



Cognitive Functions and Cross-Modal Plasticity in Children with Cochlear Implants: A Systematic Review of Research

Review article

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Abstract

This paper aims to systematically present existing research on cognitive and executive functions, speech and auditory perception, language, literacy, and academic development, and cross-modal reorganization in children with CIs. The methodology included a systematic search of databases (PubMed, Scopus, Web of Science) using keywords related to cognition and CIs. After eliminating duplicates and applying inclusion criteria, an analysis was conducted of relevant references published from 2015 to the present, which were analyzed both in tables and narratively. Research confirms that the cognitive development of children with CIs depends on auditory input and the brain's ability to integrate information from different sensory modalities. Multisensory and interactive approaches to rehabilitation have the potential to enhance cognitive development and should be further researched and applied in practice.

Keywords: *cognition, cochlear implant, deaf, multisensory integration, cross-modal plasticity*

Cognition represents a set of mental processes through which the brain processes, stores, and uses information after receiving it. The cognitive development of children with hearing loss, especially those children with a cochlear implant (CI), is increasingly

attracting the attention of experts in the field of educational rehabilitation and neuropsychology. The cochlear implant is one of the most significant achievements of modern medicine in the treatment of severe forms of sensorineural deafness, because it

allows access to auditory information that is crucial for the development of language and speech. With the development of cognition, language also develops. Cognition is a basic condition for language development and an important factor in rehabilitation (Hasanbegovic, 2009). Auditory stimuli dictate the psychological processing that results in listening, and other sensory modalities dictate action and reaction to the received stimulus. By integrating sensory modalities, experience is created, and experience is the result of continuous learning. Enrichment of experience can be equated with learning, and learning can be the main purpose of communication. Learning affects the development of cognition, and cognition affects the willingness to communicate (Hasanbegovic and Kovacevic, 2014). Children with CI often show variable outcomes in the domains of attention, working memory, executive functions, and other aspects of cognition. CI users have difficulties in cognitive and language skills, as well as in acoustic coding (Kronenberger et al., 2014; Wie et al., 2020). Compared to children with normal hearing, children with CI are at 2 to 5 times greater risk of significant deficits in working memory, comprehension, and conceptual learning, memory, attention, sequential processing, and novel problem solving (Kronenberger et al., 2014). Wass et al. (2008) report that children with CI have deficits in phonological working memory, phonological discrimination, and lexical access, but equivalent visuospatial working memory capacities compared to children with normal hearing. Hearing loss hurts a child's daily activities, self-esteem, and personal independence (Almomani et al., 2021). These findings stimulate interest in investigating the impact of periods of auditory deprivation and subsequent activation of auditory function on a wider range of cognitive processes.

The cognitive development of children with CI does not depend exclusively on auditory input, but also on the brain's ability to integrate information from different sensory modalities. Sensory deficits in one modality lead to functional changes in brain structures. Neural reorganization can result in sensory compensation and improved performance on sensory sensitivity tests. Various studies have investigated the impact of deafness on the functioning of intact

senses. Research (Dewey et al., 2015) shows that sensory deficits in one modality can enhance neural processing of sensory input from intact senses. This phenomenon, known as sensory compensation, has been observed in people with severe sensory impairments such as deafness. Scientific research increasingly points to the importance of cross-modal plasticity – a phenomenon in which the auditory cortex can be recruited to process visual or tactile stimuli due to auditory deprivation. Studies of cognitive function and cross-modal plasticity in children with CI explain why developmental outcomes after implantation are often variable. Cognitive abilities provide the foundation for acquiring language, literacy, and academic skills, while cross-modal brain plasticity reveals how visual and tactile modalities take over the function of auditory regions in conditions of hearing loss. Understanding these processes is critical for identifying children at risk for slower language and academic development, and for designing targeted rehabilitation programs that include multisensory and cognitive strategies. This neuroplasticity opens up possibilities for the application of polysensory stimulation in rehabilitation, with the aim of compensating deficits and strengthening cognitive functions. Modern approaches in rehabilitation include multisensory and interactive learning methods, which potentially provide a stronger boost to cognitive development compared to traditional, unisensory approaches. It is assumed that the simultaneous involvement of multiple senses can further enhance brain plasticity, especially in children with sensory deficits. This topic is becoming more and more relevant in contemporary rehabilitation practice, given the need for more effective support for the overall development of children with CI.

The paper aims to review the results of research on the cognitive development of children with CI, with a focus on cognitive and executive functions, speech and auditory perception, language, literacy, academic development, and cross-modal reorganization. The review includes papers from the fields of neuropsychology and audiology, with particular attention paid to implications for therapeutic practice and future research. Such research also has significant scientific value because children

with CI represent a unique model for studying neuroplasticity in development.

