useful during implant activation, programming, or monitoring. A P300 peak would indicate that the auditory pathways' cortical regions have been stimulated by electrical stimulation (Oviatt and Kileny, 1991). They also proved that, in cochlear implant users, the amount of cortical activation was directly correlated to the duration of implant use and indirectly related to the age of the implant. The purpose of using P300 cognitive ERP in CI recipients has two purposes: First, to determine the feasibility of a neurophysiologic indicator of discrimination abilities of cochlear implant users, and secondly, to investigate the effect of central nervous system factors beyond peripheral nerve survival on performance with cochlear implants (Kinley, 1991).

Late ERPs have several advantages over subjective assessment measures. They are suitable to use in children with CI, require less cooperation from the children, and provide valuable data on the functionality of cognitive neural processes underlying discrimination of dissimilar sensory stimuli. It does not require intensive user training and is easy to administer and interpret. Even though p300 recording has several advantages, it is known to provide low real-time detection accuracy. Several human perceptual phenomena such as attentional blink, repetition blindness, and habituation can be potential sources of error in P300 detection (Fazel-Rezai, 2009; Citi et al., 2008). Although P300 cannot be used as a solitary measure to ascertain cognitive deficit, it can be used to analyse the functional network involved in the areas implicated in sensory and cognitive modalities. It can complement the results of behavioural measures and provide physiological evidence for the abilities measured (Vanaja & Sharda, 2019).

1.3 Need for the study

A systematic review provides the highest level of evidence by collecting all relevant studies related to a given topic and analysing their results. It enables the interpretation of old literature and helps to shed light on new developments in the field. The review also helps establish the relevance of older materials and identify gaps in the literature. These gaps can further be explored in research to establish new theories and facts in that field (Tolley et al., 2016).

As previously established, cognition plays an important role in a child's overall development. It includes important brain functions like thinking, reasoning, problem-solving, paying attention, and memory. A review done by Taljaard et al. (2016) showed that cognition is significantly poorer in individuals with untreated hearing impairment, and the degree of the cognitive deficit is significantly associated with the degree of hearing impairment. Even in the elderly population, hearing loss is associated with reduced cognitive functioning and the occurrence of dementia. The authors of the auditory scaffolding theory also ascertain that because the sound is a temporal signal by nature, a lack of auditory stimulation early in life may retard the development of cognitive skills involving the interpretation of sequential patterns (Conway et al., 2009). The auditory connectome model given by Kral et al. (2016) considers how the brain's connectivity is impacted by sensory loss; it emphasizes the neural connections between the auditory system and other cortical regions, such as those supporting higher-level cognitive abilities.

It is hypothesized that modifications to these connections brought on by hearing loss may have long-term effects on how cognitive capacities develop. Early sensory deprivation causing cognitive deficits in children can further affect their learning and development (Kral et al., 2016). Providing auditory stimulation through devices such as cochlear implants will help to restore these cortical changes. Hence, it is required to evaluate cognition in implanted children to determine if cochlear implants are effective at restoring cognitive abilities.

Previously published behavioral and electrophysiological studies on cognitive assessment have used various tools such as standardized questionnaires and checklists, which vary for different populations. These studies lack uniformity in terms of assessment protocols, thus showing varied results. This compels for a review that compiles all the information and provides clarity regarding the change in the cognitive skills following cochlear implantation in children. Hence, there is a need for carrying out a systematic review on the behavioral and objective assessment of cognition to better understand the broader performance outcomes in cochlear implantees.

1.4 Aim of the study

The aim of the study was to systematically review research papers published on the effect of cochlear implantation on cognitive outcomes using subjective and objective assessment in children with CI.

1.5 Objectives of the study

The objectives of this study are:

1. To undertake a systematic review of studies that evaluate the effect of cochlear implantation on cognitive abilities in children with a cochlear implant
2. To report the role of behavioral and electrophysiological measures of cognitive assessment in children with a cochlear implant.

1.6 Research question

This review made an attempt to address the following question:

- What is the effect of cochlear implantation on cognitive outcomes assessed through behavioral and electrophysiological measures?

CHAPTER 2

METHOD

The systematic review has been reported in accordance with the Preferred Reporting Items for Systematic Review and Meta-analysis (Page et al., 2020). Literature reporting included several stages as follows:

Stage 1: Search in databases
Stage 2: Selection and screening of articles
Stage 3: Data extraction
Stage 4: Quality assessment

2.1: Search in databases

The possible keywords and related search words were determined with the help of MeSH (the medical subject headings) strategy. The following two sets of keywords were used for searching the databases to get relevant articles for the two objectives of this review.

a) "Cochlear implant" [MeSH] AND "prelingual" AND "pediatric OR children" AND "cognition" AND "P300" OR "P3" AND "Late cognitive potential" [MeSH]
b) “Cochlear implant” AND “pediatric OR children” AND “cognition” [MeSH] AND “cognitive subjective test” [MeSH] AND “memory” OR “attention” [MeSH]

The studies were searched on various electronic search engines like Google Scholar, Science Direct, and PubMed (National Center for Biotechnology Information) using the above-mentioned possible keywords and related search MeSH words. Boolean keywords used were 'AND' and 'OR.'

2.2: Study selection and screening of literature

Study selection was based on the inclusion and exclusion criteria defined in a PICO format. PICO stands for patient population or the disease being addressed (P), intervention or the evaluation (I), control group (C), and the outcome or endpoint (O) (Liberati et al., 2009). This format helped in screening and analyzing relevant articles. Studies that met the following PICO criteria were included in the study.

- **Population**: Paediatric cochlear implanted participants till 15 years of age was included in the review. Studies that have included participants with multiple disabilities were excluded from the review.
- **Intervention/evaluation**: Studies that have administered objective (P300) and/or subjective measures to study cognition post cochlear implantation in children.
- **Control group**: Studies with normal hearing individuals as a control group or within-subjects repeated measures designs were selected.
- **Outcomes:** The outcome of the review provided insight regarding the changes seen in cognitive skills in cases with cochlear implants.

2.3: Data extraction:

Two independent reviewers screened the papers by going through the titles and abstracts. The references of the relevant studies were analysed in order to recognize more relevant articles in the review. Further, the justifications for exclusion were documented and checked in agreement with PRISMA criteria.

Details obtained from selected papers were organized in a table in the following sections: Study population, tests administered, domains assessed, participant demographics, age of implant, implant period, and results from different domains on cognitive tests. Studies that have used similar assessment tools were combined in groups, and outcomes were recorded accordingly.

2.4: Quality assessment:

Critical appraisal skills programme (CASP) given by Ruth Brice (2018) was used for the quality assessment of the articles. Cohort version of CASP was used in the current review as most of the studies included in the review were cohort studies. It has 12 questions divided into three sections. These questions had to be answered as either 'yes', 'cannot tell', or 'no.'

CHAPTER 3

RESULTS

This current chapter details the results of a systematic review involving cognitive outcomes in children after cochlear implantation. The results are divided into the following sections:

3.1 Results of database extraction

3.2 Results of quality analysis

3.3 Characteristics of the selected articles

3.4 Cognitive outcomes of cochlear implant using behavioural measures

3.5 Cognitive outcomes of cochlear implant using electrophysiological measures

3.1 Results of database extraction

A total of 7,339 articles were extracted after a thorough search of the databases. Out of which, 4,546 records were eliminated as they were duplicates. Title and abstract screening were carried out for the remaining 2793 articles, out of which 2,743 were rejected as they did not meet the objective of the review. Full-text screening was carried out for all the articles available in English text. Of the 45 articles reviewed, two published articles that included a study population with additional disabilities were not considered for the review. A study done by Kinley (1991) was not considered for the review due to insufficient subjects in the study. Three more articles were excluded as the results of correlation between cogntion and other variables such as reading skills, social development were oly given and not the data specific to cognition (Khoramian, 2018; Lina-Granade, 2010; Pisoni & Geers, 2000). Two other studies compared cognition test scores among the cochlear implanted group with good and poor speech outcomes (Daza, 2014; Mikic, 2014). These studies fall beyond the scope of this review, and thus these were excluded. A total of 34 articles were finalized for quality analysis. Of the 34 articles, 29 focused on cognitive assessment using subjective measures and five on objective measures. Details of the above are presented through PRISMA flowchart in Figure 3.1.

