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Perceptual evaluation of speech intelligibility in children using bimodal devices, unilateral cochlear implants, hearing aids, and normal hearing peers: A comparative study

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Abstract
Background: Speech intelligibility is a critical outcome in pediatric habilitation of children with hearing impairment. While cochlear implants (CIs) and hearing aids (HAs) are established interventions, the benefit of bimodal stimulation (CI in one ear, HA in the other) on speech intelligibility remains underexplored.
Objective: To assess and compare perceptual speech intelligibility among children with normal hearing (NH), children using bilateral hearing aids, children with unilateral cochlear implants, and children using bimodal devices. Methods: Fifty-five children aged 5.5-7 years were recruited across four groups: NH (n=15), HA users (n=15), unilateral CI users (n=15), and bimodal users (n=10). Speech intelligibility was evaluated using the Picture Speech Intelligibility Evaluation Test (SPINE), featuring bisyllabic words. Speech samples were rated by three trained listeners. Statistical analyses included one-way ANOVA and LSD post hoc tests.
Results: Significant differences were observed among groups ($p<0.001$). Mean intelligibility scores were highest in NH children (97.9%), followed by bimodal users (56.8%), unilateral CI users (49.8%), and HA users (27.6%). Post hoc comparisons revealed significant differences between all pairs, with bimodal users performing better than unilateral CI users (p=0.016).
Conclusion: Bimodal stimulation offers perceptual intelligibility advantages over unilateral CI or HA alone, though NH children still demonstrate superior outcomes. Findings underscore the potential benefit of bimodal fitting for improving speech production outcomes in children with hearing impairment.

Keywords: Speech intelligibility, bimodal hearing, cochlear implant, hearing aids, pediatric audiology, SPINE test

Introduction
Speech intelligibility is one of the most fundamental components of successful oral communication. For children, intelligible speech serves not only as a medium for expressing thoughts and emotions but also as a cornerstone for academic achievement, social inclusion, and psychological well-being. When a child's ability to produce clear and understandable speech is compromised, it can lead to difficulties in classroom participation, reduced peer interaction, and even long-term psychosocial consequences such as social withdrawal and lowered self-esteem. Thus, intelligibility is not simply an outcome of habilitation in children with hearing loss; it is a central indicator of overall communicative competence and a predictor of life outcomes. The acquisition of speech intelligibility is closely tied to auditory access. Children with intact auditory systems typically acquire speech in a natural and effortless manner through constant exposure to spoken language in their environment. In contrast, children with hearing loss often experience reduced or distorted auditory input, which disrupts the natural mapping between acoustic signals and articulatory patterns. This lack of clear auditory feedback leads to delays in speech and language development and often results in reduced intelligibility. Over the last few decades, however, advances in hearing technology—particularly digital hearing aids and cochlear implants—have dramatically improved auditory access for children with hearing impairment, opening new

possibilities for developing speech that approximates the clarity of their peers with normal hearing.

Hearing aids have long been the standard rehabilitative device for children with mild to severe hearing loss. By amplifying acoustic signals, they make speech more accessible to the auditory system. Nevertheless, their effectiveness is significantly limited in children with profound hearing loss, where amplification alone cannot fully compensate for damaged cochlear structures or restore access to high-frequency cues that are critical for distinguishing consonants and achieving clear speech. For such children, cochlear implants have emerged as a transformative intervention. These devices bypass the damaged cochlea and directly stimulate the auditory nerve through electrical impulses, allowing access to a much broader range of speech sounds than hearing aids can provide. Research consistently shows that children with cochlear implants develop superior speech perception and production skills compared to those using hearing aids alone. Yet, despite these benefits, cochlear implant users often continue to lag behind their peers with normal hearing in achieving native-like speech intelligibility, particularly in languages with complex phonological systems.

In recent years, bimodal hearing—using a cochlear implant in one ear and a hearing aid in the contralateral ear—has attracted growing clinical interest. This configuration takes advantage of the complementary benefits of electric and acoustic stimulation. While the cochlear implant provides access to high-frequency sounds, which are crucial for consonant recognition, the hearing aid supplies low-frequency acoustic information that supports vowel clarity, pitch perception, prosody, and overall naturalness of speech. Studies in English-speaking children suggest that bimodal users often outperform unilateral cochlear implant users in auditory tasks such as speech perception in noise and sound localization. However, there remains a paucity of evidence on whether these perceptual benefits also extend to speech production and intelligibility—skills that are equally, if not more, vital for daily communication.