Method

A selection of papers was made in PubMed, Scopus, and Web of Science. Key words were: cognition, cochlear implant, deaf, multisensory integration, cross-modal plasticity. The criteria for the analysis of the articles in the review were: articles that were published in their entirety, articles that dealt with the research of cognitive and executive functions, speech and auditory perception, language, literacy, and academic development, cross-modal reorganization,

and that the subjects were people with CI. Based on the defined criteria, an analysis of significant references published in the period from 2015 to the present was performed. A tabular presentation of the results was made, and a narrative summary of each article was provided.

Results and Discussion

Articles were sorted into four categories: cognitive and executive functions, speech and auditory perception, language, literacy and academic development, and cross-modal reorganization.

Table 1.

Cognitive and Executive Functions - Literature Review

Authors, year, country, title	Goal	Sample	Method	Conclusion
Izabela A. Jamsek, William G. Kronenberger, David B. Pisoni, Rachael Frush Holt 2022. SAD <i>Executive functioning and spoken language skills in young children with hearing aids and cochlear implants: Longitudinal findings</i>	To examine the predictive and reciprocal relationships between executive functions and spoken language in children with hearing impairment (DHH) who use hearing aids or CIs, compared to hearing children, over one year.	A total of 112 children aged 3 to 8 years: 53 children with hearing impairment (DHH) 59 hearing children.	Assessment of receptive spoken language: vocabulary, understanding sentences, and following verbal instructions. Assessment of executive functions: questionnaires filled in by parents, focused on the child's daily behavior. Two field visits: measurements were made during two visits, one year apart.	Hearing-impaired children with better executive functions at the beginning of the study had better results in understanding sentences and following verbal instructions after one year. Conversely, initial language skills did not predict later executive function development in the same group of children. In hearing children, no significant association was found between language and executive functions over one year.
Fidaa Almomani, Murad O. Al-Momani, Never Garadat, Safa Alqudah, Manal Kassab, Shereen Hamadneh, Grant Rauterkus, and Richard Gans 2021. Jordan <i>Cognitive functioning in Deaf children using Cochlear implants</i>	To investigate the impact of cochlear implantation on cognitive functions (visualization, reasoning, memory, and attention) in deaf children in Jordan, with a special focus on differences in relation to the age at which the implantation was performed.	22 deaf children were implanted at the age of 4-6 years 16 deaf children were implanted at the age of 7-9 years 48 hearing children.	Cognitive functions were assessed using the Leiter-R scale at three time points: before implantation, 8 months, and 16 months after implantation. The same time periods were used to test the hearing of children.	The results suggest that cochlear implantation not only improves communication skills but can also improve cognitive function in deaf children. It was found that the degree of improvement depends on the age at which the intervention was performed. The early period of implantation (4–6 years) is associated with greater cognitive improvements compared to later implantation (7–9 years).

Table 1 (continued).*Cognitive and Executive Functions - Literature Review*

Matthew L. Hall, Inge-Marie Eigsti, Heather Bortfeld, Diane Lillo-Martin 2018. SAD <i>Executive Function in Deaf Children: Auditory Access and Language Access</i>	To investigate whether difficulties in executive functions (EF) in deaf children are the result of a lack of auditory perception (sound) or a lack of language input, and to examine how early access to language, whether sign or spoken, affects the development of EF.	116 children aged 5–12, divided into three groups: 45 hearing children 45 deaf children exposed to American Sign Language (ASL) from birth 26 deaf children of CI users who did not have full access to language before implantation.	Assessment of executive functions using a combination of parent report and performance tasks, including the Behavior Rating Inventory of Executive Function (BRIEF) and the NEPSY Tower subtest.	The results show that executive function difficulties in deaf children are more related to a lack of early language input than to a lack of auditory input. Children who had early access to language, either signed or spoken, performed better on executive function tasks.
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According to the authors analyzed in the paper on the topic of Cognitive and executive functions, early access to language, whether spoken or signed, is crucial for the development of cognitive abilities and executive functions in deaf children. Hall et al. (2018) indicate that language deprivation, and not the lack of auditory stimulation itself, most affects the development of executive functions. Jamsek et al. (2022) report that better executive functions are a strong predictor of later language development in children with hearing aids and CIs. This relationship is unidirectional; while executive functions predict language development, the reverse is not true. This implies the importance of including cognitive exercises in rehabilitation and educational intervention programs. Almomani et al. (2021) as

well as Jamsek et al. (2022) found that cochlear implantation can have a positive effect on cognitive functions in children. The implantation must be done as early as possible, because younger children (4–6 years) show significantly better cognitive outcomes compared to children implanted at a later age (7–9 years). While Almomani et al. (2021) emphasize the importance of auditory stimulation through CI for cognitive progress, Hall et al. (2018) insist that auditory input alone is not enough. They believe that the key factor is early and rich linguistic input. This difference stems from different theoretical frameworks: neuroplasticity through sensory stimuli (Almomani) versus language deprivation theory (Hall).