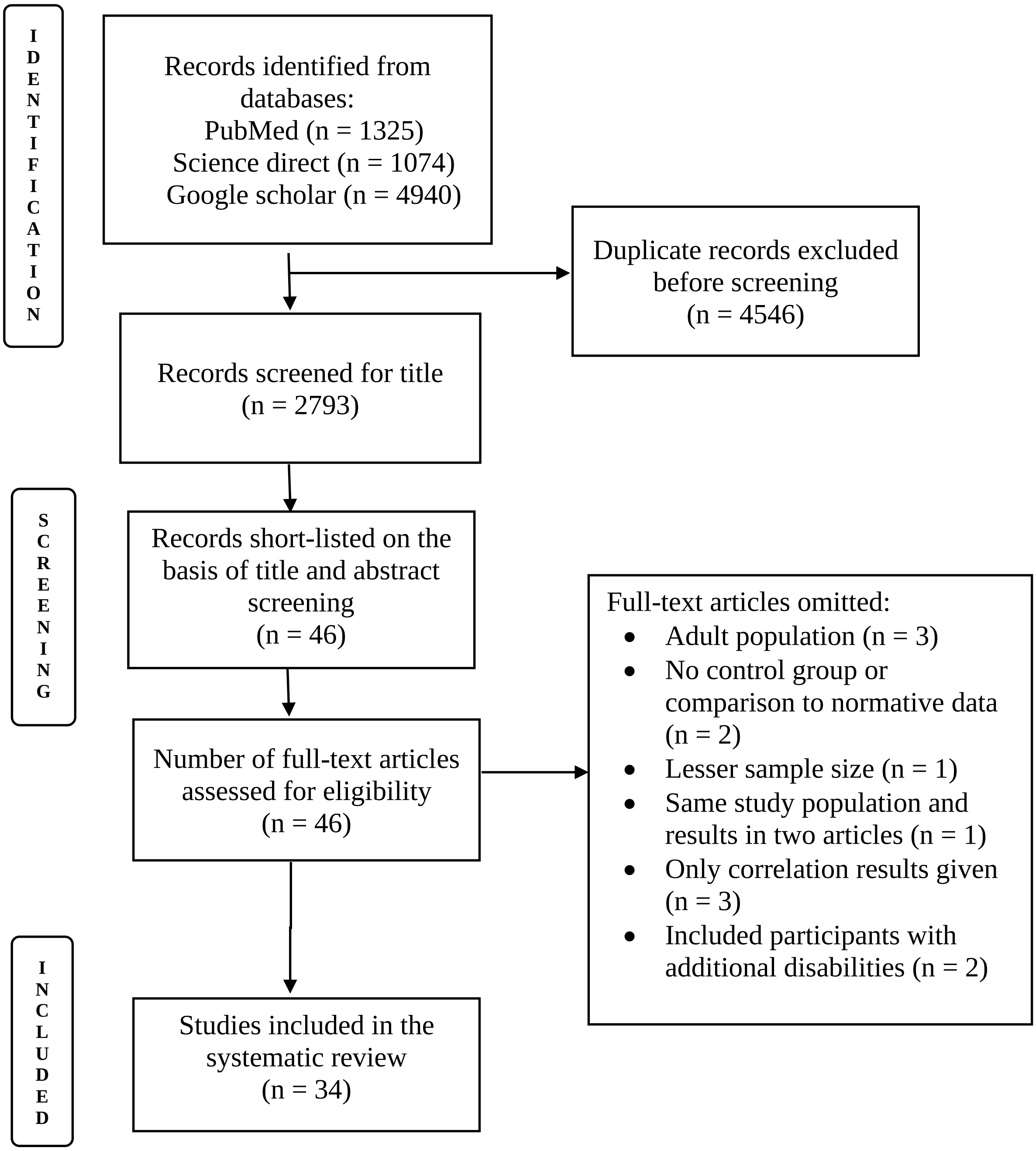

FIGURE 3.1

PRISMA flowchart to represent the selection process of articles included in the review.

3.2 Result of qualitative analysis

The articles extracted and screened in the initial step underwent a quality analysis using the Critical Appraisal Skills Programme (CASP) for cohort studies questionnaire (Ruth Brice, 2018). A majority of the articles selected were cohort studies, and hence the CASP-cohort questionnaire was selected. CASP checklist included 12 questions which were answered with a 'yes,' 'cannot say' or a 'no'. A determining criterion was decided to establish a comparable study quality. Two independent reviewers involved in the study decided on the inclusion criterion of a minimum of 5 for each article on close-ended questions. For open-ended questions, both the reviewers decided on the article's quality.

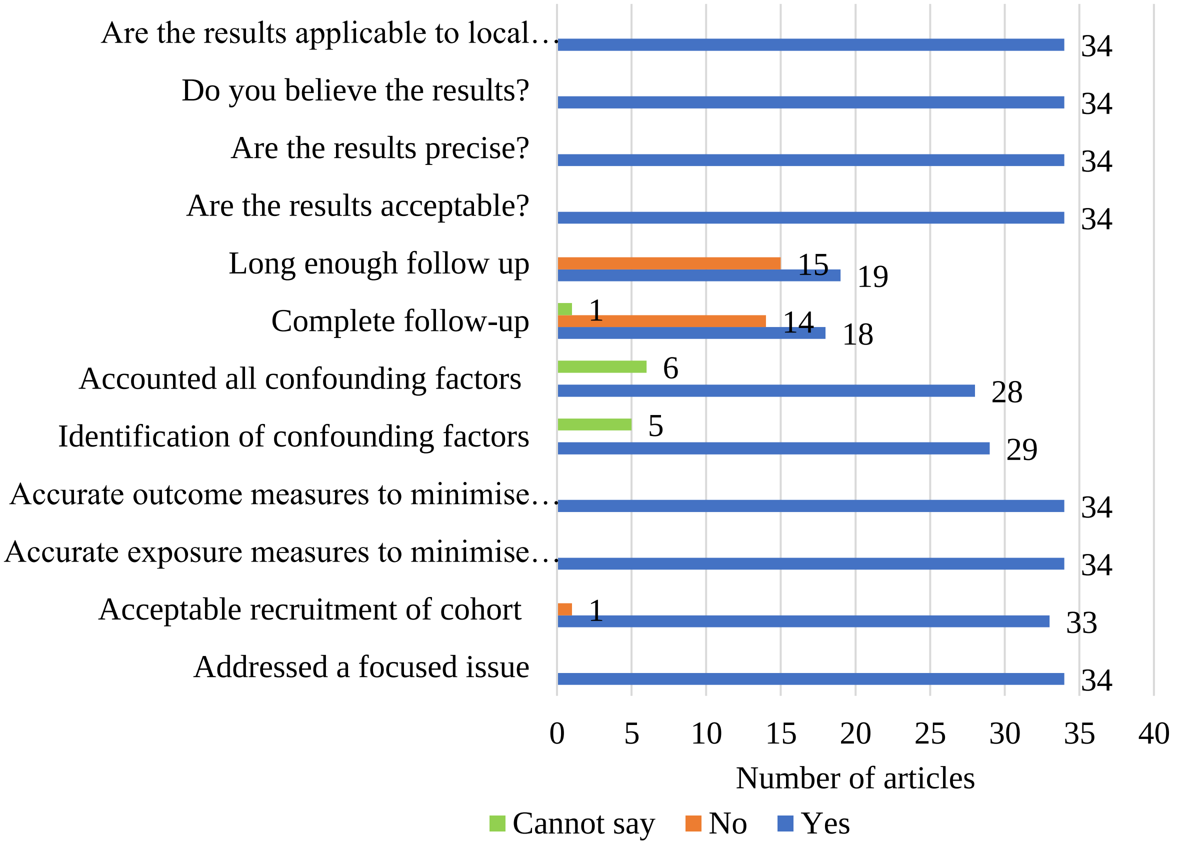

Figure 3.2

Quality analysis of the selected articles from the literature

Quality analysis of the selected studies is mentioned in Figure 3.2. The bar graph for each question shows how many studies said "yes," "no," or "cannot say." The number of articles showing "yes" were represented in blue, and "no" were represented in orange. Thirty-four articles met the cut-off criteria of more than 5 for close-ended questions and thus were included in the review.

