Journal on Mathematics Education
Volume 16, No. 1, 2025, pp. 173-196

Rehabilitation of children with a cochlear implant: Overcoming difficulties in solving mathematical problems

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Received: 25 September 2024 | Revised: 2 February 2025 | Accepted: 7 February 2025 | Published Online: 20 February 2025

Abstract

Children with cochlear implants face cognitive and linguistic challenges, particularly in the relationship between auditory perception and mathematical cognition. While auditory rehabilitation has advanced, there is a gap in understanding how integrating mathematical problem-solving with language rehabilitation can improve both cognitive and linguistic outcomes for these children. This study explores the potential of structured mathematical interventions to enhance cognitive flexibility, numerical reasoning, and verbal communication. The research was conducted in multiple phases, each increasing in complexity to assess cognitive and linguistic changes under various intervention conditions. Pre-intervention assessments compared cognitive and linguistic performance through auditory and verbal tests, quantitative evaluations, and real-time speech monitoring. The intervention involved structured mathematical modules combining arithmetic and logical reasoning with verbal learning, alongside multisensory approaches to integrate auditory and visual stimuli. Post-intervention analysis utilized statistical methods including χ^2 for categorical data, ANOVA for intra-subject variations, and t-tests for inter-group comparisons. Results revealed significant improvements in cognitive adaptability ($\chi^2 = 29.41$, $p \leq 0.001$) and numerical thinking, with enhanced logical sequencing, arithmetic operations, and spatial structuring. Speech comprehension showed a marked shift from predominantly gestural and visual communication ($\chi^2 = 12.36$, $p \leq 0.01$) to active verbal responses to abstract mathematical concepts ($p \leq 0.05$, Cohen's $d = 0.82$). Additionally, there was a 1.5-fold increase in multi-sentence responses ($p \leq 0.05$), indicating improved linguistic processing skills. These findings emphasize the importance of incorporating mathematical thinking into auditory-verbal therapy, redefining problem-solving as a dual-mode intervention that enhances both cognitive and linguistic development. Educational programs for children with cochlear implants should integrate mathematical foundations, such as spatial arithmetic and logical reasoning, to support linguistic adaptation and bridge numerical abstraction with verbal comprehension in rehabilitation.

Keywords: Auditory and Speech Development, Children, Cochlear Implants, Math Problems, Pedagogical Methods

How to Cite: Sikinbayev, B., Alwaely, S. A., & Ganeeva, A. (2025). Rehabilitation of children with a cochlear implant: Overcoming difficulties in solving mathematical problems. *Journal on Mathematics Education, 16*(1), 173–196. https://doi.org/10.22342/jme.v16i1.pp173-196

The rehabilitation of children with cochlear implants extends beyond the mere restoration of auditory perception, encompassing the broader domain of cognitive restructuring. Children receiving cochlear implants frequently encounter significant challenges in assimilating numerical concepts and engaging in mathematical reasoning due to auditory-verbal impairments, which interfere with the executive functions responsible for logical reasoning, sequential processing, and problem-solving—key components of higher-order cognitive skills. The difficulty in internalizing numerical patterns, which is directly associated with delayed phonemic differentiation, creates systemic barriers to the integration of arithmetic comprehension with linguistic expression. These challenges necessitate an interdisciplinary approach, combining auditory-verbal therapy with structured mathematical problem-solving strategies, aimed at enhancing neurocognitive flexibility and linguistic accuracy. This approach emphasizes the importance of cross-modal reinforcement to support the development of numerical representations and phonological structures.

Hearing loss is a prevalent condition, affecting approximately 4 to 6 percent of the global population (Contrera et al., 2015). Moreover, an alarming trend indicates that the incidence of hearing loss is projected to increase by 2 percent annually (Sharma et al., 2020). By 2020, the global prevalence of hearing loss had risen by one-third (Clinkard et al., 2015). Cochlear implantation is one of the most effective methods for restoring auditory function, with approximately 100,000 individuals worldwide having received cochlear implants (Liu et al., 2019). However, the social integration and adaptation of these individuals remain challenging, necessitating further research in this area. Cochlear implantation has been utilized for over 30 years (Chang et al., 2016), and according to the standards set by the Independent Center for Cochlear Implantation in Belgium, the procedure can be performed as early as two years of age for children with severe deafness, or between one and two years for children with profound deafness (Chen & Oghalai, 2016). In cases of congenital deafness, implantation is typically performed in preschool-aged children, as this period is critical for the development of speech and cognitive functions (Peixoto et al., 2013). The degree of success in a child's adjustment to their environment is largely influenced by their integration into a society where hearing is typical. Numerous studies have shown that, if not addressed appropriately, childhood hearing loss can lead to speech and language impairments (Black et al., 2012; Chen & Wong, 2017; Clinkard et al., 2015). Speech plays an essential role in both social communication and cognitive development, serving as a medium for expressing and understanding thoughts. Consequently, children who are unable to perceive speech face significant difficulties in societal integration. Supporting these children requires a collaborative effort from a multidisciplinary team, including medical professionals, psychologists, special education teachers, speech therapists, and other educators (Yoshinaga-Itano et al., 2018).

Cochlear implantation restores auditory perception; however, the inclusion of a speech processor does not automatically guarantee speech comprehension. As such, auditory-verbal rehabilitation becomes a critical priority following implant surgery. Consequently, substantial pedagogical efforts are required to support children with cochlear implants, as their social and speech dynamics are profoundly influenced by these efforts. The demand for technologies focused on the auditory and speech rehabilitation of cochlear-implanted children is currently significant (Cowan et al., 2018).

For children, understanding the meaning of spoken language is central to their communication and overall development. Equally important is the level of cognitive skills, which encompasses the ability to perceive, understand, and assimilate information, particularly in the context of educational material. As such, new pedagogical approaches are being developed to enhance the cognitive abilities of children with special needs. One such approach involves the use of mathematical problem-solving and the integration of mathematical applications into the educational process (Zhang et al., 2015). Engaging in mathematical problem-solving enhances cognitive processes such as critical thinking, information analysis, systematization, and the formation of cause-and-effect relationships (Sirota et al., 2021). For children with cochlear implants, solving mathematical problems fosters improvements in reasoning, logical thinking, and strategic planning. Moreover, it supports memory training and activates cognitive functions (Stelzer et al., 2021). Thus, mathematical problem-solving enables children with cochlear implants to structure their thoughts through communication, stimulating brain activity before verbal expression. Additionally, it has been shown to improve emotional regulation and psychological well-being, which can facilitate better social integration and communication skills in children with special needs (Mathieson & Homer, 2022).