Table 2.*Speech and Auditory Perception - Literature Review*

Authors, year, country, title	Goal	Sample	Method	Conclusion
Lidija Ristovska, Zora Jachova, Jasmina Kovacevic, Husnija Hasanbegovic 2025. Bosnia and Herzegovina <i>Audiologic Assessment of Preschool Children with Hearing Loss in a Secondary Health Care Setting</i>	To assess the audiological profile of preschool children with hearing impairment, i.e., to determine the type, degree, and configuration of hearing impairment, to assess the amplitude of otoacoustic emissions, and to analyze the ability to recognize words in relation to the type and degree of hearing impairment.	260 preschool children, aged 4 to 6 years, were examined at the Department of Otorhinolaryngology, Department of Audiology, General Hospital "8. September", Skopje, in a period of 5 years.	The findings of the audiological evaluation were analyzed, which included: pure tone audiometry, tympanometry with a 226 Hz probe, DPOAE (distorted otoacoustic emissions), and speech audiometry.	Audiometric findings indicate communication barriers and educational implications of hearing impairment. Mild conductive hearing loss with type B tympanogram is most common in preschool children. Children with sensorineural impairment do not have otoacoustic emissions, and the OAE test is a good additional examination in addition to pure tone audiometry. Children with conductive impairment have a normal ability to recognize words, while children with sensorineural and mixed impairment show variable results. Most children seen in the ENT department have temporary hearing loss that can be treated, but special attention should be paid to detecting permanent damage that was not detected by neonatal screening or appeared later.
Puttaraju Sahana, Puttabasappa Manjula 2024. India <i>Vocal Emotion Perception in Children Using Cochlear Implant</i>	To examine the perception of vocal emotions in children who use CI and bimodal hearing aids in one ear and a hearing aid in the other, and compare them with hearing (NH).	20 children with congenital hearing impairment (aged 4–10 years) using a unilateral CI and a contralateral hearing aid (HA). 20 hearing children (NH), matched by gender and listening experience.	Evaluation of the perception of vocal emotions using semantically neutral sentences spoken with the emotions "happiness", "sadness", and "anger". Test with three offered answers (3AFC): The children chose the appropriate emoji that represented the emotion they perceived.	Hearing children showed significantly better perception of vocal emotions compared to children using CI. Both groups recognized the emotion "happiness" most accurately. In children with CI, adding a hearing aid to the contralateral ear (bimodal stimulation) improved recognition of the emotions "sadness" and "anger", reducing confusion between the emotions. The improvement is attributed to the additional time and frequency information provided by the hearing aid, especially in the low-frequency range.
Y. Yaar-Soffer, R. Kaplan-Neeman, T. Greenbom, S. Habiballah, Y. Shapira, Y. Henkin 2023. Israel <i>A cortical biomarker of audibility and processing efficacy in children with single-sided deafness using a cochlear implant</i>	To investigate the auditory perception and cortical processing of speech in children with single-sided deafness (CHwSSD) who use CI, and to evaluate the possibilities of developing binaural processing.	22 children with unilateral deafness Average age at implantation: 4.7 years Average age at testing: 5.7 years	Recording of P1 potentials evoked by acoustically presented speech (/m/, /g/, /t) Testing in three listening conditions: Normal listening (NH) Listening via CI Bilateral listening (NH + CI)	P1 potentials were recorded in all subjects in NH and bilateral conditions. P1 potentials were present in most children, but with reduced amplitude and prolonged latency. No significant binaural processing was noted. The results indicate that, although the CI allows a certain level of auditory perception, there is a significant discrepancy in the timing and synchronization of cortical processing between the CI and the NH ear, which is an obstacle to the development of effective binaural interaction