3.3 Characteristics of the selected articles

The details of the study characteristics of all the selected articles are summarized in Table 3.1. The table includes a summary of all the cognitive tests performed, the type of study, the study population and their characteristics, control group or normative data comparison, and the outcome of each of the cognitive tests in PECO format. The individual names of the tests used to assess cognition are also mentioned in the summary table.

Table 3.1

The details of the studies and participant characteristics.

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
1.	Khan et al. (2005)	Cross-sectional study	• Three groups were assessed. • The first group had 25 children (10 males and 15 females, mean age: 4.22 years) with CI . • The second group had 13 children (8M:5F; mean age: 4.31 years) using bilateral hearing aids. • The third group had 18 (6M:12F; mean age: 3.95 years) normal hearing (NH) children.	• The visualization and reasoning battery and the attention and memory battery of LIPS-R were administered.	18 normal hearing children (Between-group comparison)	• The LIPS-R scores of the children in the HA group were lower than those of the other two groups. • With the exception of the attention subtest, the children in the CI and NH (normal hearing) groups performed equally well on the LIPS-R.
2.	Almomani et al. (2021)	Cohort study	• 38 children with CI were included (22 children in the age range of 4-6 years and 16 in the age range of 7-9 years).	• The cognitive abilities of imagery, reasoning, memory, and attention were evaluated using LIPS-R subtests. • Testing was done	48 children with normal hearing	• Before implantation, children scored higher on the visualization subtest than the NH children for both age groups.

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
			- The control group had 48 children with NH (24 children in each age range)	before implantation (Pre-CI) and eight months and 16 months post-CI.		- Memory and reasoning subsets showed poorer scores in the CI group compared to NH across all testing times and age groups. - Scores in the attention subset were similar among CI and NH groups.
3.	Huber and Kipman. (2012)	Case-control study	- 40 children with CI (19 males and 21 females, mean age: 10.1 years) - The control group had 40 children with NH (19 males and 21 females, mean age: 10.1 years)	- German version (CFT) of CFIT to assess inductive reasoning. Number sequences and arithmetic operations subtest of HRT test battery to assess deductive reasoning. - Coding, Digit Span, Comprehension, and Vocabulary subtests of HAWIK measures selective visual attention, short-term memory, common-	40 children with NH	- Children with CI scored identically to the NH group in inductive reasoning, auditory STM, visual STM, and selective visual attention tasks but poorer in deductive reasoning, common sense knowledge, and vocabulary (mathematical logical reasoning) tasks.

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				sense reasoning, and language skills, respectively.		
4.	Lyxell et al. (2008)	Case-control study	• 31 children with CI in the age range of 6-13 years (13 males and 18 females, mean age: 8.6 years) • The control group had 96 children with NH in the age range of 6-13 years	• Block design test of WISC-III battery to assess non-verbal intelligence. • Working memory tests: serial recall of non-words and non-word repetitions; sentence completion and recall; visual matrix patterns.	96 children with NH	• In all tests, with the exception of the visuospatial WM test, CI performed worse than NH. • Non-verbal intelligence (WISC results) in CI was on par with NH children.
5.	Shin et al. (2007)	Cohort study	• 17 children with CI were assessed (mean age of 6.65 years at the time of baseline testing)	• PTI Korean pictorial intelligence test; Leiter-R; ROCF to assess organizational ability and nonverbal memory. The Grooved Pegboard Test and Developmental Test of Visual-Motor Integration to assess	Compared to normative scores	• On the Korean PTI, the mean IQ score was at the borderline level. The subjects' full-scale pre-implantation mean IQ was 76.6, and at the 6-month follow-up, there was no discernible difference (79.4). • Prior to cochlear implantation, children

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				visuomotor coordination. • Korean Kaufman assessment battery for children to assess working memory. • Tests were done pre-implantation and six months post-implantation. • Korean version of Visual Continuous Performance Test (ADHD Diagnostic System) to assess selective and sustained attention ability attention.		with CI had normal, developmentally appropriate visuomotor coordination (The Grooved Pegboard Test). • Higher visuospatial organisational capacity (ROCF test) in deaf youngsters, however, appears to be fairly undeveloped but has improved after implantation. • The nonverbal intelligence subtests of the Leiter-R also significantly improved to the normal range at the follow-up. • Working memory assessed using the Korean Kaufman assessment battery showed significant improvement after

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
						implantation, but difficulty sustaining visual attention was noted in the Visual Continuous Performance Test.
6.	Bharadwaj et al. (2016)	Case-control study	• 10 children were included in the study (4M:6F) within the age range of 7-11 years.	• The WJ-III COG NU's numbers-reversed and auditory working memory subtests. • The WISC-IV Integrated visual working memory (Spatial Span) subtests. • The KABC-verbal II's knowledge subtests (Verbal Knowledge, Riddles, and Expressive Vocabulary), as well as the short-term memory subtests (Number Recall, Word Order, and	Compared to normative scores	• On activities involving visual working memory, children with CI showed average performance (scores ranging 85-115) and below average (standard scores below 85) on tasks involving auditory working memory. • The mean standard scores on the visual-motor (visual-motor) STM measures involving hand motions were substantially within the usual range, but the mean standard

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				Hand Movements).		scores on the auditory (word order and numerical recall) STM measures were below normal. • On all of the KABC II's verbal knowledge subtests, participants performed below average.
7.	Cejas et al. (2018)	Cohort study	• 136 children with CI (mean age at baseline: 2.2 years) • 75 children with NH (mean age at baseline: 2.3 years)	• IQ evaluation was done at the baseline using BSID-II or Leiter-R (which forms the Brief IQ Composite). • WISC-IV: Intelligence was measured using two indices: Perceptual Reasoning (PRI) and Processing Speed (PSI). • The assessment was done at the baseline, once every 6 months	97 children with NH	• Although the CI group showed significantly lesser scores in the baseline IQ, PRI, and PSI of WISC-IV, compared to NH individuals, their scores were well above normal.

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				for 3 years and annually for the next 5 years.		
8.	Caudle et al. (2014)	Cohort study	• 35 children with CI (21 males and 14 females; mean age at baseline testing: 2.05 years)	• MSEL was administered before implantation as a baseline measure. LIPS-R was administered after CI.	Compared to normative data	• Scores of the Visual Reception subtest of MSEL and Full IQ score of LIPS-R correlated well . Hence, results from both the tests across timelines were comparable. • Overall LIPS-R scores at follow-up were higher than MSEL scores measured at the baseline.
9.	De Giacomo et al. (2013)	Case-control study	• 20 children with CI (12 males and 8 females, mean age: 9.17 years). All the children were implanted at a mean age of 3.12 years • 20 children with NH (12 males and 8 females, mean age: 10.08 years)	• All the subtests of LIPS-R were administered to both groups. Ten subtests of the Visualization and Reasoning battery and 10 subtests of the Attention and Memory battery were carried out.	20 children with NH (both the groups were compared to normative data)	• No significant group differences were found in Full IQ score. • Of the participants in the CI group, 55% had scores that fell within the normal range, 40% were borderline, and 5% had scores that fell into the mild

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				• Full IQ score, which measures a general non-verbal intelligence, was calculated for statistical analyses.		impairment range. In contrast, in the NH group, 60% of the participants had scores in the normal range, 30% had scores that were borderline, and 10% had scores that indicated mild impairment.
10.	Tharpe et al. (2002)	Cross-sectional study	• 9 children with CI (4 males and 5 females; aged 5-11 years; mean age at testing: 10.25 years) • 10 children with NH (3 males and 7 females; mean age: 10.58 years)	• Visual attention was assessed using Continuous Performance Test (CPT), in which the participants were instructed to press a number if the target pair (1 and 9) appeared sequentially. • A second test Letter Cancellation task (LCT), was administered where the participants had to strike out target letters	10 children with NH	• There were no main group effects seen for both continuous performance test and for letter cancellation test. • All the groups performed similarly for the sustained visual attention tasks.