Another important limitation in existing research is its concentration on English-speaking populations. Languages differ in their phonological structures, and these differences can influence how hearing-impaired children acquire and produce speech. Phonological system includes a high frequency of vowel-final words, retroflex consonants, and other contrasts not present in English. These linguistic features may require particularly precise auditory feedback and articulatory control, raising important questions about how children with hearing impairment navigate such demands and whether modern auditory devices can adequately support intelligible speech in this linguistic context.

Against this backdrop, the present study sought to assess and compare the speech intelligibility of children across four groups: those with normal hearing, those using bilateral hearing aids, those with unilateral cochlear implants, and those with bimodal devices. By situating the investigation in a non-English linguistic context and employing perceptual evaluations of speech intelligibility, this research aims to generate novel insights into the outcomes of different hearing technologies and to explore the specific advantages of bimodal stimulation. Ultimately, the findings of this study may help refine clinical decision-making and guide more effective rehabilitative strategies for children with hearing impairment in India and beyond.

Methods

This study employed a cross-sectional, observational design and was conducted between January and July 2025. Data were collected from multiple sites, including auditory-verbal therapy centers, tertiary hospitals, and special schools catering to children with hearing impairment. Ethical approval for the study was obtained from the institutional review board, and the research adhered strictly to established ethical standards for research involving human participants. Informed consent was obtained from the parents or legal guardians of all children prior to their inclusion in the study.

A total of fifty-five children participated, with ages ranging between 5.5 and 7 years (mean age 6.3 years). Participants were stratified into four groups based on their hearing status and rehabilitative device use. The first group consisted of fifteen children with normal hearing. Their hearing sensitivity was confirmed through pure-tone audiometry, with thresholds ≤20 dB HL across the frequency range of 250 Hz to 8,000 Hz. These children had no prior history of speech, language, or neurological disorders and exhibited age-appropriate cognitive development. The second group included fifteen children with bilateral severe-to-profound sensorineural hearing loss who were using bilateral digital behind-the-ear hearing aids. All children in this group had been fitted with hearing aids before the age of 30 months and had at least three years of consistent device use. The third group comprised fifteen children with unilateral cochlear implants, all of whom had a minimum of 18 months of implant experience at the time of testing. Their devices had been fitted following standard clinical protocols, and they were enrolled in auditory-verbal therapy programs. The final group consisted of ten children using a bimodal configuration: a cochlear implant in one ear and a digital hearing aid in the contralateral ear. All children in this group had at least 18 months of cochlear implant use and at least 12 months of contralateral hearing aid experience. Across all groups, children were required to demonstrate the ability to identify and produce bisyllabic words, ensuring a minimum level of linguistic competence for test participation.

Speech intelligibility was assessed using the Picture Speech Intelligibility Evaluation Test (SPINE), developed by K. N. Rao (1998) [21]. The SPINE is a standardized tool specifically designed for100 pictorial flashcards representing high-frequency bisyllabic words familiar to young children. The test stimuli were carefully selected to ensure familiarity, ease of picturability, and coverage of a wide range of phonemes. These included bilabial and velar stops (/p/,/b/,/k/,/g/), dental and retroflex stops (/t/,/d/), palatal affricates (/c/,/j/), fricatives (/s/,/v/,/h/), and nasals and liquids (/n/,/r/,/l/). This diversity of sounds ensured comprehensive sampling of phonetic contrasts that are critical for assessing speech intelligibility.

Prior to formal testing, all children underwent a familiarization session in which they were introduced to the pictorial stimuli to ensure recognition of the items. During test administration, the cards were presented in random order, face-down, to avoid examiner bias. Each child was instructed to pick a card, name the picture, and set the card aside. Responses were recorded using a Sony digital voice recorder positioned approximately 15 cm from the child's mouth in a quiet environment, ensuring high-quality recordings suitable for subsequent analysis.

The recorded speech samples were subjected to perceptual evaluation by three independent listeners. All listeners were postgraduate students in speech-language pathology and possessed normal hearing as confirmed by audiological screening. They were blinded to the group identity of the children to avoid potential bias. Each judge was instructed to listen to the recordings and write down what they perceived the child to have said, without the aid of visual prompts. A response was scored as correct if the transcribed word matched the target stimulus exactly. Each child's final speech intelligibility score was calculated as the total number of correctly identified words divided by the total number of test words, expressed as a percentage.

To ensure reliability of the perceptual ratings, inter-rater agreement was assessed. Although subjective variability is inherent in perceptual judgments, the use of multiple trained raters and independent scoring minimized individual bias. Statistical analysis of inter-rater reliability indicated acceptable levels of agreement, supporting the validity of the perceptual evaluation method.