Table 2 (continued).*Speech and Auditory Perception - Literature Review*

Authors, year, country, title	Goal	Sample	Method	Conclusion
Luise Wagner, Reyhan Altindal, Stefan K. Plontke, Torsten Rahne, 2021. Germany <i>Pure Tone Discrimination with Cochlear Implants and Filter-Band Spread</i>	To investigate how differences in frequency relative to the frequency bands of the CI electrodes affect the user's ability to distinguish between pure tones.	34 CI users 19 hearing subjects of the same age	Representation of two sinusoidal tones with varying frequency differences Reference frequencies selected according to the central frequencies of the basal or apical electrodes Psychophysical measurement of discrimination ability using the three-interval, two-alternative, forced-choice method (3I-2AFC) Measurement of the accuracy of recognition of differences in pitch in relation to the limit frequencies of the electrode frequency bands	CI users had an average accuracy of about 60% in pitch discrimination, while hearing subjects achieved about 90% The minimum difference limit (difference line) for CI users was two semitones, while hearing subjects could detect a difference of one semitone This study provides insight into the limitations of pitch perception in CI users.
Jace Wolfe, Mickael Deroche, Sara Neumann, Lindsay Hanna, Will Towler, Caleb Wilson, Alexander G. Bien, Sharon Miller, Erin C. Schafer, Vincent Gracco 2021. SAD <i>Factors Associated with Speech-Recognition Performance in School-Aged Children with Cochlear Implants and Early Auditory-Verbal Intervention</i>	To examine factors associated with speech recognition success in school-aged children with CI, with a particular focus on language abilities, implant use, and attendance at auditory-verbal (AV) therapy.	A total of 50 children between the ages of 7 and 17, who were unilaterally or bilaterally implanted by the age of four. Group with high language abilities (High Language): 26 children with age-appropriate speech abilities. Group of low language abilities (Low Language): 24 children with a delay in speech abilities.	A single-center cross-sectional study with repeated measures. Assessment of recognition of words and sentences in silence and noise. Analysis of the influence of demographic characteristics, use of CI, and attendance at AV therapy on speech recognition results.	Children in the group with low language abilities had significantly worse results in recognizing speech in silence and in noise compared to children in the group with high language abilities. A greater number of hours of CI use and regular attendance at AV therapy are associated with better results in speech recognition.
Iliza M. Butera, Ryan A. Stevenson, Brannon D. Mangus, Tiffany G. Woynaroski, René H. Gifford, Mark T. Wallace 2018. SAD <i>Audiovisual Temporal Processing in Postlingually Deafened Adults with Cochlear Implants</i>	To investigate how adults with postlingual deafness who use CI process temporal relationships between auditory and visual stimuli, and how this affects their ability to integrate this information in everyday communication	48 adult CI users with postlingual deafness 54 hearing adults	Application of simultaneous judgment (SJ) and order judgment (TOJ) tasks for auditory, visual, and audiovisual stimuli. Varying the temporal differences between the auditory and visual components of the stimulus (eg, syllables/highlights and simple flashes/sounds) Analysis of points of subjective simultaneity (PSS) and time binding windows (TBW)	No significant difference in temporal binding window width (TBW) was found between CI users and hearing subjects for speech and non-speech stimuli. CI users showed a shift in the point of subjective simultaneity (PSS) for speech stimuli, indicating a reduced need for visual stimuli to precede auditory stimuli to be perceived as simultaneous.

Table 2 (continued).*Speech and Auditory Perception - Literature Review*

Authors, year, country, title	Goal	Sample	Method	Conclusion
Jeroen P. M. Peters, Alice van Zon, Adriana L. Smit, Gijsbert A. van Zanten, G. Ardine de Wit, Inge Stegeman, Wilko Grolman, 2015. The Netherlands <i>CINGLE-trial: cochlear implantation for siNGLE-sided deafness, a randomised controlled trial and economic evaluation</i>	To assess the effectiveness and cost-effectiveness of cochlear implantation treatments for single-sided deafness (SSD), including bone conduction devices (BCDs) and contralateral sound systems (CROS), focusing on speech perception in noise, sound localization, tinnitus, and quality of life.	120 adult patients with SSD (duration of deafness >3 months and ≤10 years) Randomized into three groups: CI group Group with order BCD, then CROS Group with order CROS then BCD.	Single-center randomized controlled trial (RCT) Assessment of results at baseline and during follow-up in the period from 6 to 60 months Measurement of speech perception in noise, sound localization, tinnitus, and quality of life Economic evaluation and monitoring of side effects.	CI may outperform BCD and CROS in improving speech perception in noise, sound localization, reducing tinnitus, and improving quality of life in patients with SSD.

Although the technology has proven successful in restoring auditory function, the authors point out that the complexity of auditory processing and speech recognition is significantly greater than listening to sounds. Wolfe et al. (2021) most clearly link language and auditory perception. They believe that language ability is the strongest predictor of success in speech perception in children with CI. This research implies a two-way relationship: auditory stimulation facilitates language development, but developed language also improves auditory interpretation, especially in complex sound environments. The authors additionally emphasize the importance of regular use of CI and auditory-verbal therapy, thereby confirming that rehabilitation must be continuous and functionally oriented. Sahana and Manjula (2024) analyzed vocal emotion recognition in children with bimodal hearing. Children who use both AI and a hearing aid showed better results in the detection of emotions, especially those that have acoustically subtle cues (such as sadness). These results indicate that auditory perception involves not only the recognition of phonemes and words, but also the affective layers of speech, which are important for social communication. However, the authors did not analyze how this ability affects speech production, which would be important for a comprehensive understanding of communication development. In a study by Wagner et al. (2021), which focuses on frequency discrimination, it directly speaks to