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				embedded in a background of a similar letter. The scoring was based on the time taken to strike out all stimuli.		
11.	Jeddi et al. (2014)	Cohort study	• 15 children with CI (7 males and 8 females; mean age of 3.7 years)	• A Persian cognition assessment scale Newsha developmental scale, was used. • Using this scale, development age and development rate were measured. • Assessment was carried out at the baseline (before CI) and at every two months, up to 8 months after the implantation.	Compared to normative data of their chronological age	• At the baseline, the CI group showed a remarkable delay in cognitive skills compared to their chronological age. • The mean developmental age of the child increased with every follow-up assessment (2 months), and by the end of 8 months, it reached their mean chronological age. • The development rate of cognition significantly improved after implantation.
12.	Wass et al.	Case-	• 34 children with CI	• All the test items were	120	• Visuo-spatial working

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
	(2010)	control study	(age range: 5.7-13.4 years) • 120 children with NH (age-matched to the CI group)	presented using SIPS (Sound Information Processing System). • Phonological working memory was assessed using a non-word repetition task • Visuospatial WM was tested by means of a matrix pattern span test. • Complex working memory was measured in sentence completion and recall test.	children with NH	memory of children with CI was equivalent to that of hearing children. • Only 30% of the children in the CI group had complex working memory in the normal range (1 SD of the mean), which was significantly different from the comparison group of children with NH. • The greatest difficulty was seen in Phonological working memory, where only 12% of the CI children scored within the normal range (1 SD of the mean).
13.	Edwards et al. (2008)	Cohort study	• 20 children with CI (10 males and 10 females; mean age at baseline testing: 3.2 years)	• LIPS-R was administered before implantation as a baseline measure and	Compared to normative data	• There was no evidence of any change in the visual memory abilities during follow-up

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				during a one-year post-CI follow-up.		testing. • The fluid reasoning composite which requires higher-order cognitive function, significantly improved during the follow-up. • Scores on the Attention Sustained subtest improved significantly after the children had been using their implants for a year.
14.	Conway et al. (2011)	Case-control study	• 24 children with CI (15 males and 9 females; mean age: 7.5 years) • 31 children with NH (17 males and 14 females; mean age: 7.4 years)	• Nonverbal cognition was assessed using a neuropsychological (NEPSY) instrument. The following four subsets of NEPSY were used. • Response inhibition (knock and tap task), tactile perception (finger discrimination), motor sequencing (fingertip	31 children with NH	• Cochlear implant recipients demonstrated age-appropriate abilities in tactile discrimination, response inhibition (knock and tap), and visual-motor integration (design copy). • When compared to normative scores and the NH control group,

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				tapping task), and visual motor integration (design copy task). • Using CMS, visual-spatial learning and memory were evaluated.		children in the CI group clearly demonstrated a delay on the fingertip tapping activity.
15.	Nittrouer et al. (2013)	Case-control study	• 50 children with CI (24M:26F; mean age: 8.5 years) • 48 children with NH (22M:26F; mean age: 8.6 years). Implantation age of all children was less than 24 months	• Using a serial recall task, working memory storage and processing were evaluated. Rhyming and non-rhyming words were utilised as standardised stimuli. 3 sets of 8 stimuli made up the test stimuli. • Accuracy and response rate were measured during the task.	48 children with NH	• Both the groups showed a significant difference in recall accuracy, which suggests poor functioning of storage in working memory. However, the results did not show any difference in the response rate.
16.	Colletti et al. (2011)	Mixed (cross-sectional and	• Three groups of CI children • 19 children who were 2 to 11 months old at	• Children aged 0 to 8 years were assessed using three GMDS subscales for non-	Between-group comparison	• At baseline, GMDS showed no difference across age groups. • At the follow-up

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
		cohort)	the baseline. - 21 children between the ages of 12 and 23 months at the baseline - 33 children aged between 24 and 35 months at the baseline.	verbal cognitive assessments (Subtests: locomotor, performance, and eye and hand coordination,) LIPS-R was administered on children greater than 8 years. Visual/spatial attention (figure-ground test and form completion) and fluid reasoning (sequential order and repeated pattern) scores were used for the current study. - Tests were performed at the baseline (before CI) and 5 or 10 years after implantation.		testing, improvement was seen in performance and eye-hand coordination subtests compared to baseline. There was also a significant difference in performance mean scores of all the three age groups. - At the 10-year follow-up, there were significant improvements in non-verbal cognitive function with the LIPS-R. - Age had an impact on all subtests during the follow-up testing, with the exception of the figure-ground test.
17.	Pisoni and Cleary. (2003)	Case-control study	- 176 children with CI (aged 8-9 years old) had used their CI for at	- Forward and backward auditory digit spans of WISC-	45 children with NH. Compared	- Digit span scores of NH children were well within the norms of

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
			least 3½ years. - 45 children with NH	III were administered to both the groups.	to normative data	WISC. However, children with CI scored noticeably lower scores compared to normative scores and NH children.
18.	Ulanet et al. (2014)	Case-control study	- 22 children with CI (13 males and 9 females, mean age of CI: 1.12 years; mean age of testing: 6.2 years)	- Baseline non-verbal IQ was tested using either LIPS-R, BSID-II, or MSEL. - The KABC-II sequential processing scale (Word Order, Hand Movements, and Number Recall) and simultaneous processing scale (Rover, Triangles, Conceptual Thinking, Gestalt Closure, Face Recognition, and Block Counting) were both administered. The latter concerns children's language processing abilities.	Compared to normative scores	- Non-verbal IQ of test participants was within average to the very superior range. - Scores for both the scales were within or above the average level of the normative. Although in the normal range, the simultaneous processing scale showed better scores compared to the sequential processing scale.

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				•		
19.	Lyxell et al. (2011)		• 50 children with CI aged between 5.5 to 11.2 years. • 125 children with NH (61 males and 64 females)	• All the test items were presented using SIPS (Sound Information Processing System). • Non-word repetition tasks and the serial recall of non-words tests were used to evaluate phonological working memory. • Visuospatial WM was tested using a matrix pattern span test. • Complex working memory was measured in sentence completion and recall test.	125 children with NH	• Children with CI have generally average visual working memory (WM) abilities, significantly decreased general WM abilities, and relatively subpar phonological WM abilities.
20.	Udholm et al. (2016)	Cross-sectional study	• 58 children with CI (29M:29F; mean age at testing 9.4 years)	• Bayley-III was administered to children aged between 0 and 3.5 years. • The Snijders-Oomen Nonverbal Intelligence Test	Compared to normative data.	• Using the Bayley, SON-R, or WISC-IV cognitive tests, 34 (or 59 percent) of the 58 kids scored in the age range for those tests. Mild cognitive