To identify potential distortions in auditory-verbal communication, it is crucial to thoroughly examine the speech patterns of children who have received cochlear implants. Such assessments are vital for providing competent support from both psychologists and educators. Cochlear implants function by converting speech sounds into electrical signals, which are then transmitted directly to the auditory nerve. These signals reach the auditory centers in the brain, enabling the perception of speech as well as other sounds (Incerti et al., 2018). Compared to hearing aids, cochlear implants offer the advantage of transmitting high-frequency sounds that hearing aids cannot process. Furthermore, cochlear implants provide selectivity, allowing the differentiation of speech signals from background noise—an ability that hearing aids, which simply amplify existing signals, lack. This selective transmission enables the recognition of softer speech signals, thereby enhancing overall auditory perception (Kulkarni et al., 2018).

Speech disorders encompass a broad spectrum of conditions, particularly in individuals with hearing impairments (Peixoto et al., 2013). Individuals with underdeveloped hearing often exhibit an impaired ability to recognize speech sounds, as they are unable to fully perceive speech through auditory means. This results in difficulties in comprehending spoken language, particularly the speech of unfamiliar individuals, as well as impairments in their own speech production. These impairments manifest in various areas, including pronunciation, grammatical structure, and vocabulary limitations (Tao et al., 2018). The reduction in speech comprehension arises from an inability to distinguish similar sounds or perceive the emotional content within spoken messages. For many children with hearing loss, the merging of multiple pairs of sounds occurs, necessitating reliance on context to differentiate sounds (Black et al., 2012). Contextual understanding, however, is often hindered by a limited vocabulary and insufficient grammar knowledge, which are typically absent in children with hearing impairments. Addressing these issues requires significant pedagogical intervention.

In addition to challenges with their own speech, children with hearing impairments also face difficulties in understanding the speech of others (Cowan et al., 2018). While some children can comprehend speech in familiar contexts, others may only understand learned phrases, and only a few can understand speech across diverse situations. Communication in children with hearing impairments is often facilitated by object-based thinking, and they frequently rely on gestures and facial expressions (Percy-Smith et al., 2018). These elements, combined with speech communication, distinguish hearing-impaired children from those who are profoundly deaf. The speech of deaf children, however, is more prone to distortions in both phonetics and grammar. Deaf children tend to have more limited vocabularies than their hearing-impaired counterparts (Liu et al., 2019) and often ascribe broader meanings to the words they use. Additionally, their grammatical structures are typically inaccurate. Children with hearing impairments are also prone to incorrect speech constructions, often due to limited practical communication experiences and challenges with grammar (Chen & Oghalai, 2016).

Furthermore, communication through sign language can negatively impact the development of spoken language. Adolescents with hearing impairments are generally aware of their difficulties in auditory communication, leading them to be more cautious around unfamiliar individuals and to avoid interactions with peers and adults with normal hearing (Chen & Wong, 2017; Peixoto et al., 2013). Therefore, the development of educational strategies that reduce the social isolation of children with special needs is essential. These strategies should aim to enhance their cognitive abilities, which in turn will facilitate communication skills development.

Engaging in mathematical problem-solving, which involves exploring multiple solutions and selecting the most appropriate one, activates strategic and logical thinking processes (Larkin & Jorgensen, 2016). Furthermore, proficiency in solving mathematical problems aids in the assimilation of information, enables retention of numerous concepts, and supports the expression of thoughts. When communicating with adults, children with hearing impairments often rely heavily on object-based actions, such as gestures and facial expressions, although vocal communication is also present, with nonverbal cues becoming more prominent as they age. Children with severe hearing loss (Grades 3 and 4) face significant challenges in acquiring their native language due to insufficient hearing capacity to fully perceive spoken information (Ubrig et al., 2019). Cochlear implantation offers an effective solution to address the hearing deficiencies of these children by replacing the non-functional receptors of the inner ear with electrodes that convert sound vibrations into electrical impulses, thus enabling auditory perception. However, the inability to comprehend speech remains a challenge (Sharma et al., 2020). Therefore, research focusing on the rehabilitation of hearing and speech abilities in children with cochlear implants is crucial.

Existing studies predominantly address either surgical aspects or the rehabilitation of older populations, such as the elderly (Clinkard et al., 2015; Contrera et al., 2015). While some research does focus on children, it is primarily conducted with English- and Russian-speaking populations (Black et al., 2012; Percy-Smith et al., 2018). There is a notable gap in studies specific to Kazakhstan, underscoring the relevance of this research. The findings from this study could be integrated into a global database, reflecting the challenges encountered in the rehabilitation of hearing and speech abilities across different linguistic groups, as well as the impact of mathematical tasks on the cognitive development of these children. The authors propose that the didactic approaches outlined in this study could facilitate the rapid rehabilitation of Kazakh-speaking children with cochlear implants. A potential limitation of this research is that the study sample consists solely of Kazakh-speaking children; however, the findings may be applicable to children from linguistically similar groups.

The objective of this study is to evaluate the effectiveness of using mathematical problem-solving as a pedagogical tool in auditory-verbal therapy for children with cochlear implants. Specifically, the study aims to explore how structured engagement in solving arithmetic and logical problems fosters cognitive flexibility, enhances language proficiency, and mitigates deficits in abstract thinking that may hinder mathematical comprehension, as follows:

1. To assess the impact of mathematical tasks on cognitive flexibility in children with cochlear implants, particularly their ability to analyze numerical relationships, establish logical connections, and process abstract concepts.
2. To identify specific challenges in mathematical cognition, particularly those arising from auditory and verbal impairments.
3. To develop a methodological framework that integrates mathematical problem-solving with auditory-verbal learning, and to create a system of educational interventions that enhances both cognitive and communicative abilities (combining mathematical reasoning with linguistic expression).

Theoretical Background

The issue of educating individuals with disabilities was thoroughly examined half a century ago, yet it remains highly relevant today (American Action Fund for Blind Children and Adults, 2022). One of the most significant contributions to the cultural-historical approach was made by Vygotsky (1995, 2003). He posited that impairments could be compensated for through cultural development. Vygotsky was among the first to extensively explore the possibility of compensation for both children and adults with disabilities. According to Vygotsky, organic defects—such as deafness, blindness, or limitations in motor skills or cognitive abilities—should not be viewed solely as disadvantages. Rather, they can serve as catalysts for further development. Consequently, deaf or blind children must be seen as having developed in alternative ways. These children, deprived of the ability to use their senses for perceiving the world, compensate by finding other means of interaction. For example, blind children may use tactile systems like Braille, while deaf or hearing-impaired children learn to communicate through gestures.