the capacity of CI users to discriminate pitch changes, which is crucial for the perception of intonation, prosody, and stress in speech. The results show that pitch discrimination is limited, which implies that CI users may have difficulties in distinguishing meaningful speech nuances, especially in languages where intonation plays a semantic role. The authors did not extend the analysis to speech in real conditions, which would have given the research a stronger functional relevance. Butera et al. (2018) investigated audiovisual integration through speech, finding a shift in the point of subjective simultaneity between auditory and visual cues, suggesting that CI users rely more on visual cues (e.g., lip movements) for spoken information. This dependence on the visual channel can be an adaptive strategy, but at the same time it indicates insufficient auditory reliability of speech input, especially in conditions without visual support (eg, a telephone conversation). Peters et al. (2015) measured the ability of CI users to understand speech in noise and localize the source of sound. The results showed the superiority of CI compared to other devices in people with single-sided deafness. These results are significant because speech in noise represents one of the most demanding conditions for auditory perception. However, the study did not analyze how these improvements are reflected in spontaneous speech production or social communication. Yaar-Soffer et al. (2023) used cortical auditory potentials (P1) to examine auditory processing in children

with single-sided deafness and CI. The results indicated the existence of a response, but with weaker synchronizations between the hemispheres. Although the work focuses more on the neurophysiological than the functional dimension, the finding implies that there may be a delay or reduced precision in speech perception, especially when it is necessary to integrate auditory information from both ears.

These neurophysiological and functional results complement the research results of Ristovska et al. (2025), who indicate that children with conductive hearing loss have a normal ability to recognize

words, while children with sensorineural and mixed hearing loss have variable results. They point out that it is important to detect early permanent damage that was not detected by neonatal screening or appeared later, to apply adequate interventions. The development of auditory perception in children, whether with CI or hearing, depends on the complex interaction of the physiological capacities of the sense of hearing, language abilities, therapeutic interventions, and continuous audiological support, thus emphasizing the importance of early detection and continuous functional rehabilitation.

Table 3.

Language, Literacy, and Academic Development - Literature Review

Authors, year, country, title	Goal	Sample	Method	Conclusion
Jessica A. Scott, Heidi Goldberg, Carol M. Connor, Amy R. Lederberg 2019. SAD <i>Schooling Effects on Early Literacy Skills of Young Deaf and Hard-of-Hearing Children</i>	To examine the impact of schooling on early literacy development in children who are deaf or hard of hearing (DHH), focusing on phonological awareness, letter and word recognition, and vocabulary over two school years and the summer period in between.	56 children aged 3 to 5 years 45% CI users 54% users of hearing aids Method of communication in the classroom: 61% exclusively spoken language 39% sign language	Longitudinal study (two-year follow-up of DHH children in specialized early education programs). Measuring instruments: multiple standardized tests to assess: phonological awareness (eg, First Sound Fluency), recognition of letters and words (Letter Naming Fluency), vocabulary (eg, Expressive One Word Picture Vocabulary Test - EOWPVT).	Significant progress in all skills was recorded during the two school years, while there was no significant progress during the summer period. These findings highlight the importance of early education in promoting key literacy skills in DHH children.
Matthew L. Hall, Wyattte C. Hall, Naomi K. Caselli 2019. SAD <i>Deaf children need language, not (just) speech.</i>	The goal is to critically analyze and challenge claims from previous works that advise avoiding exposing deaf children to natural sign languages, and point to the importance of the availability of natural sign language for the optimal development of language and cognition in deaf and hard-of-hearing (DHH) children.	In this article, no primary empirical research was conducted; it is already an overview and argumentative work. Therefore, there is no specific sample of respondents, because it is about the analysis and criticism of literature and methodology from other research.	Analytical and theoretical method: The authors analyze previous studies and consider their methodological shortcomings. Literature review: Uses available evidence from linguistics, developmental psychology, and neuroscience to support views on the importance of sign language.	Natural sign languages do not harm the development of spoken language in DHH children, but already contribute to the prevention of language deprivation. Exclusive orientation to the spoken language ignores the key developmental needs of children and can have negative consequences. It is recommended that DHH children get access to at least one complete language, including sign language, to ensure broader cognitive and social benefits.
Connie Mayer, Beverly J. Trezek 2018. SAD <i>Literacy Outcomes in Deaf Students with Cochlear Implants: Current State of the Knowledge</i>	To review the available peer-reviewed literature on literacy achievement in deaf children with CI, identify gaps in empirical research, and suggest directions for future research.	21 studies published between 1997 and 2016 A total of over 1,000 CI users.	A systematic review of studies reporting reading and writing outcomes in deaf children with CI. Analysis of factors affecting achievement, including: age at implantation, presence of additional difficulties, consistency of device use, and communication method.	Most reading comprehension studies show that participants scored in the average range, although wide variability was noted. Only three studies on writing were available, two of which reported lower achievement in this area compared to reading.