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				Revised (SON-R) was used to assess children aged 3.5 to 6 years, while the WISC-IV was used to assess children aged 6 to 16 years.		impairment was assigned to 13 children (or 22 percent). • Nine children (16%) could not complete the test, and three other children were categorized as having moderate to severe cognitive impairment.
21.	Soleymani et al. (2014)	Case-control study	• 50 children with CI (mean age: 6.16 years) • 50 children with NH (age and gender-matched)	• Working memory of all the participants was assessed using non-word repetition task (using test materials developed in the Farsi language), a forward and backward digit span task.	50 children with NH	• Children with CI scored significantly lower than the NH children in all the tests. • Children who were implanted at older ages had lower scores on each of the three subtests, as determined by a correlation between WM and the age of implantation.
22.	Edwards and Anderson. (2014)	Case-control study	• 66 children with CI (32 males and 34 females; mean age at testing: 8.5 years; mean age at	• The following tests were administered • Forward memory subset of Leiter-R to	Compared to normative data.	• All the subjects performed within the normal range for Forward memory

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
			implant: 3.7 years)	assess visual memory span. • Numbers forward subset of CMS to assess auditory memory span. • Fluid reasoning composite (sequential order and repeated pattern) of Leiter-R to assess visual sequential reasoning.		subset, sequential order, and repeated pattern of Leiter-R. • However, more than half the subjects scored below 1 SD of the mean for the auditory memory span test.
23.	Dawson et al. (2002)	Cross-sectional study	• 24 children with CI aged 5-11 years. Each age group has 8 subjects (4 males and 4 females) • 24 children with NH (age and gender-matched)	• Auditory sequential memory was assessed using auditory tone-motor task, auditory word-imitation task, and auditory word-motor task. • Visual sequential memory was assessed using a visual hand movement imitation task and a visual picture-motor task.	24 children with NH	• Children from the NH group demonstrated a highly significant age effect on performance, but those from the CI group demonstrated less pronounced age effects. This was because older CI kids had IQs that were below average, which affected their ability to recall information. • On all of the tasks,

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
						there were no discernible differences in the mean reaction times between the NH and CI groups. • NH group performed significantly better than CI for the word-imitation, picture motor tasks, and word-motor tasks, while there was no difference between groups for hand movement imitation and auditory tone-motor tasks.
24.	Wass et al. (2008)	Cross-sectional study	• 19 children with CI (8 males and 11 females; mean age at testing 9.0 years) across each grade (grade 1 to 6) • 48 children with NH (age and gender-matched)	• The Non-word Repetition Test and the Serial Recall of Non-words Test were used to measure phonological working memory. • The Visual Matrix Patterns assessment was used to evaluate	48 children with NH	• Across every grade, the children with CI performed noticeably poorer than the children with normal hearing. • Similar results were obtained for general WM, where three out of 14 children with CI performed within 1 SD

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				visual-spatial working memory. • Sentence completion and recall tasks were used to evaluate general working memory.		for the general WM task. • Visuo-spatial working memory did not reveal any difference between the groups
25.	Lee et al. (2018)	Case-control study	• 20 children with CI (10 females and 10 males; mean age at implantation: 2.6 years; mean age at testing: 12 years) • 20 children with NH (13 females and 7 males; mean age at testing: 12 years)	• Visual WM was assessed using digit forward, digit backward, word forward, and backward word span tasks.	20 children with NH	• Scores of all the subtests were added to get a final WM score. Both the groups differed significantly on the final score. CI children had an average score of 18.8, and NH children had an average score of 25.8
26.	Pisoni et al. (2016)	Case-control study	• 31 children with CI aged between 8-9 years • 31 children with normal hearing, age, and gender-matched	• A Simon sequence memory task was conducted in which the child had to recall a series of coloured response panels on a four-alternative Simon response box after hearing or seeing	31 children with normal hearing	• Compared to children with normal hearing, children with CI consistently had shorter overall sequence memory spans for the A-only and A+L presentation conditions. • In the L-only condition,

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				colour names displayed by the computer in either auditory or visual mode. • Three distinct blocks of sequential patterns— lights-only (L-only), auditory-only (A-only), and auditory+lights (A+L)—were presented. • Using the CVLT-free recall task, verbal learning and memory processing abilities were evaluated.		children with CI showed shorter sequence memory spans than children with normal hearing. • In comparison to the NH controls, CI users consistently displayed worse overall free recall scores.
27.	Harris et al. (2013)	Cohort study	• 66 children with CI aged 6-16 years (mean age at CI:3.81 years; mean age at first testing: 7.55 years)	• DSF (Digit span forward) and DSB (Digit span backward) of WISC-III were administered on children at 6 months intervals post-implantation for	Compared to normative data	• The DSF scores of the CI sample consistently lagged behind norms by about 1 SD at all ages, while the DSB scores fluctuated between 0.5 and 1 SD across time within CI group.

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
				children aged 0-7 years and once annually until the child was 12 years of age. • Scores of DS tests after age 6 were considered for analysis due to test normative.		• The growth of cognition over time (slope) for CI children was found to be comparable in magnitude to values obtained from the normal-hearing group.
28.	Knutson et al. (2000)	Cohort study	• 24 children with CI (13 males and 11 females; mean age at implantation: 5.6 years)	• WISC-III was used to assess verbal IQ and performance IQ. • All the subjects were annually followed up for 3 months after implantation.	Compared to normative data	• 46% of the children showed an evidence of a 0.5 SD or larger gain in performance IQ, and 56% of the children showed evidence of an increase in verbal IQ. Throughout the follow-up period, no children showed signs of IQ decline.
29.	Cleary et al. (2001)	Case-control study	• 45 children with CI (25 males and 19 females; mean age at testing: 8.10 years) • 45 children with NH	• A memory span task was carried out, which involves the presentation of a sequence of sounds in	45 children with NH	• In every condition of the memory game challenge, including the lights-only condition, children without

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
			(age and gender-matched)	conjunction with a sequence of coloured lights located on a response box. Two conditions were used: lights only and auditory names plus lights. • The child had to replicate the desired sequence by pushing the correct buttons in the right order.		cochlear implants scored much higher than those with cochlear implants for children.
30.	Ghiselli et al. (2018)	Cross-sectional study	• 8 participants with CI (mean age at testing: 13.6 years; mean age at implantation: 2.2 years) • 8 children with NH (11 males and 9 females; mean age: 2.42 years)	• P300 recording was obtained using 19 electrodes. Target and standard stimuli were 2 kHz and 1 kHz tones, respectively, of the proportion 1:7. • Latency analysis of P300 was carried out.	8 children with NH	• Latency analysis revealed a significant increase in P300 peaks in participants with CI compared to the control group. • Mean P300 latency for the CI group was 353.1 ms, and 299.5 ms for the control group.
31.	Kileny et al. (1997)	Case-control	• 14 participants with CI (age at testing: 4-12	• P300 recording was obtained using three	Compared to	• Mean latencies of P300 were compared to the

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
		study	years)	different types of stimulus contrast. - A 1500 Hz tone at 75 and 90 dBS PL (deviant). - 80 dB SPL stimuli of 1500 Hz and 3000 Hz (deviant). - A speech contrast /heed/ and /who'd/ (deviant) - Amplitude and latency of P300 responses were obtained.	normative data	normative obtained from Kraus et al. (1995) (a normative for age group of 7-11 years), which revealed slightly prolonged latencies among the CI participants. - Although not statistically significant, the frequency contrast stimuli had the shortest latency, followed by latency contrast. The speech stimuli produced the largest latency. - Amplitude was highest for speech contrast, followed by loudness and frequency contrast.
32.	Beynon et al. (2002)	Case-control study	- 10 children fitted with CI aged between 9-16 years	- P300 recording was obtained using two different types of	10 children with NH	- A large latency (300-700 ms) spread was seen in NH participants.