Vygotsky emphasized that not only the individual but also the socio-cultural environment can provide opportunities for development. To facilitate this, the cultural and social environment must be adapted to meet their needs. Thus, children with disabilities have the potential to lead fulfilling lives and develop within society, without facing the isolation that was once common. Today, efforts are being made to create an inclusive society that promotes the development of individuals with disabilities (Vygotsky, 1995). Vygotsky and his followers have played a pioneering role in advocating for social compensation for organic disabilities—not just biological ones, as traditionally understood by defectologists. These individuals overcome their impairments by transcending them, utilizing alternative strategies (Aismontas & Odintsova, 2017; Beloborodova, 2017; Lebedeva, 2018). The cultural-historical approach provides a more comprehensive framework to address the limitations of defectology and offers more effective methods for overcoming organic disabilities (Angeloni, 2013; Leontiev et al., 2015).

Leontiev (2014) argued that, although disabilities can affect the development of higher mental functions, development can still progress through alternative pathways. However, individuals with disabilities must exert greater effort to continue their development compared to those without disabilities. Furthermore, the psychological resources of people with disabilities are structured differently, in a way that helps mitigate negative effects on their psyche (Lebedeva, 2018). As a result, the mental resources in people with disabilities may not exhibit the same interconnectedness as those in individuals without disabilities. People with disabilities often experience a slower-paced world, actively monitoring processes that others may carry out unconsciously. The exploration of compensatory mechanisms and resources in children with disabilities, within the context of the cultural-historical approach, remains a crucial area of research, as highlighted in the present study.

Cochlear implantation is a neuroprosthetic intervention designed to restore auditory perception by utilizing an electronic device that directly stimulates the auditory nerve through electrical impulses (Van Bogaert et al., 2023). The rehabilitation process post-implantation involves a series of adaptive mechanisms, including sensorimotor recalibration, phonemic restoration, and linguistic integration. The success of cochlear implantation is influenced by various factors such as the age at implantation, neuroplasticity, and the intensity of postoperative rehabilitation (Belash & Revina, 2024).

Cognitive skills, also referred to as neurocognitive abilities, are crucial for information processing, conceptual synthesis, and executive functioning. These skills encompass working memory, logical reasoning, pattern recognition, and strategic adaptivity, all of which underpin learning dynamics and problem-solving capabilities. Working memory is responsible for short-term data retention and retrieval, while logical reasoning involves the inductive and deductive organization of mental frameworks. Pattern recognition refers to the systematic identification of numerical and linguistic structures, and strategic adaptivity enables flexible responses to novel cognitive tasks (Bivarchi et al., 2023). In children with cochlear implants, cognitive plasticity is enhanced by the interaction between auditory-verbal rehabilitation and multimodal neural processing (Neagos et al., 2024).

The rehabilitation of children with cochlear implants, situated at the intersection of pedagogy, neurophysiology, and cognitive psychology, remains a complex and evolving area that demands continuous methodological refinement (Van Bogaert et al., 2023). While the primary goal of cochlear implantation is the restoration of auditory perception, its subsequent effects on cognitive abilities, particularly mathematical cognition, are not yet fully understood, despite a growing body of research exploring this topic (Bivarchi et al., 2023). Existing literature primarily focuses on surgical rehabilitation and speech therapy, with limited discussion on abstract thinking and numerical cognition. However, emerging data indicate that engaging in mathematical problem-solving may serve as a catalyst for cognitive flexibility, linguistic precision, and strategic thinking (Akay, 2023).

Mathematical exercises involve structured cognitive tasks that demand logical reasoning, quantitative abstraction, and relational thinking. Within the context of cognitive rehabilitation, these exercises function as "neural triggers" that enhance the stability of executive functioning, particularly in individuals with auditory deficits (Akay, 2023). They promote neural synchronization in key areas such as the inferior parietal lobule and prefrontal cortex, reinforcing cognitive pathways tied to linguistic articulation and conceptual structuring (Sihem, 2024). Consequently, mathematical cognition emerges as a pedagogical intervention that not only bolsters cognitive function but also enhances verbal-linguistic competence through structured problem-solving paradigms (Santopietro et al., 2024).

Mathematical cognition in children with cochlear implants is marked by a range of interconnected cognitive deficits that impact their ability to process auditory and verbal information, as well as their working memory and the formation of numerical abstractions. These deficits underscore the need for an educational approach that is specifically tailored to the cognitive abilities of children with cochlear implants (Neagos et al., 2024). A common consequence of hearing loss, speech impairment, is linked to a lack of phonological awareness, which in turn negatively affects numerical literacy and arithmetic reasoning (Sihem, 2024). The connection between auditory perception and numerical cognition is not incidental but rather inherent, as evidenced by research indicating a decline in the performance of children with cochlear implants on tasks involving mental arithmetic, numerical search, and quantitation (Taha et al., 2023). These disorders arise from neuroplastic adaptation following auditory deprivation, which alters cortical networks and reduces the importance of phoneme discrimination, a critical element of numerical reasoning (Gharashi & Abdi, 2022).

A significant gap in the current discourse lies in the absence of studies examining the role of mathematical problem-solving as a rehabilitation tool within auditory-verbal learning paradigms (Zakirjanovna, 2024). Despite a robust body of research on speech rehabilitation techniques, including auditory-verbal therapy (AVT) and cued speech, the integration of numerical reasoning tasks into language rehabilitation remains insufficient (Van Bogaert et al., 2023). This gap is particularly noteworthy given the cognitive parallels between arithmetic structuring and syntactic analysis, both of which rely on working memory, sequencing, and deductive logic (Santopietro et al., 2024). Although there is some evidence suggesting that structured problem-solving activities can develop executive functioning in children with hearing impairments, the potential of mathematical cognition as a compensatory mechanism for linguistic deficits remains an underexplored area (Faramarzi et al., 2020).

The revision of existing rehabilitation techniques calls for a shift away from traditional models of auditory-verbal therapy. A comprehensive system is needed that integrates mathematical reasoning with linguistic information processing (Belash & Revina, 2024). Empirical evidence indicates that there are overlapping neural networks involved in numerical cognition and phonological processing, specifically in the inferior frontal gyrus and superior temporal gyrus. This suggests that mathematical activity may enhance auditory discrimination (Li et al., 2022). Children with cochlear implants, through structured exercises that require sequential thinking and pattern recognition, are better able to learn spoken language and differentiate between phonemes. These findings have important implications for education and justify the incorporation of mathematical exercises in auditory therapy programs aimed at enhancing cognitive flexibility in children with hearing impairments (Mashhadi et al., 2022).

The current study aims to address this theoretical gap by developing a methodological approach that integrates mathematical problem-solving into the rehabilitation program for children with cochlear implants. This approach is based on the hypothesis that numerical reasoning enhances both linguistic and cognitive abilities in these children (Rijke et al., 2019). Unlike existing methods that prioritize isolated phoneme recognition, the proposed model emphasizes that arithmetic instruction contributes to the development of a dual-channel reinforcement mechanism, which strengthens both logical structuring and the syntactic organization of spoken language (Torppa et al., 2019). This paradigm shift calls for a reevaluation of traditional pedagogical strategies and suggests an interdisciplinary approach that places numerical literacy at the core of auditory-verbal rehabilitation (Parmar et al., 2023).