Table 3 (continued).*Language, Literacy, and Academic Development - Literature Review*

Authors, year, country, title	Goal	Sample	Method	Conclusion
Marc Marschark, Elizabeth Machmer, Linda J. Spencer, Georgianna Borgna, Andreana Durkin, Carol Convertino 2017. SAD <i>Language and Psychosocial Functioning among Deaf Learners with and without Cochlear Implants</i>	To investigate how actual and perceived language abilities (spoken and sign language) influence psychosocial functioning, including quality of life and cultural identification, in deaf students with and without CI during their first year in college.	Deaf students with and without CI in their first year of study at the university.	Longitudinal study during the first year of college Assessment of actual language abilities through formal tests Self-assessment of language abilities by participants Measurement of psychosocial factors, such as quality of life and cultural identification	There are significant differences in some aspects of psychosocial functioning and language abilities between students with and without CI, but not in all the expected directions. Participants' cultural identification was more related to their perceived language abilities than to actual abilities determined by formal assessments.

The development of language and literacy in children and young people with CI is a complex process influenced by numerous factors, including age at implantation, access to language (spoken and/or signed), educational environment, and the presence of additional difficulties. Several authors emphasize that early access to language (either spoken or signed) significantly affects cognitive and language development. In parallel with speech development in deaf children, it is necessary to start language rehabilitation, with an emphasis on literacy. In this way, by learning the language, deaf children would practice speaking and, through the dynamic component of the rehabilitation process, increase responsibility in work, awaken the child's attention, mobilize cognitive functions, and extend the duration of the child's memory (Hasanbegovic, 2009). Hall et al. (2019) point out that deaf and hard-of-hearing people need not only an auditory signal, but full linguistic input – including natural sign language – to prevent language deprivation and enable optimal language and cognition development. This view partly coincides with the results of Mayer et al. (2018), who, in their systematic literature review, confirm the importance of early implantation and consistent use of devices for literacy achievement, but warn of high variability of results and lack of research on writing. A similar emphasis on the importance of the educational context is found in Scott et al. (2019), who, through longitudinal monitoring of children aged 3 to 5 years, show that the greatest progress in literacy skills occurs

during the school years, while during the summer break, this progress almost stops. These findings highlight the importance of continuous educational interventions in early childhood, including during the summer, to ensure a stable foundation for further literacy development. When it comes to language modality, several authors point to the benefit of sign language in an academic context. Marschark et al. (2017) found that perceived language abilities, including sign language proficiency, were more closely related to psychosocial outcomes, such as quality of life and cultural identification, than objective measures of language competence. Despite agreement on the importance of early language input and the role of education, the authors differ in their views on the role of spoken language as the dominant modality. Hall et al. (2019) criticize attitudes that advise avoiding sign language, considering them potentially harmful to the overall development of the child. On the other hand, some studies, although they do not deny the importance of sign language, are more focused on the analysis of factors related to the use of CIs, such as age at implantation and consistency of device use. Unequal representation of certain aspects of literacy, especially written expression, represents a serious methodological flaw in the majority of previous studies. The number of studies dealing with writing in children with CI is small, and the available data show lower achievements in this domain compared to reading (Mayer et al., 2018). This indicates the need for future research that will systematically analyze all domains of

literacy. The mentioned authors indicate that CI can be a useful tool in the development of language and literacy, but only if it is part of a wider, linguistically rich, and supportive environment. In addition, it emphasizes the need for an individualized approach, which

takes into account the specific linguistic and cultural characteristics of each child, which can improve rehabilitation and educational practices and reduce the risk of language and academic deprivation.

Table 4.

Visual, Sensory, and Precognitive Reorganization (Cross-Modal Plasticity) - Literature Review