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
			• 10 children with NH aged between 9-16 years.	stimulus contrast. • a) 500 Hz and 1000 Hz tone (deviant). • b) /b/-/d/ contrast and /i/-/a/ contrast.		Mean latency was shortest for vowel contrast, followed by tone and consonant contrast. No statistically significant differences in P300 latency were found between the children with NH and CI groups on any of the contrast tests.
33.	Munivrana Dervišbegović and Mildner. (2019)	Case-control study	• 20 children fitted with CI aged between 8-10 years • 10 children with NH (age-matched)	• P300 recording was obtained using 32 channels. • Double syllables ka-ka and te-te (target) were used as the stimuli and were presented at 70 dB.	10 children with NH	• There was no statistical difference between the two groups for both latency and amplitude measures.
34.	Bharadwaj and Mehta. (2016)		The study had two groups. • A group of 18 children with CI (10 girls and 8 boys; mean age: 7.8 years) • 19 children with	• Visual memory, visual discrimination, and visual sequential memory subtests from the Test of visual perceptual skills.		• For visual discrimination and visual memory task, the two groups did not reveal any significant differences. However,

SL. No	Author/year	Study design	Population	Evaluation	Control	Outcome
			normal hearing (11 girls and 8 boys; mean age: 8.4 years)	- Event-related potential – P300 was measured to assess visual sequential processing. Stimuli consisted of a sequence of shapes, and the child had to match the sequence by pressing a response button.		for the visual sequential memory subtest task, group differences were seen. - ERP analysis also showed a significant latency delay in CI group. This correlates with the behavioural result obtained for visual sequential task.

- Note: **CI** – Cochlear implant; **NH** – Normal hearing; **LIPS-R/Leiter-R** - Leiter International Performance Scale-Revised; **CFIT** - The Culture Fair Intelligence Test; **HRT** - The Heidelberger Rechentest; **HAWIK** - The Hamburger-Wechsler Intelligenz-Test für Kinder; **ROCF** - Rey-Osterreith Complex Figure Test; **WJ III COG NU** - Woodcock Johnson III Tests of Cognitive Abilities, Normative Update; **WISC-IV Integrated** - Wechsler Intelligence Scale for Children-IV Integrated; **KABC-II/K-ABC** - Kaufman Assessment Battery for Children II; **BSID-II/Bayley-III** - Bayley Scales of Infant and Toddler Development, Second Edition/Third edition; **MSEL** - The Mullen Scales of Early Learning; **CMS** – Children's Memory Scale; **GMDS** - The Griffiths Mental Developmental Scale; SON-R - Snijders-Oomen Nonverbal Intelligence Test Revised; **CVLT** - California Verbal Learning Test

3.4 Results of cognitive assessment using behavioural measures

Among the reviewed studies, Leiter International Performance Scale, Third Edition (Leiter-3/; Roid & Miller, 1997) and the Leiter International Performance Scale-Revised (LIPS-R) were the most widely used non-verbal cognitive test which assessed visualization, reasoning, attention, and memory. Khan et al. (2005) studied the cognitive outcome of children with CI, children wearing hearing aids, and normal hearing children using the LIPS-R battery. Results of this study revealed that children with CI achieved the same scores as normal-hearing children in all domains, except for attention. In contrast, children with the hearing aid did not match the cognitive level of normal-hearing children.

Leiter-R was also used by Edwards and Anderson (2014) to assess fluid reasoning composite, which is a measure for visual sequential reasoning. Similar to the previous study, the group with CI did not differ from the normative data. De Giacomo et al. (2013) evaluated implanted children using all the subtests of LIPS-R, which yet again revealed no difference compared to the normal-hearing group in full IQ scores.

In a cohort study by Colletti et al. (2011), LIPS-R was used to assess the improvement in cognitive performance 10 years after implantation. During the follow-up, visual/spatial attention and fluid reasoning tests revealed a substantial improvement in non-verbal cognitive function. Almomani et al. (2021) and Edwards et al. (2008) measured similar outcomes in children with CI, one year after implantation. These studies found no changes in visual memory abilities during follow-up testing, and the visualization scores of the baseline testing were well above normal-hearing children. Fluid reasoning composite, which requires higher-order cognitive function, showed poorer scores in CI children but significantly improved during the follow-up. Scores in the attention subset were similar in both groups.

Wechsler Intelligence Scale for Children (WISC-III) is another popular assessment tool for assessing non-verbal intelligence. The Block design test of the WISC-III battery revealed normal non-verbal intelligence in CI children compared to NH children (Lyxell et al., 2008). Visual working memory subtests of WISC-IV Integrated showed average performance of CI children compared to normative, but their auditory working memory was below average (Bharadwaj et al., 2016). WISC-IV also measured intelligence using two tests: Perceptual Reasoning (PRI) and Processing Speed (PSI). A cohort study carried out by Cejas et al. (2018) showed improvement in PRI and PSI after implantation, and their scores were well above the normal average.

WISC-III has also been used to assess working memory using forward and backward auditory digit spans. Pisoni and Cleary (2003) compared forward, and backward auditory digit spans and revealed that children with CI scored noticeably lower scores compared to normative scores and NH children. Harris et al. (2013) found a similar finding in their cohort study, wherein scores of forward digit span of the implanted population were consistently below 1 SD behind normative values at all ages, and the backward digit span scores ranged from 0.5 to 1 SD behind normative, during annual follow-ups for 12 years. However, the growth over time (slope) for CI children was found to be comparable in magnitude to values obtained from the normal-hearing group.

Working memory (WM) was assessed in different domains such as phonological, visuospatial, and general WM. Studies were done by Wass et al. (2008); Lyxell et al. (2008); Wass et al. (2010) showed that visuospatial working memory of children with CI was equivalent to the hearing children whereas, general WM was slightly affected (30% of the children were within normal range). Phonological WM was the most affected type of all WM, with only 12% of the children falling under the normal range. Working memory was assessed using digit forward, digit backward, word forward, and backward word span tasks by Lee et al. (2018), which revealed reduced working memory capabilities among implanted children. Similar results were noted by Soleymani et al. (2014) in non-word repetition tasks and forward and backward digit span tasks, demonstrating lower working memory capabilities in CI children. A study done by Nittrouer et al. (2013) examined the storage and processing in WM using a serial recall task. Results revealed a significant difference in recall accuracy, depicting poor functioning of storage in WM of children with CI.

Pisoni et al. (2016) administered Simon sequence memory task to assess sequence memory span. This test included only a presentation in auditory and visual + auditory modes. Children with CI differed in sequence memory span in both the presentation modes when compared to normal children. Cleary et al. (2001) used a similar procedure to assess memory span using lights only (visual) and auditory plus lights (visual + auditory mode). The results obtained were identical to Pisoni et al. (2016), where CI children scored lower than NH children. Dawson et al. (2002) inspected the difference in visual and auditory sequential memory. They found that CI children performed poorly in the auditory sequential task but not in the visual sequential task (with the exception of the visual-picture motor task). However, the reaction time of both groups did not differ. Edwards and Anderson (2014) used the Children's Memory Scale (CMS) to assess auditory memory span and found that half of the implanted children scored lower than 1 SD of the mean when compared to the normative.

Kaufman Assessment Battery for Children (KABC-II) has been helpful in examining short-term memory (STM). Bharadwaj et al. (2016) utilized the short-term memory subtests (Number Recall, Word Order, and Hand Movements) of KABC-II. While the mean, standard scores for STM measures (word order and numerical recall) using the auditory modality were found to be below average, the mean, standard scores for STM measures involving hand motions (visual-motor) were well within the average range. Shin et al. (2007) used a similar assessment battery in the Korean language (Korean Kaufman assessment battery for children) to assess cognitive enhancement after implantation. In the follow-up measure after six months of implantation, children showed significant improvement in working memory, but difficulty sustaining visual attention was noted.

Tharpe et al. (2002) examined selective visual attention among children with CI. A subtest of CPT (Continuous Performance Test) was chosen for this purpose. The study revealed no difference in sustained visual attention among CI and NH children. Similar results were noted in Huber and Kipman (2012), where visual attention was assessed using a subtest of The Hamburger-Wechsler Intelligenz-Test für Kinder (HAWIK). Shin et al. (2007) aimed at assessing sustained visual attention using a Korean version of Visual Continuous Performance Test (CPT). Difficulty in sustaining visual attention was noted in children with CI on CPT test.