Statistical analyses were carried out using SPSS version 17.0. Descriptive statistics (means and standard deviations) were computed for each group. A one-way analysis of variance (ANOVA) was performed to test for overall differences in speech intelligibility across the four groups. Post hoc pairwise comparisons were conducted using the Least Significant Difference (LSD) test to identify specific group differences. Statistical significance was set at $p<0.05$ for all analyses. Additionally, effect sizes were calculated to provide an indication of the magnitude of differences between groups, thereby supplementing the significance testing with measures of clinical relevance.

Results

The analysis of the data revealed striking differences in speech intelligibility across the four groups of children. As expected, the normal hearing group demonstrated near-ceiling performance, with a mean intelligibility score of 97.9% and a very narrow standard deviation of 2.01. This indicates that almost all children with normal hearing consistently produced speech that was highly intelligible to listeners. Their performance set the benchmark against which the outcomes of the three hearing-impaired groups were compared.

In contrast, children who used hearing devices exhibited significantly reduced intelligibility. Among these groups, bimodal device users achieved the highest mean score, with an average intelligibility of 56.8% and a standard deviation of 7.97. Although considerably lower than the normal hearing group, these scores indicate that bimodal users were able to produce speech that was correctly understood by listeners more than half of the time. The greater variability within this group suggests that while some bimodal users approached near-normal intelligibility levels, others still struggled to produce clear speech, highlighting individual differences in benefit from bimodal stimulation.

Children fitted with unilateral cochlear implants obtained a mean intelligibility score of 49.8% with a standard deviation of 9.91. While their performance was lower than that of the bimodal users, they nevertheless achieved substantially higher scores compared to children using bilateral hearing aids. This finding suggests that cochlear implants provide access to a wider range of speech cues, particularly in the high-frequency range, thereby supporting better production of consonantal contrasts that are critical for intelligibility. However, the absence of contralateral acoustic input may have limited their ability to integrate prosodic and low-frequency cues, resulting in somewhat reduced clarity compared to the bimodal group.

The poorest outcomes were observed in children using bilateral hearing aids. Their mean intelligibility score was only 27.6% with a standard deviation of 3.87, indicating that more than two-thirds of the words produced by these children were not accurately understood by listeners. The narrow range of variability within this group further highlights that the limitation of hearing aids in cases of profound hearing loss was consistent across all participants. These results confirm that, despite advances in digital technology, hearing aids alone may not provide adequate access to the full spectrum of speech sounds necessary for intelligible speech production in children with severe-to-profound hearing loss.

A one-way analysis of variance (ANOVA) confirmed that the differences in speech intelligibility among the four groups were highly significant. The analysis yielded an F-value of 288.03 with a p-value of less than 0.001, indicating that the observed differences were unlikely to have occurred by chance. Post hoc pairwise comparisons using the Least Significant Difference (LSD) test further clarified the nature of these differences. Each group differed significantly from the others, including within the hearing-impaired subgroups. Notably, bimodal users performed significantly better than unilateral cochlear implant users, with a mean difference of 6.73 percentage points ($p = 0.016$). The difference between bimodal users and hearing aid users was even more pronounced, amounting to 28.73 percentage points ($p<0.001$). Similarly, unilateral cochlear implant users outperformed hearing aid users by 22.2 percentage points ($p<0.001$).

The effect sizes of these comparisons highlight the clinical relevance of the findings. The difference between normal hearing children and hearing aid users represented an extremely large effect, while the difference between bimodal and unilateral cochlear implant users, though smaller, still carried meaningful implications for speech production outcomes. These results underscore the importance of considering bimodal fitting in children with residual low-frequency hearing, as it appears to provide a measurable advantage in speech intelligibility over a unilateral cochlear implant alone.

The patterns of group differences are further illustrated in the figures. The bar chart with error bars (Figure 1) visually demonstrates the stark gap between normal hearing children and those with hearing impairment, as well as the relative advantage of bimodal stimulation. The boxplot (Figure 2) highlights the variability within each group, showing that while normal hearing children were tightly clustered near 100%, the scores of the hearing-impaired groups were more dispersed, particularly among bimodal and cochlear implant users. This suggests that individual outcomes in these groups may be influenced by additional factors such as age of implantation, duration of device use, and quality of auditory-verbal therapy.