An analysis of rehabilitation pathways indicates that children who undergo cochlear implant surgery and engage in structured mathematics exercises demonstrate enhanced neurocognitive flexibility, as evidenced by improved working memory capacity, enhanced pattern recognition skills, and superior problem-solving abilities (Grigsby et al., 2024). The cognitive benefits of mathematics education extend beyond numerical literacy to include the development of metacognitive skills, which foster linguistic articulation and enhance abstract thinking (Moradi et al., 2021). Incorporating arithmetic problem-solving in rehabilitation programs can help alleviate the cognitive asymmetries caused by auditory deprivation (Mostafa et al., 2021).

Given the strong interdependence between numerical cognition and language processing, there is an urgent need to reconsider rehabilitation techniques. An interdisciplinary approach that integrates mathematical reasoning with auditory-verbal learning is necessary. By positioning arithmetic exercises as foundational to cognitive rehabilitation, this research seeks to challenge current pedagogical practices, advocating for a comprehensive, integrated approach that transcends traditional speech therapy boundaries (Agostinelli et al., 2022). Theoretical and empirical findings suggest that this research has the potential to reshape auditory-verbal rehabilitation, offering a new approach to enhancing the cognitive abilities of children with cochlear implants.

METHODS

Research Sample

This study was conducted in 2019 at a specialized preschool in Almaty, Kazakhstan, catering to children with hearing and speech development disorders. Two experimental groups were involved in the intervention: (1) children with cochlear implants (diagnosed with deafness or moderate to profound hearing loss) and (2) children using hearing aids. Each group comprised 10 participants (mean age: 5.1±0.9 years, range: 4-6 years). Inclusion criteria were based on strict adherence to factors influencing cognitive and linguistic rehabilitation, such as auditory status (cochlear implant or hearing aid), age (4-6 years), and the absence of concurrent neurological or intellectual disabilities. These criteria were designed to ensure uniformity across the experimental groups.

The cochlear implant group was selected based on the severity of hearing loss (congenital deafness or moderate to profound hearing loss), implantation duration (at least 12 months), and active participation in auditory-verbal rehabilitation programs aimed at assessing cognitive adaptability. In contrast, the hearing aid group followed a distinct auditory rehabilitation program tailored to their residual hearing level and adaptive plasticity. This distinction facilitated the comparative analysis of numerical cognition across different auditory conditions.

The control group consisted of children with normal hearing, matched for age and non-verbal IQ (assessed using Raven's Progressive Matrices), ensuring cognitive equivalence independent of auditory factors. Additionally, socioeconomic status (parental educational level, family income) and home language environment (exposure to Kazakh/Russian language) were considered, as these factors may influence language development and numerical abstraction, requiring statistical adjustments. The sample size (10 participants per group) was determined based on a preliminary power analysis with $\alpha = 0.05$ and $\beta = 0.80$, ensuring the ability to detect moderate effects (Cohen's $d > 0.50$), thus validating the statistical conclusions despite the study's methodological limitations.

Research Design

Prior to the intervention, the research team collected anamnesis for each child through a review of medical records. In addition, parents completed a questionnaire, the results of which were compared with the medical records to ensure consistency. This process was crucial for providing adequate follow-up for each child. The analysis of psychological and pedagogical characteristics indicated that the majority of children were active and socially engaged (60%), while the remainder showed a preference for independent task completion. A subset of children exhibited developmental immaturity, characterized by unstable attention, dominance of play motives, and increased fatigue and inattention.

The parental questionnaires, aligned with medical records, assessed various aspects of child development, including auditory functions (perception thresholds, phonemic differentiation), cognitive processes (memory, executive control), language development (lexical range, syntactic structures), and socio-emotional adaptation (interpersonal tendencies, behavior regulation). These parameters were cross-referenced with the child's medical history to establish correlations between clinical factors, such as implantation duration and residual hearing, and pedagogical interventions related to structured mathematical cognition. This approach ensured the comprehensive profiling of individual cognitive trajectories, enhancing methodological transparency and the reliability of the data.

A multidisciplinary team, comprising specialists in psycholinguistics, rehabilitation pedagogy, and clinical neuropsychology, conducted observational assessments. These assessments were organized using established categories, including delayed responses to verbal stimuli, use of alternative communication methods (gestures and visual cues), and the frequency of interactive engagement. Observational parameters included the spontaneity, lexical diversity, and syntactical complexity of communication in both structured and unstructured activities, providing an accurate representation of each participant's cognitive-linguistic adaptation. These observational protocols laid the foundation for cross-phase analyses, investigating intrapersonal changes throughout the intervention.

Ethical Considerations

The study adhered to widely recognized ethical and moral standards. Parental consent was obtained through detailed explanation of the study's aims and procedures. Parents provided verbal consent, followed by written contracts ensuring anonymity and confidentiality. The preschool's name was kept confidential. Participation was limited to children whose parents had signed the consent form. Furthermore, children with significant chronic neurological conditions or genetically determined disorders (e.g., Down syndrome, dementia) that might interfere with the study's outcomes were excluded.

Research Methods

The theoretical framework of this study is grounded in a multidisciplinary synthesis of pedagogical strategies, neurocognitive rehabilitation methods, and theories of mathematical cognition. The study seeks to empirically analyze the interaction between auditory-verbal activities and problem-solving tasks in children with cochlear implants.

The research was conducted in multiple phases, each progressively more complex. The first phase involved basic auditory-verbal assessments (baseline stage), followed by structured pedagogical interventions in the form of mathematical learning modules. The final phase consisted of post-intervention assessments. The research procedure included: (1) initial cognitive-linguistic diagnostics (comparing participants' abilities before and after cochlear implantation), (2) structured mathematical tasks (with increasing complexity, focusing on arithmetic and logical reasoning), (3) real-time communication observations (unrestricted interaction and speech monitoring via games), and (4) periodic auditory perception assessments (compliance with verbal instructions and accuracy of responses). Participants engaged in problem-solving tasks in varying scenarios (independently or with a tutor). The effects of structured interventions on cognitive and linguistic flexibility were subsequently analyzed.

To assess linguistic and cognitive correlations, the study employed stratified assessment protocols that encompassed oral comprehension (listening-only or auditory-visual learning), mathematical abstraction (numerical modeling and spatial logical structuring), and verbal articulation (dialogical formulation within task-based exchanges). Evaluation criteria for cochlear implants' impact on cognitive and mathematical adaptation included phonemic accuracy and conceptual coherence. Controlled experimental conditions enabled a nuanced analysis of auditory-cognitive improvements due to neural plasticity versus those resulting from structured pedagogical interventions.