Authors, year, country	Goal	Sample	Method	Conclusion
Ola Badarni-Zahalka, Ornella Dakwar-Kawar, Cahtia Adelman, Salma Khoury-Shoufani, Josef Attias 2025. Switzerland <i>Visual Cortical Processing in Children with Early Bilateral Cochlear Implants: A VEP Analysis</i>	To examine how early bilateral implantation of CI affects visual cortical processing in children.	Children with CI (exact number not specified). To examine cross-modal reorganization, visual evoked potentials (VEPs) were recorded in response to stimuli in 25 children with CI (mean age at implantation: 1.44 years) and 28 age-matched hearing children (NH).	Visually evoked potentials (VEP) – an electroencephalographic (EEG) measurement of brain activity to visual stimuli.	Children with early bilateral CI show changes in visual cortical processing, which may be the result of neuroplastic changes induced by hearing loss and auditory stimulation via CI. Early bilateral cochlear implantation preserves global visual processing, indicating minimal maladaptive reorganization.
David P. Corina, Sharon Coffey-Corina, Enrica Pierotti, Kelsey Mankel, Lee M. Miller 2024. SAD <i>Electrophysiological Study of Visual Processing in Children with Cochlear Implants</i>	To examine differences in visual processing between children with CI and hearing children using VEP signals	28 children with CI (implanted before 31 months of age) and 28 hearing children of the same age.	EEG recordings of VEP – components P1, N1, and early frontal component N1a were analyzed	Children with CI show higher amplitudes of the VEP signal, especially the P1 and N1 components. Early frontal negativity (N1a) was also observed, indicating increased visual attention and redistribution of processing resources. The results indicate that changes do not occur in the auditory cortex but in higher cortical regions related to attention and salience.
Amanda M. Fullerton, Deborah A. Vickers, Robert Luke, Addison N. Billing, David McAlpine, Heivet Hernandez-Perez, Jonathan E. Peele, Jessica J.M. Monaghan, Catherine M. McMahon 2023. Australia United Kingdom <i>SAD Cross-modal functional connectivity supports speech understanding in cochlear implant users.</i>	To examine how cross-modal functional connectivity between the auditory and visual cortex affects speech understanding in CI users, especially in the context of the presence of background noise.	14 adults with postlingual deafness using CI. 17 hearing adults.	Functional near infrared spectroscopy (fNIRS): Measurement of hemodynamic responses in auditory and visual cortical areas during tasks involving auditory and visual speech and non-speech stimuli. Functional connectivity analysis: Assessment of coherence between left auditory and visual cortex during processing of speech and non-speech stimuli.	CI users showed increased cross-modal functional connectivity between the left auditory and visual cortex during visual speech processing. This increased connectivity positively correlated with better speech understanding in the presence of background noise, suggesting that cross-modal plasticity may play an adaptive role in improving speech perception in CI users.

Table 4 (continued).*Visual, Sensory, and Precognitive Reorganization (Cross-Modal Plasticity) - Literature Review*

Authors, year, country	Goal	Sample	Method	Conclusion
Xiao-Feng Qiao, Lu-Dan Liu, Ling-Yan Han, Ying Chen, Xin Li 2023. <i>Exploring cross-modal plasticity in the auditory-visual cortex post cochlear implantation: implications for auditory and speech function recovery and mechanisms.</i>	To investigate the cross-modal reorganization in the auditory-visual cortex after cochlear implantation and to understand its implications for auditory functions, speech, and related neurobiological mechanisms.	CI patients (exact number not specified in abstract, usually tens of subjects) Control group.	Functional magnetic resonance imaging (fMRI) and EEG Assessment of auditory and speech function through standardized clinical tests Analysis of brain activity in the auditory-visual cortex during auditory and visual tasks	Cross-modal reorganization in the auditory-visual cortex can have a bidirectional effect on listening and speaking after cochlear implantation. In some cases, plasticity supports better functional outcomes, while in others it can be maladaptive and negatively affect auditory functions.
Garrett Cardon, Theresa Hennesy, Julia Campbell, Hannah Glick, Don Bell-Souder, Anu Sharma 2022. SAD <i>Cross-Modal Reorganization From Both Visual and Somatosensory Modalities in Cochlear Implanted Children and Its Relationship to Speech Perception</i>	To examine whether children with CI show cross-modal reorganization of the auditory cortex via visual and somatosensory modalities, and how these changes are related to speech perception.	13 children with CI, aged from 5.84 to 15.43 years (average age 10.61 years). 10 children had cortical visual evoked potentials (CVEPs) and cortical somatosensory evoked potentials (CSEPs). 3 children had only CVEP. Control data were used from previous studies with hearing children.	Recording of cortical responses to visual and somatosensory stimuli. Analysis of sources of brain activity during stimulus processing.	There was a positive correlation between visual and somatosensory cross-modal reorganization, suggesting the interconnectedness of neuroplastic changes in different sensory systems. Children with CI who had good results in speech perception did not show recruitment of the frontal or auditory cortex during visual processing, in contrast to children with worse results.

Table 4 (continued).*Visual, Sensory, and Precognitive Reorganization (Cross-Modal Plasticity) - Literature Review*