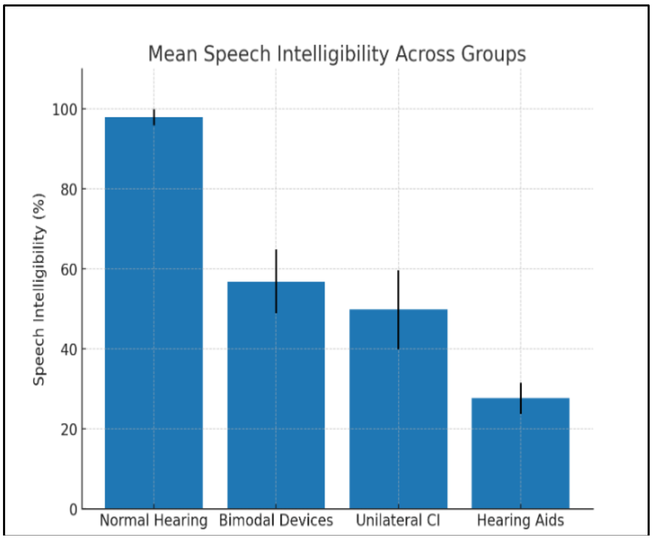

Fig 1: Bar chart with error bars showing mean speech perception scores across groups, illustrating the performance gap and bimodal advantage.

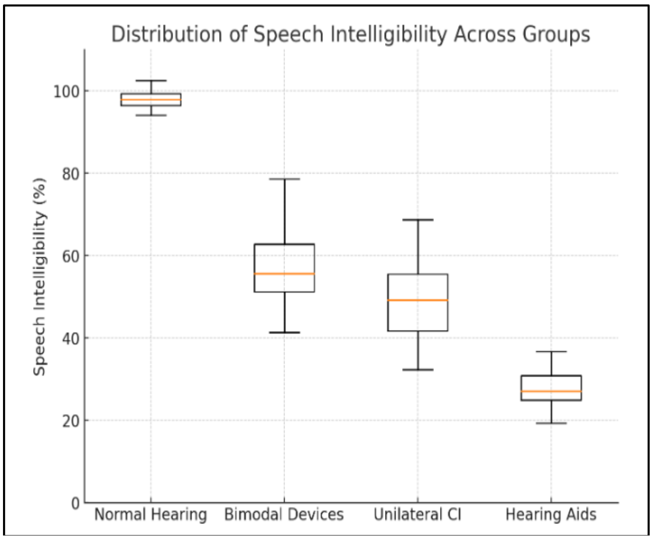

Fig 2: Boxplot displaying score variability within groups, emphasizing the wider dispersion among hearing-impaired participants.

Overall, the results provide strong statistical and clinical evidence that bimodal stimulation offers a distinct advantage for speech intelligibility compared to unilateral cochlear implants or bilateral hearing aids. However, the findings also emphasize the persistent gap between children with hearing loss and their peers with normal hearing, highlighting the ongoing challenges faced in achieving fully natural and intelligible speech in this population.

Discussion

The findings of this study provide important insights into the impact of different hearing technologies on speech intelligibility. As anticipated, children with normal hearing demonstrated near-perfect speech intelligibility, reaffirming the central role of intact auditory mechanisms in the natural acquisition of clear and comprehensible speech. These results are consistent with established literature that identifies normal auditory access as the most significant determinant of speech development, allowing children to establish accurate phonological representations and refine their articulatory patterns with ease (Boothroyd, 2008) [2]. The consistently high performance of normal hearing children in the present study underscores the contrast between typical development and the challenges experienced by children with hearing impairment, even when advanced amplification or implantable technologies are used.

A particularly noteworthy outcome of this study is the superior performance of bimodal device users compared to both unilateral cochlear implant and bilateral hearing aid users. This finding adds to a growing body of evidence suggesting that bimodal hearing provides tangible benefits for children with severe-to-profound hearing loss. Previous research, particularly in English-speaking populations, has shown that bimodal users often achieve better outcomes in speech perception tasks such as recognition in noise, sound localization, and even music appreciation (Ching *et al*., 2004; Dunn *et al*., 2010) [4, 6]. The present study extends these findings to speech production, showing that the advantages of combining electric and acoustic stimulation are not confined to auditory perception but also translate into clearer and more intelligible spoken output.

The observed advantage of bimodal stimulation likely arises from the complementary roles of the cochlear implant and the hearing aid. The implant provides access to high-frequency information, which is essential for distinguishing many consonant contrasts, while the hearing aid supplies low-frequency cues that carry information about pitch, vowel formants, and prosody. Together, these dual inputs may foster richer phonological representations and support more natural articulation. This interpretation is consistent with theories of auditory integration, which suggest that the brain is capable of merging electric and acoustic signals into a more complete auditory percept, thereby enhancing both perception and production of speech (Wilson & Dorman, 2008; Nittrouer *et al*., 2012) [27, 18].