This study systematically explored the specific role of cochlear implantation in restructuring auditory cortical areas. Cognitive indicators such as working memory involvement, phonological recalibration, and syntactical complexity were used to monitor linguistic progress. Longitudinal analysis revealed differentiated response patterns at various intervention stages, highlighting the gradual reduction in compensatory reliance on gestures and a shift toward phonemic articulation in structured mathematical reasoning. These findings underscore the importance of integrating cognitive-mathematical exercises within rehabilitation programs to optimize auditory-verbal assimilation and neurocognitive engagement.

The primary mathematical tasks aimed at developing fundamental arithmetic skills, logical reasoning, spatial awareness, and problem-solving abilities. These tasks were tailored to the cognitive and linguistic abilities of the participants, progressing in difficulty to foster analytical and cognitive growth. Participants completed a series of ten activities designed to progressively enhance their reasoning abilities, including:

1. Counting and categorization (e.g., "How many red pencils are in a box containing five red, three green, and two blue pencils?"),
2. Basic arithmetic operations (e.g., "If you have three apples and take one away, how many are left?"),
3. Spatial reasoning tasks (e.g., "Place a book under the table and then move it onto a chair"),
4. Pattern recognition (e.g., "What number comes next in the sequence: 2, 4, 6, 8...?"),
5. Verbal problem-solving using real-life scenarios (e.g., "If a car travels 5 kilometers in 10 minutes, how far will it travel in 30 minutes?"),
6. Logical reasoning (e.g., "In a box containing only cubes or balls, if there are three cubes, how many balls are there?").

Each task was evaluated according to the participant's level of comprehension, performance, and autonomy in task completion, with scores ranging from 0 (basic) to 3 (advanced). Initially, verbal instructions were provided to the participants, with supplementary visual cues—such as object pointing or picture representations—used as needed to facilitate multisensory comprehension.

In addition to evaluating mathematical problem-solving abilities, a subset of tasks was designed to assess the integration of mathematical reasoning with interpersonal communication skills. A cooperative game was conducted, wherein participants worked in groups to complete tasks involving counting, sorting, and spatial arrangement. For example, one task required participants to "load a toy truck with five blocks and then unload three blocks." The analysis focused on the predominance of verbal versus non-verbal communication during these interactions, with particular attention to the fluency of speech, the complexity of linguistic structures (ranging from simple phrases to more elaborate sentences), and the contextual appropriateness of responses.

A comprehensive rubric was developed to assess participants' performance across several domains: comprehension, task completion, cognitive adaptability, and verbal expression. Specifically, the understanding of verbal instructions (both auditory and auditory-visual) was evaluated on a 0-6 point scale, reflecting a continuum from minimal to advanced levels of understanding. The verbal expression used in response to visual stimuli (e.g., image analysis) was scored based on the complexity of the response, from single words (1 point) to well-structured sentences (3 points).

Dialogic interactions were further assessed to explore the pragmatic aspects of speech development. A set of ten structured questions was designed to elicit responses ranging from factual information (e.g., "What is your name?") to inferential reasoning (e.g., "Why do you think the bird is flying in the picture?"). The responses were evaluated based on their accuracy, contextual relevance, and level of detail, with scores ranging from 0 to 3 points. Additionally, intonation perception was assessed using flashcards featuring visual cues such as question marks and exclamation marks. Participants were also tasked with completing narrative exercises that involved identifying emotions and tonal patterns within a familiar fairy tale. The primary criterion in this case was the ability to align intonation patterns with the appropriate emotional or contextual cues.

Statistical Analysis

The statistical analysis employed both parametric and non-parametric methods, including the χ^2 test to assess auditory perception gradients, repeated measures to compare linguistic indicators before and after the intervention, and independent t-tests to evaluate the effectiveness of mathematical problem-solving between experimental and control groups. Effect size calculations (Cohen's d, η^2) were conducted to quantify the impact of the intervention, with thresholds for statistical significance set at $p \leq 0.01$ and $p \leq 0.05$ in cognitive and linguistic domains. The post-hoc Bonferroni correction was applied to mitigate the risk of Type I errors and ensure the rigor of the analysis.

RESULTS AND DISCUSSION

The results revealed that the majority of the children demonstrated an understanding of the verbal tasks presented by the teachers and were able to solve mathematical problems across various levels of complexity (see Table 1). Notably, children in the control group exhibited superior performance compared to those both prior to and following cochlear implantation, particularly in areas such as active speech development, mathematical problem-solving, and speech levels during play. Specifically, the number of children demonstrating high and intermediate levels of comprehension was four times greater than those displaying low comprehension levels ($p \leq 0.01$). Furthermore, the findings indicated that 70% of the children exhibited a high level of cognitive development when solving mathematical problems, while 20% were at an average level and 10% demonstrated a low level. These findings underscore the positive impact of cochlear implantation on the cognitive development of children, particularly in the context of solving mathematical tasks.

Table 1. Results of the auditory-speech activity assessment of children with a cochlear implant in different activities

Type of Activity	High, %	Average, %	Low, %	Basic, %
Level of children's understanding of speech tasks after cochlear implantation	40	40	20	-
Understanding the teacher's spoken language by children after cochlear implantation	-	80	20	-
Level of active speech development	40 (90)	40 (10)	10	10
The level of thinking in solving mathematical problems	70 (90)	20 (10)	10	-
Speech level when playing	30 (70)	60 (30)	-	10

Note: * parameter values for the control group (children without disability) are shown in parentheses.

The analysis of children's comprehension of speech (see Table 1) revealed that no individuals exhibited a high level of understanding ($\chi^2 = 12.36$; df = 2; $p \leq 0.01$). Moreover, the prevalence of the average comprehension level was four times greater than that of the low level, suggesting a statistically significant imbalance in cognitive abilities. Regarding the active use of speech ($\chi^2 = 29.41$; df = 3; $p \leq 0.001$), children demonstrated a clear predominance of average and high levels, with the ratio of average/high to low/basic levels being 8:1. This result reflects a deviation from typical speech development patterns.

Concerning communicative interactions during play, the analysis indicated a marked asymmetry in communicative activity: children classified as having "high" or "average" levels outperformed those categorized as "low" by a factor of nine ($\chi^2 = 33.27$; df = 2; $p \leq 0.001$). Furthermore, speech was not the predominant mode of communication; articulation at the sentence level occurred at half the frequency of phrase-level expressions ($\chi^2 = 5.84$; df = 1; $p \leq 0.05$). This suggests a cognitive and linguistic shift towards more complex structures. Additionally, a single instance of non-response to verbal stimuli, with gesture-based responses predominating, was identified as an extreme outlier, potentially indicating the presence of alternative processing mechanisms.