Authors, year, country	Goal	Sample	Method	Conclusion
Hyo-Jeong Lee, Daniel Smieja, Melissa Jane Polonenko, Sharon Lynn Cushing, Blake Croll Papsin, Karen Ann Gordon, 2020. <i>Consistent and chronic cochlear implant use partially reverses cortical effects of single-sided deafness in children.</i>	To investigate how the use of CI affects cortical reorganization in children with single-sided deafness (SSD) and whether such use can partially reverse the effects of single-sided deafness.	22 children with unilateral deafness: 15 children with early onset SSD 7 children with late-onset SSD.	Measurement of auditory-evoked potentials via electroencephalography (EEG) to assess cortical activity before and after implantation. Monitoring the use of CI devices in children over different time periods. Comparison of cortical responses between children with early and late onset SSD.	Single-sided deafness during childhood can lead to cortical reorganization, with increased activity in the cortex associated with the healthy ear. In children with late-onset SSD, use of CI can reduce abnormal activity from the healthy ear, but responses from the deaf ear remain attenuated despite use of CI. This study highlights the importance of early diagnosis and intervention in children with single-sided deafness and the potential benefits of cochlear implantation in improving auditory function.
Faizah Mushtaq Ian M. Wiggins, Patrick T. Kitterick Carly A. Anderson, Douglas E. H. Hartley 2020. Switzerland <i>The Benefit of Cross-Modal Reorganization on Speech Perception in Pediatric Cochlear Implant Recipients Revealed Using Functional Near-Infrared Spectroscopy</i>	To investigate how the reorganization of brain functions (cross-modal plasticity) affects the perception of speech in children using CI, using functional near-infrared spectroscopy (fNIRS) to measure brain activity.	Children users of CI Hearing children	Application of fNIRS technology to measure brain activity in the temporal cortex during exposure to auditory and visual speech. Comparison of brain activity between CI users and hearing children.	CI users showed significantly greater brain responses to visual speech compared to the control group. There were no significant differences in brain responses to auditory speech between the two groups. The results confirm that visual and auditory speech are synergistically processed in the temporal cortex of children with CI.

A cochlear implant not only affects the auditory pathways but also initiates a series of neuroplastic changes involving visual and other sensory modalities. These changes are the result of a cross-modal reorganization that results in a functional redistribution of brain activity due to sensory deprivation and subsequent stimulation through CI.

Research by Lee et al. (2020) showed that consistent use of CI in children with unilateral deafness can partially reverse the cortical effects of unilateral auditory deprivation. The research indicated the importance of early implantation, especially in children with early onset of unilateral deafness, because early and continuous stimulation of CI has the potential of neuroprotective action, stabilizing activity in the auditory cortex, and limiting improper

reorganization of brain function. Studies using functional near-infrared spectroscopy (fNIRS), such as research by Mushtaq et al. (2020), showed that children with CI recruit the temporal cortex to process visual speech to a greater extent than their hearing peers. These results suggest that cross-modal reorganization may have an adaptive function, allowing more efficient use of visual information (eg, lip reading) to compensate for reduced auditory processing. Fullerton et al. (2023) state that the functional connectivity between the visual and auditory cortex can predict the success of speech understanding in noisy environments in adult CI users. This implies that visual compensation may represent a key strategy in postimplantation speech processing processes. Neurophysiological approaches, including EEG and measurement

of visual evoked potentials (VEP), have further clarified visual processing patterns in children with CI. Badarni-Zahalka et al. (2025) found that early bilateral implantation maintains relatively typical patterns of visual cortical processing, although there are subtle changes in the left occipital region. In contrast, Corina et al. (2024) talk about increased VEP amplitude and recruitment of frontal regions in children with CI, which indicates a redistribution of attention and increased salience of visual stimuli.

A significant role in the understanding of cross-modal reorganization is also played by research involving multiple sensor systems. Cardon et al. (2022) determined that children with CI show reorganization of the auditory cortex not only through visual, but also through somatosensory stimuli, and the degree of this reorganization was related to the ability to perceive speech. Also, they indicate that specific patterns of reorganization may explain variations in functional outcomes after implantation. Qiao et al. (2023) elaborate on the double character of cross-modal reorganization: it can support the development of listening and speaking, and in certain circumstances, it can have maladaptive consequences. In this context, individualized rehabilitation and understanding of specific patterns of brain reorganization are key guidelines for future work with CI users.

Conclusion

Polysensory stimulation through the combination of auditory, visual, and somatosensory inputs through the integration of multiple modalities facilitates the acquisition of phonological and semantic content and reduces the cognitive load when decoding speech. Although there is clear evidence that polysensory stimulation contributes to the improvement of functional abilities and the strengthening of cognitive connections, the results are heterogeneous and depend on several factors: the age at which the implantation was performed, the duration of sensory deprivation, the preoperative language status of the child, individual differences in neuroplasticity, specific forms of intervention, and rehabilitation.

In the rehabilitation of implanted children, it is necessary to use a polysensory

approach in order to exploit the possibilities and potential of cross-modal plasticity due to the improvement of cognitive and communication results. By presenting the results of the research, it was established that in children who have been exposed to auditory deprivation for a longer period, visual and tactile modalities are dominant due to the brain's ability to reorganize neural networks after hearing damage. The functional connectivity of sensory modalities and the ability of the cortex to reorganize functions after CI implantation are key mechanisms for the improvement and development of cognitive abilities. Future research should examine the quality and context of the integration of different sensory modalities in order to create more effective strategies to support optimal cognitive development.

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