Despite this advantage, it is important to note that even the bimodal group fell far short of the performance achieved by normal hearing children. This persistent gap reflects the limitations of current auditory technologies in fully replicating the complexity of natural hearing. Research has consistently highlighted the difficulty that cochlear implant users face in accessing fine-grained pitch and temporal cues, which are particularly important for prosody and suprasegmental aspects of speech (Faulkner *et al*., 2000; Geurts & Wouters, 2001) [7, 9]. For features retroflex consonants, long-short vowel contrasts, and a predominance of vowel-final syllables, the absence of such fine details may have a particularly pronounced effect on intelligibility. The language-specific phonological demands likely exacerbate the challenges faced by hearing-impaired children, further explaining why even bimodal stimulation could not close the gap with normal hearing peers.

The results for the unilateral cochlear implant group were consistent with earlier studies showing that while implants provide significant improvements over hearing aids, they still fail to fully normalize speech production (Spencer & Tomblin, 2009) [24]. These children achieved higher scores than hearing aid users, reflecting the implant's ability to provide access to a broader speech spectrum, but they underperformed relative to bimodal users, likely due to the absence of complementary low-frequency acoustic cues. This finding has practical clinical implications: while cochlear implantation alone is a highly effective intervention, retaining residual hearing and supporting it through contralateral amplification may offer additional benefits that should not be overlooked.

Children using bilateral hearing aids had the poorest outcomes, with scores indicating consistently low intelligibility across the group. This result aligns with a long-standing body of evidence that hearing aids, though effective for children with mild-to-moderate hearing loss, are insufficient in cases of severe-to-profound impairment (Yoshinaga-Itano *et al*., 1998; Serry & Blamey, 1999) [28, 23]. Even with advances in digital processing, hearing aids are unable to provide adequate access to high-frequency sounds, resulting in omissions and distortions of consonants and severely limiting intelligibility. The narrow variability within this group suggests that the limitation is systemic and not easily overcome through rehabilitation alone, further underscoring the importance of considering cochlear implantation when conventional amplification proves inadequate.

An important strength of the present study is its focus unique phonological characteristics. The majority of existing research on speech intelligibility in hearing-impaired children has focused on English, and findings cannot always be generalized across languages. By situating the analysis in the study addresses a significant gap in the literature and highlights the importance of considering linguistic context in auditory rehabilitation. These findings suggest that clinical recommendations should not be made solely based on studies from English-speaking populations, as different phonological structures may place different demands on auditory and articulatory systems.

Nevertheless, the study is not without limitations. The relatively small sample size, although sufficient to detect significant differences, may limit the generalizability of the findings. Moreover, intelligibility was assessed using perceptual ratings, which, while clinically meaningful, are inherently subjective. Although inter-rater reliability was acceptable, future research could incorporate objective acoustic analyses, such as measures of formant frequency accuracy, temporal precision, and prosodic features, to provide a more comprehensive understanding of speech production in these populations (Kent *et al*., 1994) [11]. Longitudinal designs would also be valuable for tracking how speech intelligibility develops over time, particularly as children gain more experience with their devices and continue therapy. Additionally, socioeconomic factors, parental involvement, and quality of intervention programs may have influenced the outcomes and warrant further investigation.

Overall, the results of this study add to the evidence base supporting the clinical value of bimodal stimulation in children with hearing loss. They highlight the need for individualized decision-making in auditory rehabilitation, taking into account residual hearing, language-specific demands, and the potential for combining technologies to maximize speech intelligibility outcomes.

Conclusion

This study highlights clear differences in speech intelligibility among children with normal hearing, bilateral hearing aids, unilateral cochlear implants, and bimodal devices. Children with normal hearing achieved near-perfect scores, while those with hearing loss faced persistent challenges despite amplification or implants. Bimodal users showed the highest intelligibility, outperforming unilateral cochlear implant and bilateral hearing aid users, underscoring the benefit of combining electric and acoustic stimulation. Unilateral cochlear implants proved superior to bilateral hearing aids, yet fell short of bimodal outcomes. The limited success of bilateral hearing aids reinforces the need for early cochlear implantation when residual hearing is insufficient. Importantly, results demonstrate that language-specific phonological features must be considered in intervention. Despite improvements, even bimodal users did not match normal-hearing peers, indicating the need for comprehensive rehabilitation beyond device fitting.

Future research should explore long-term outcomes, cross-linguistic differences, and individual factors affecting intelligibility. Overall, bimodal stimulation offers significant clinical advantages and should be prioritized in managing severe-to-profound childhood hearing loss.

Conflict of Interest
Not available

Financial Support
Not available

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