With regard to the children's ability to evaluate the content of pictures, most children provided correct answers, with a ratio of four correct responses for every incorrect one ($p \leq 0.01$, see Table 2). Consequently, half of the children required no assistance from the teacher, 1.5 times as many needed partial assistance ($p \leq 0.05$), and twice as few required full assistances ($p \leq 0.05$). Children in the control group demonstrated a higher number of correct answers, required less teacher intervention, expressed their responses in full phrases, and performed better in solving mathematical problems (see Table 2).

The majority of children (70%) expressed their responses using full sentences or phrases, while twice as many children preferred gestures or failed to complete the task ($p \leq 0.05$). As a result, four times as many children fully or partially understood the questions posed to them ($p \leq 0.01$) compared to those who demonstrated low levels of comprehension. These findings indicate a high level of mathematical problem-solving ability among children with cochlear implants. Specifically, 70% of the children performed at a high level, 20% at an average level, and 10% at a low level, with no children exhibiting basic-level performance. The data for mathematical problem-solving ability strongly suggest the dominance of high cognitive skill development in children with cochlear implants.

Table 2. Results of assessing children's understanding of the questions and tasks, their performance, and the need for the teacher's help

	High (%)	Average (%)	Low (%)	Basic (%)
Adequacy of the answer to the content of the picture	80 (yes) (100)	-	-	20 (no)
The need for teacher assistance	50 (no help) (70)	30 (partially)	-	20 (need help)
Way of expressing answers	40 (word) (10)	30 (phrase) (90)	10 (gesture)	20 (non-compliance)
Level of understanding of the questions	60 (100)	20	20	-
Ability to solve mathematical problems	70 (90)	20 (10)	10	-
Understanding and reproduction of intonation, trial 1	- (70)	40 (30)	60	-
Understanding and reproduction of intonation, trial 2	20 (80)	40 (20)	30	10
Understanding and reproduction of intonation, trial 3	10 (90)	60 (10)	20	10

Note: * parameter values for the control group (children without disability) are shown in parentheses.

The results from the trials on reproduction and intonation, however, yielded varying outcomes. In Trial 1, high scores were not achieved, and children predominantly demonstrated average results, with low scores occurring 1.5 times more frequently ($p \leq 0.05$). Trial 2 showed a subset of children achieving high scores, although their number was half that of those with average scores ($p \leq 0.05$). In general, children with average results made up the majority of respondents, outnumbering those with high, low, or basic results by a factor of 1 to 2 ($p \leq 0.05$). Notably, significant differences were observed in the performance of the children between the beginning (ascertaining stage) and the end (control stage) of the experiment, as shown in Figures 1-4.

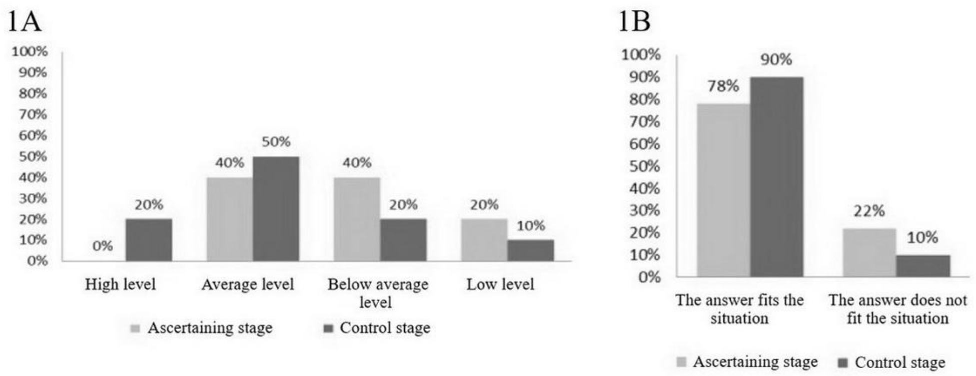

Figure 1. Test results of children with auditory-verbal development defects at the initial (ascertaining) and final (control) stages of the experiment (Part 1)

Children who scored highly on speech perception tasks were predominantly observed in the control group (Figure 1A, $p \leq 0.01$ when compared to the ascertaining stage). At the control stage, children's responses more frequently aligned with the given situation ($p \leq 0.05$), while discrepancies in their responses were half as frequent ($p \leq 0.05$, Figure 1B). This indicates an improvement in the children's oral comprehension, as they were also twice as likely to complete the tasks successfully at the control stage (Figure 2A, $p \leq 0.05$). Moreover, children began to provide more frequent verbal responses in the form of phrases (Figure 2A, $p \leq 0.05$).

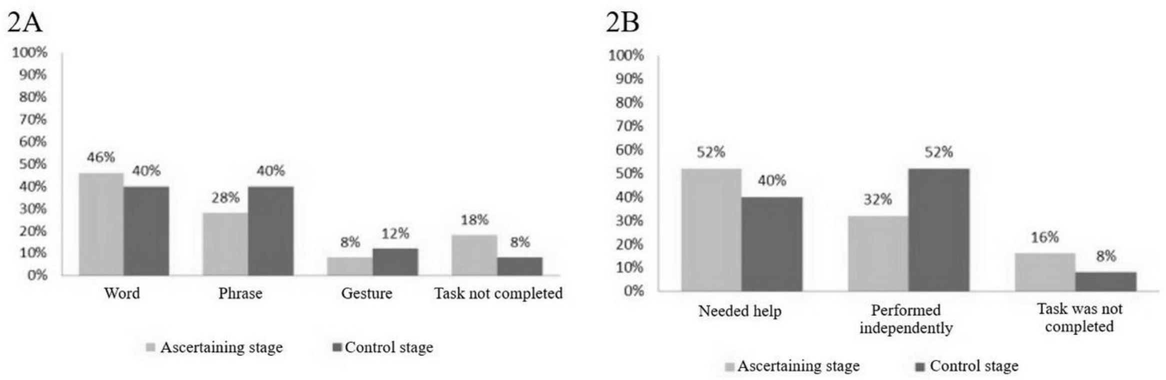

Figure 2. Test results of children with auditory-verbal development defects at the initial (ascertaining) and final (control) stages of the experiment (Part 2)

Less than half of the children required teacher assistance at the control stage (Figure 2B, $p \leq 0.05$), with half completing the task independently ($p \leq 0.05$ compared to the ascertaining stage, Figure 2B). However, twice as many children failed to complete the task at the control stage (Figure 2B, $p \leq 0.05$). Additionally, children were 1.3 times more likely to succeed in answering simple questions ($p \leq 0.05$, Figure 3A), and there was a twofold decrease in the number of children providing low or average responses ($p \leq 0.05$, Figure 3A).