Inductive and deductive reasoning was assessed using the German version of CFIT (The Culture Fair Intelligence Test) and HRT test battery (The Heidelberger Rechentest), respectively (Huber and Kipman, 2012). Implanted children showed similar results to NH in the inductive reasoning test but performed poorly for deductive reasoning (involving mathematical, logical reasoning).

Jeddi et al. (2014) used a different Persian cognitive measure, Newsha developmental scale, to obtain cognitive developmental age and developmental rate in implanted children in a longitudinal study. At the baseline assessment, CI group showed a remarkable delay in cognitive skills compared to their chronological age. However, the mean developmental age of the child increased with every follow-up assessment (2 months), and it reached their mean chronological age by the end of 8 months. The development rate of CI children improved significantly after their implantation.

Conway et al. (2011) assessed nonverbal cognition using a neuropsychological (NEPSY) instrument. Motor sequencing, tactile perception, response inhibition, and visual motor integration were assessed on CI children to check several cognitive processes such as sensorimotor functions, attention/executive functions, visual-spatial processing, and memory and learning. Except for motor sequencing (finger tapping task), children performed on par with NH children for all non-verbal cognitive tests. Visual-spatial learning and memory were also assessed using CMS (Children's Memory Scale), and the CI group showed similar scores when compared to the NH group, but CI exhibited above normal scores when compared to the normative of the CMS test.

In summary, the non-verbal cognitive tests such as LIPS-R and non-verbal intelligence test such as WISC revealed similar results in children with CI compared to children with NH. A modality specific cognitive scores were obtained from children with CI as they showed normal visual memory scores and poorer auditory memory scores. Phonological working memory showed poorer results in children with CI but the visuo-spatial memory revealed normal scores. In the reasoning domain, inductive reasoning was well in the normal range but deductive reasoning such as logical reasoning, showed poor scored compared to children with CI.

3.5 Results of cognitive assessment using objective (electrophysiological) measures

Ghiselli et al. (2018) compared P300 in eight implanted children to eight normal-hearing children. The recording was done using 19 electrodes. Target and standard stimuli used were 2 kHz and 1 kHz tones. After latency analysis, the authors revealed an increase in P300 peaks when compared to control group, with the mean latency for the CI group being 353.1 ms and 299.5 ms for the control group. Similarly, Kileny et al. (1997) and Beynon et al. (2002) studied cognitive potentials in cochlear implanted children. Both the studies used tone (duration or frequency deviant) and speech contrasts, and the results were compared to the normative data/control group. The results obtained from Kileny et al. (1997) revealed slightly prolonged latencies among CI children, while the study done by Beynon et al. (2002) showed no discernible difference in latency between the two groups. In both studies, tonal stimuli produced shorter latency than speech stimuli. Amplitude was the highest for speech stimuli.

Another study by Munivrana-Dervišbegović and Mildner (2019) recorded P300 in 20 children aged 8-10 years. Their scores were compared to 10 children with normal hearing. The recording was done using 32 channel electrode, and double syllable speech stimuli at 70 dB were used. The mean latency of P300 of the control group and CI group was 404.8 ms and 390.8 ms, respectively. The results did not reveal latency or amplitude differences among the CI group and NH children.

Bharadwaj and Mehta (2016) clearly showed a correlation between behavioural and electrophysiological test results for visual sequencing task. In this study, test of visual perceptual skills was used to assess visual memory, discrimination, and visual sequential memory, and using similar stimuli, P300 was also recorded for visual sequential memory. P300 was obtained using visual modality. The results from this study showed that in behavioural tests, visual sequential memory showed a lower score in CI children compared to normal hearing control group. Visual memory and visual discrimination task did not reveal any difference between the groups. P300 latency analysis also revealed a significantly longer latency for visual sequential stimuli, thus concluding that visual sequential memory is affected in children with CI while visual memory is intact.

To summarize, studies done by Munivrana-Dervišbegović and Mildner (2019), Ghiselli et al. (2018) and Beynon et al. (2002) did not find any difference in latency and amplitude between CI children and NH children. Bharadwaj et al. (2016), and Kileny et al. (1997), in contrast, showed a delayed latency in children with CI.

CHAPTER 4

DISCUSSION

The current study aimed to review articles on cognitive outcomes in children after cochlear implantation. The results of the review are discussed in the following sections:

4.1 Role of behavioural measures in assessing the cognitive outcomes in children after implantation

4.2 Role of objective measures in assessing the cognitive outcomes in children after implantation

4.3 Limitations of the reviewed articles

4.1 Role of behavioural measures in assessing the cognitive outcomes in children after implantation

Among the articles reviewed, Leiter-R or LIPS-R (Leiter International Performance Scale), KABC (Kaufman Assessment Battery for Children), WISC (Wechsler Intelligence Scale for Children) were the predominantly used cognitive assessment batteries. The non-verbal cognition skills assessed using Leiter-R test showed that the children with CI had normal cognitive skills as compared to normal hearing children (Edwards and Anderson, 2014; De Giacomo et al., 2013; Almomani et al., 2021; Edwards et al. 2008). Since speaking or signing languages are related to higher cognitive performance, the cognitive alteration after implantation was attributed to the availability of a new language (Conrad & Weiskrantz, 1981; Sisco & Anderson, 1980). Thus, improved understanding and usage of the new language could have facilitated cognitive change. The findings were also supported by functional imaging of the brain after receiving cochlear implant, which showed altered functional specificity within the cortex of the brain (Giraud et al., 2001). Khan et al. (2005) also hypothesized that the advanced cognitive improvement after implantation could be a result of the implant itself. After the implant, parents, and teachers may have higher expectations of the child, which could influence how they interact. There may also be more access to speech and language treatment. Almomani et al. (2021) found remarkable improvements in the Leiter-R memory and reasoning subset in CI children during follow-up testing. CI children showed improvement in their memory and reasoning scores 16 months after implantation, which highlights the importance of auditory input to cognitive functioning.

Higher or comparable visual-spatial skills in children with CI have already been discussed before. Similarly, Bharadwaj et al. (2016) showed that visual working memory scores were within the normal range. However, the implanted children showed lower than normal scores for auditory memory tasks. The findings of this study further support the hypothesis that WM capacity is modality specific in young children with hearing loss because the performance on WM tasks by the children with CI was below average for auditory tasks but not for those tasks dependent on the visual modality. The strengths on visual WM tasks and the difficulty on auditory WM tasks may provide evidence to support the presence of these distinct, modality-specific subsystems in working memory (Baddeley et al., 1998). Furthermore, the difficulty observed in auditory WM tasks lends support to the auditory scaffolding hypothesis, which proposes that sensory deprivation caused by early onset hearing loss impacts cognitive processes such as memory and production of sequential information within the auditory sphere. (Conway et al., 2009). It has also been proved that early auditory experience has an important influence on human memory system that is used for encoding and retaining phonological data in immediate memory (Soleymani et al., 2014)

Phonological WM, general WM, and visuospatial WM were assessed by Wass et al. (2008), Lyxell et al. (2008) and Wass et al. (2010). The relative strength of cochlear implanted children was their visuospatial WM which was at the same level as that of normal hearing children. The children with CI further had specific problems in tasks of phonological processing, such that their performance varied as a function of demands on phonological skill and phonological WM. Furthermore, when real words were to be processed rather than non-words, the phonological issues were less noticeable. This may suggest that with time and repetition, children with CI, like children without hearing loss (Swingley, 2003), establish relatively distinct phonological representations for commonly used words. Because of their impaired memory accuracy and intact recall rate, Nittrouer et al. (2013) hypothesised that children with CI showed poor storage functioning but not WM processing.