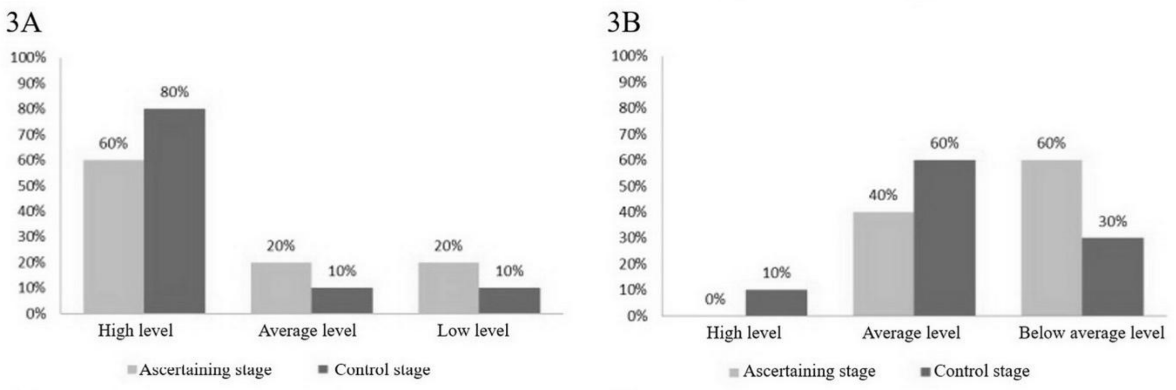

Figure 3. Test results of children with auditory-verbal development defects at the initial (ascertaining) and final (control) stages of the experiment (Part 3)

Regarding intonation perception in Trial 1, the control stage revealed the emergence of children with high-level perception for the first time, and the number of children demonstrating an average level of perception increased 1.5 times in the control group ($p \leq 0.05$, Figure 3B). Furthermore, children with a low level of perception were twice as few in the control group ($p \leq 0.05$, Figure 3B).

In Trial 2, although there was no increase in the number of children exhibiting high-level perception, the number of children with average-level perception was 1.5 times higher (Figure 4A, $p \leq 0.05$), and the number of children with below-average perception decreased threefold ($p \leq 0.01$, Figure 4A). In Trial 3, there was a slight increase in the number of children with average perception levels, while no significant changes were observed for other performance indicators ($p \geq 0.05$, Figure 4B).

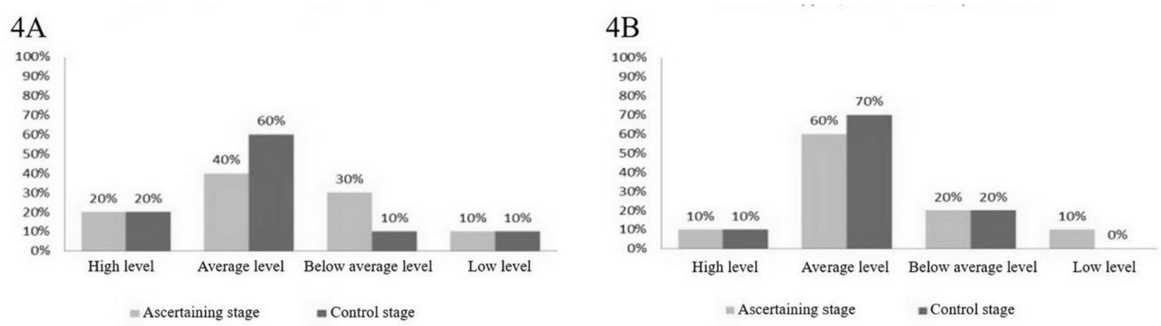

Figure 4. Test results of children with auditory-verbal development defects at the initial (ascertaining) and final (control) stages of the experiment (Part 4)

The findings indicate that the applied methods led to significant improvements in the auditory and verbal development of children with cochlear implants. The authors attribute these positive outcomes to the comprehensive approach used in conjunction with mathematical tasks designed to foster cognitive skills in children with cochlear implants.

Individuals with disabilities often face more complex pathways to realization compared to those without disabilities. People without disabilities typically enjoy broader opportunities, not only in their professional choices but also in various activities. This disparity also extends to children. The current study highlights the enhanced capabilities of children in the control group, who did not have disabilities. For individuals without disabilities, the opportunity to engage in activities they do not enjoy can be offset by financial rewards or familial support. In contrast, for individuals with disabilities, aligning intrinsic motivation with the activity they are involved in is of paramount importance (Beloborodova, 2017). Furthermore, engaging in activities that are disliked can significantly impact the quality of life and psychological well-being of individuals with disabilities.

On the other hand, physical limitations may narrow the range of choices, enabling individuals with disabilities to more quickly navigate the remaining options. This narrowing of choices can, in some instances, serve as a motivating factor (Vygotsky, 2003). Despite impairments, individuals continue to develop in a manner similar to those without disabilities, albeit at a different pace. However, individuals with disabilities are often more sensitive to errors, which underscores the need for careful attention to their specific challenges. It is crucial to address these impairments by tailoring support to help overcome organic deficiencies. The results of this study suggest that cochlear implants can play a significant role in this process, as children with implants showed performance levels closer to those of the control group.

The conditions for cochlear implant surgery are generally well-established (Geers et al., 2017). These include:

1. Diagnosis of bilateral deafness, with the use of hearing aids,
2. A sound perception threshold exceeding 85-90 decibels at frequencies between 2 and 4 kilohertz,
3. An observable improvement in sound perception with the use of hearing aids,
4. No cognitive impairments and sufficient family support.

Families of children undergoing cochlear implantation must be prepared for long-term rehabilitation, which involves working with various specialists' post-surgery (Dettman et al., 2016). A crucial aspect of rehabilitation is the development of children's cognitive skills, particularly in areas such as perception, memory, information processing, and critical thinking. The present study demonstrates that, with the proper application of didactic methods—such as solving mathematical problems—it is possible to significantly enhance these cognitive abilities in children with cochlear implants. However, it should be noted that the study excluded children with mental developmental issues, as such conditions are generally considered an impediment to typical developmental progress. Moreover, a key requirement for cochlear implantation is that children exhibit normal neuropsychological functioning prior to the procedure (Bruijnzeel et al., 2016; Dettman et al., 2016; Nasralla et al., 2018). This is supported by research showing that complications, such as focal brain lesions, can severely hinder development after surgery (Mikic et al., 2016). For instance, a two-year-old child with bilateral temporal lobe lesions who underwent cochlear implantation demonstrated markedly slow speech development (Sennaroğlu & Bajin, 2017).

Furthermore, children in need of cochlear implantation should undergo assessment by educators to determine their speech and hearing development, as well as the dynamics of their speech acquisition. The effectiveness of cochlear implants in children with varying degrees of deafness depends greatly on the timing of the hearing loss. Children who lose their hearing after acquiring speech tend to show quicker speech development post-implantation (Morlet et al., 2017). In contrast, children with congenital deafness or severe hearing loss often exhibit slower development (Valero et al., 2012). This study focused on children with congenital or early-onset hearing loss, and as expected, their speech development was relatively slow during the one-year study period. Research indicates that for children with congenital deafness, cochlear implants represent the primary means of restoring hearing (Birman et al., 2015).

Integrating children with hearing impairments into mainstream society remains a challenge (Daneshi et al., 2018). Historically, children with hearing and speech impairments were placed in specialized institutions, particularly in the former Soviet republics. However, children who undergo cochlear implantation, especially those with profound bilateral deafness or hearing impairments of degree 3 or 4, can achieve hearing and speech capabilities comparable to their hearing peers, provided they receive adequate hearing and speech rehabilitation (Sennaroğlu & Bajin, 2017). With appropriate pedagogical and psychological support, including didactic methods, these children can catch up with their peers and thrive in regular educational settings (Smith et al., 2017). The development of cognitive skills through mathematical problem-solving in children with cochlear implants is an emerging area of study. Research shows that engaging in mathematical problem-solving fosters the development of mathematical thinking, which aids in the formation of perceptual skills, enhances information processing through data decomposition, and strengthens general educational competencies, including the study of humanities (Drijvers et al., 2019; Tran et al., 2017).

The success of auditory rehabilitation is contingent upon several factors, including medical conditions, as well as social and psycho-individual elements. Children with cochlear implants often face challenges in perceiving oral speech messages (Hyde & Punch, 2011). They struggle to identify and analyze sounds, and understanding what teachers communicate through these sounds can be particularly difficult. Consequently, consistent and targeted work with these children is necessary to achieve progress in their auditory-verbal development. Without practice, their auditory and verbal abilities may regress (Peters et al., 2010), as observed in children with lower developmental levels in the present study.

To further develop mathematical abilities in children with cochlear implants, alternative methods such as mental arithmetic may be employed. This technique fosters computational skills through the use of an abacus and integrates visual, figurative perception with verbal ability development (Ganeeva & Anisimova, 2020). Future efforts should focus on creating effective auditory-verbal rehabilitation techniques suitable for remote learning environments, particularly in light of the COVID-19 pandemic.

The experimental data collected in this study show that children with cochlear implants follow a unique trajectory in their cognitive and mathematical adaptation. Notable improvements were observed in numerical abstraction and fluency after the intervention ($\chi^2 = 12.36$; $p \leq 0.01$), although these children's scores remained lower than those of the control group, which comprised children without auditory impairments. This finding is consistent with neurocognitive models (Geers et al., 2017) that emphasize the importance of auditory-verbal plasticity in mathematical cognition. However, it contrasts with prior studies (Nasralla et al., 2018) that suggest cochlear implant recipients achieve comparable performance to normative controls within a similar timeframe. An asymmetry in the structure of verbal responses—where children relied more on phrases than full sentences ($\chi^2 = 5.84$; $p \leq 0.05$)—indicates a persistent deficit in language development, which may be attributed to delayed phonemic integration (Sennaroğlu & Bajin, 2017). This highlights the significance of computational competence and effective verbal encoding in cognitive engagement with mathematical problem-solving (Peters et al., 2010).

The study's results supported the hypothesis that children with cochlear implants face difficulties in mathematical problem-solving. While cognitive performance (task completion speed and adherence to verbal instructions) significantly improved following rehabilitation, it has not yet fully matched that of children without impairments. This suggests that auditory rehabilitation alone is insufficient for complete cognitive integration (Drijvers et al., 2019). These findings expand upon existing theoretical frameworks (Vygotsky, 2003) by demonstrating that structured educational interventions—such as multimodal scaffolding and auditory-verbal reinforcement—can influence cognitive plasticity. However, these interventions require further refinement to optimize neural reorganization. Future research should explore the longitudinal effects of linguistic reinforcement on mathematical cognitive development, particularly examining whether sustained exposure to structured interventions, such as mental arithmetic training and prosodic modulations, facilitates adaptation. Additionally, interdisciplinary approaches to the cognitive rehabilitation of children with hearing impairments should be further explored.

CONCLUSION

The findings of this study provide robust evidence supporting the effectiveness of structured mathematical problem-solving activities in fostering cognitive development in children with cochlear implants. These activities were shown to significantly enhance the children's ability to analyze numerical patterns, establish logical connections, and process abstract concepts, as demonstrated by a marked improvement in cognitive flexibility ($\chi^2 = 12.36$, $p \leq 0.01$). Additionally, the proposed didactic approach highlighted the positive correlation between mathematical cognition and linguistic competence. In particular, structured mathematical tasks were found to contribute to improved syntactic articulation, as evidenced by an increase in phrase-level responses when compared to isolated word production ($\chi^2 = 5.84$, $p \leq 0.05$). The study also revealed that the children exhibited greater stability in executive functions, such as enhanced working memory and strategic adaptability, which are critical for effective learning. However, it was noted that their efficiency in verbal encoding remained lower than that of children without auditory impairments, pointing to the ongoing need for refinement in pedagogical strategies.

Despite these promising results, several limitations of the current study should be acknowledged. The sample was exclusively comprised of Kazakh-speaking children, which, while ensuring linguistic consistency, limits the generalizability of the findings to other linguistic and cultural contexts. Further cross-lingual validation is necessary to determine whether the observed effects hold true across different language groups. Additionally, while the study demonstrated a significant difference in mathematical thinking between the experimental and control groups, the research was limited to a relatively short intervention period. As such, the long-term effects of structured mathematical instruction on language development and cognitive functioning remain unclear. The study's scope also did not include any exploration of the neuroplastic changes that may occur over extended periods of intervention, which warrants further investigation in future research.

Finally, several avenues for future research are recommended. Longitudinal studies should be conducted to assess the enduring impact of structured numerical instruction on phonemic recalibration and the potential convergence of cognitive development with normative cognitive indicators, especially in areas such as phonological encoding and syntactic structuring. Additionally, there is a need for the development and empirical validation of adaptive mathematics modules integrated into digital rehabilitation platforms. Such platforms could provide more accessible auditory-verbal learning opportunities for children with cochlear implants. Future studies should also include multi-group comparative designs to further test the efficacy of integrating mathematical and linguistic reinforcement in rehabilitation programs. Interdisciplinary approaches that incorporate both mathematical and linguistic components into rehabilitation strategies should be systematically explored, as this could contribute to more effective and holistic therapeutic interventions for children with cochlear implants.

Acknowledgments

Not applicable.

Declarations

Author Contribution	:	BS: Conceptualization, Formal analysis, Project administration, Supervision, Writing - review & editing, and Validation SAA: Funding acquisition, Methodology, Software, Writing - original draft, Writing - review & editing, and Validation AG: Data curation, Investigation, Visualization, Resources, Writing - review & editing, and Validation
Funding Statement	:	Not applicable.
Conflict of Interest	:	The authors declare no conflict of interest.
Additional Information	:	Not applicable.

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