Pisoni et al. (2016) and Cleary et al. (2001) studied sequence memory span using Simon game using different presentation modes (visual and visual + auditory). Children with CI differed in sequence memory span in both the presentation mode when compared to normal children. When different presentation modes were compared, normal-hearing children showed a longer memory span in visual+auditory mode than in visual-only condition. This advantage, termed as redundancy gain, was not seen in CI children. Children with CI did not seem to use the informationally redundant auditory cues as effectively as the normal-hearing children. Pisoni et al. (2016) also assessed memory processing using a free recall task where they found lower scores in CI children than in normal-hearing children. This suggested that semantic clustering strategies used to recall were significantly compromised in cochlear implant users. CI children show little evidence of effectively utilising word semantic similarity relationships to aid in retrieving information from long-term memory.

In one of the studies (Khan et al., 2005), the results of the sustained attention task of Leiter-R showed lower than normal scores. The author attributed this finding to lower attention scores in the CI group, even before receiving implantation. Thus, their post-implantation scores also could have been affected. In a longitudinal study done by Edwards et al. (2008), attention scores significantly improved one year after the implantation. This was driven by the fact that before implantation, when they had little or no access to the sounds around them, they were constantly scanning their surroundings visually for information that a hearing child could perceive and process without interrupting what they were doing. Once individuals had access to auditory information, they could concentrate more on the visual cancellation task (Leiter-R) and less on the environment.

One striking result of cochlear implanted children is the exceptional scores in visualization subtest of LIPS-R. Studies by Almomani et al. (2021) and Edwards et al. (2008) showed that deaf children outperformed NH children on the tests of visualization at baseline, suggesting a visual-spatial advantage and enhanced visual cognition. This might be because cochlear implant recipients rely more on visual cues and spatial diagrams than their hearing peers do when learning and solving problems (Colletti et al., 2015). This assumption has also been supported by MRI studies where functional migration was seen due to developmental brain plasticity in children with hearing loss.

Previously discussed visual attention using Leiter-R showed strong effects of age. Tharpe et al. (2002) found both normal hearing group and children with cochlear implant group performed well within normative. However, children with cochlear implants had significantly lower scores on a sustained visual attention task than the normal hearing group. The authors justified this finding saying, visual vigilance tasks used to measure sustained attention were relatively tedious. Shin et al. (2007) found similar findings of increased difficulty in sustained attention in children with CI. After implantation, interference from external auditory stimuli was assumed to be the cause of this poor attentional performance.

4.2 Role of electrophysiological measures in assessing the cognitive outcomes in children after implantation

Five articles were found in relation to electrophysiological studies performed on cochlear implanted children. Ghiselli et al. (2018) and Beynon et al. (2002) showed a comparable P300 latency result in children with early implanted CI. However, they also revealed that in children who had were implanted late, showed a poorer latency when compared to children with NH. One possible explanation could be the lack of maturity of the central auditory pathway among the late implanted children as they were implanted at a relatively advanced age. Kileny et al. (1997), in contrast, showed a delayed latency in children with CI. Authors attributed this difference to slightly younger age of the participants of their study compared to the normal group.

Bharadwaj et al. (2016) studied visual sequential processing of CI using ERP and correlated it with subjective measures. The P3 component, which is considered to be an index of target detection and evaluation, was found to be significantly delayed in children with CI. Reaction times revealed that children with CI take longer to evaluate the visual stimuli when compared to their NH peers. These investigations appear to be founded on the idea that the appropriate development of each sensory system depends on the integration of information from other senses and that delays in one sensory system may result in corresponding disruptions in others. This could be attributed to the complexity of the visual sequential processing task which required memorization of lengthy sequences of visual stimuli.

4.3 Limitations of the reviewed articles

One of the limitations, as pointed out by Khan et al. (2005), is that the data given by LIPS-R does not clearly state whether children with additional disabilities were included or not. This necessitates having a control group in studies that used LIPS-R and do not rely on the normalization data available with LIPS-R. Studies by Caudle et al. (2014), Edwards et al. (2008), Shin et al. (2007), and Edwards and Anderson (2014) did not include a control group of normal hearing children but instead compared the scores to the normative provided by LIPS-R which could give varied the results. However, since ample studies have used the same normative scores and arrived at similar results, it can be considered for the review.

Almomani et al. (2021) included slightly older children (6.16 years). This could have resulted in poorer scores in cognition since early implanted children have shown better cognitive skills compared to late implanted children (Kinley et al., 1997). Shin et al. (2007) described a similar reason which makes it difficult to generalize the results obtained. Munivrana-Dervišbegović and Mildner (2019) included a small number of participants in their study which prevents generalization, but the results could be helpful in planning speech and language therapy.

There is no information on the kind and frequency of the various therapies that the study's cochlear implant participants received. This could be another limitation as cognitive skills development can result from different treatments working together.

The influence of SES on cognitive development is well-established (Hanscombe et al., 2012). The study done by Cejas et al. (2018) has mentioned that the control group consisted of children mostly from the higher SES. The decreased cognitive abilities in children with CI may have been caused by this difference. As indicated in the prior quality analysis, some studies did not consider confounding variables such as the age of implantation, schooling type, SES, school type, father and mother's education levels, and the child's primary method of communication. Factoring all the confounding variables in one study can be a tedious task, and this can be taken up in further research.

CHAPTER 5

SUMMARY and CONCLUSION

The present study aimed to conduct a systematic review on cognitive outcomes in children with CI. Initially, out of 2793 articles, 46 were selected for a full-text review. Thirty-four articles were finalized based on the inclusion and exclusion criteria. The process of screening and including the articles was done using PRISMA.

The general trend of most cognitive results in children suggested a significant advantage of CI on cognition. Along with benefits in cognitive functioning, cochlear implants also showed enhanced communication skills in hearing impaired children. The cognitive scores after implantation were significantly higher than they were before implantation. However, it took the CI children a long time to get their cognition scores in the normal range. When children with CI were tested for cognition using non-verbal tests such as LIPS-R, scores were on par with the normal hearing children, but when verbal tests were used, CI children showed lower than normal scores in cognition. Behavioural and electrophysiological measures used for cognition assessment showed comparable results. Behavioural measures provided a detailed assessment of each cognitive domain, whereas P300 provided information on attention and memory only.

Among the longitudinal studies carried out to assess cognition, it was seen that cognition improved over the 10 years of implantation and reached the level of normal hearing children. Higher cognitive aspects such as reasoning developed over the years at a similar rate as that of normal hearing children.

In conclusion, significantly better cognitive scores were seen in children after implantation. When non-verbal behavioural cognitive tests were used, children showed better scores than verbal tests. Behavioural tests provided a more detailed assessment of cognition when compared to electrophysiological tests.

5.1 Clinical implications of the current review

The current systematic review gives a gist of the overall cognitive changes occurring due to the inclusion of auditory sensation through cochlear implants. Clinical practice should focus on the importance of early implantation and the suitable rehabilitation for appropriate cognitive development. Both behavioural and electrophysiological methods can be used to monitor cognitive development following implantation, and both produce adequate findings. However, with behavioural assessments, each cognitive subtest can be precisely evaluated using non-verbal tests suitable for the hearing-impaired population.

The review also emphasises how children with CI exhibit modality-specific cognitive performance. With the addition of auditory input, auditory memory and auditory attention improved in these children. As a result, the tests used for assessment should be carefully chosen.

5.2 Future directions

Cognition is not an unconnected process. It is influenced by number of factors such as the child's environment, parent's education socio-economic status, and it also influences the child's language and overall development. It was found that the current review did not account for all the confounding variables that might have helped with the cognitive enhancement. Future studies can be focused on measuring cognitive growth because of auditory stimulation while controlling for other contributing factors. Further, cognitive assessment can be carried out using behavioural and electrophysiological methods to better understand the correlation between the two methods.

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