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RESEARCH ARTICLE

Spoken Word Recognition in Prelingual Cochlear Implanted Children using Full Spectrum Continuous Stimulation

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ABSTRACT

Aims & objectives: Cochlear implant (CI) is established as an accepted treatment for children with congenital bilateral severe to profound hearing loss to attain listening and develop speech and language skills. Children who receive Cochlear implants improve their quality of life and also improve their families' quality of life through enhanced communication skills with them. The study was aimed at documenting the status of speech perception in children post-cochlear implantation using full-spectrum continuous stimulation.

Material and Methods: A prospective cohort study was conducted on 19 children who have had unilateral cochlear implantation. Speech Recognition thresholds & Word Recognition Scores through picture identification using 20 common monosyllabic and disyllabic word lists were evaluated. "Revised Category of Auditory Performance (Revised CAP)" scores were taken on set time frequencies of pre-switch on, 3 months, 6 months, 9 months & 12 months post-implantation. Sound field-aided thresholds were measured before speech audiometry testing. Monosyllabic and disyllabic words lists consisting of 50 common word categories such as kinship terms, fruits, transport, and vegetables were included and validated by five audiologists and speech-language pathologists on Likert scale of the "level of acceptability". The outcomes of speech recognition performance based on speech recognition threshold and word recognition scores at 3 months, 6 months, 9 months & 12 months post switch on were documented.

Results: Auditory Verbal Therapy resulted in improvement in the Revised CAP, Aided Threshold, Speech Recognition threshold and Word Recognition Scores of children over time. The implantees showed better improvement with respect to speech perception. The children implanted more than five years of age showed a significant improvement over the time with a continuous electric analog signal.

Conclusion: Intensive rehabilitation for children having undergone cochlear implantation in which their individual and optimal needs should be considered and is necessary to achieve the best results. The study indicated that the speech perception of the children improved over the period of time with a cochlear implant device. Cochlear implant stimulation with continuous electric analog signal is a novel and considerable approach in the pursuit of cochlear implants.

Keywords: Cochlear implantation, Speech recognition threshold, Word recognition score, Speech awareness threshold, Aided threshold, Revised category of auditory performance, Full spectrum continuous stimulation.

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INTRODUCTION

Children with sensorineural hearing loss face challenges in speech perception, making it essential to provide amplification devices and rehabilitation programs. Cochlear implants are the most effective neural prosthesis for individuals with severe to profound SNHL. It converts sound energy into electrical signals that stimulate the auditory nerves. This allows the brain to process and interpret speech stimuli effectively. Several sound processing strategies have been developed and evaluated since the introduction of the first stimulation strategies in commercial cochlear implants over 30 years ago. These strategies aim to improve the spectral representation, distribution of stimulation across electrodes, and temporal representation of the input signal. The most frequently employed strategies include the advanced combination encoder (ACE) utilizing spectral features for channel selection, MP3000 utilizing spectral masking for channel selection and stimulation, fine structure processing (FSP) focusing on temporal feature enhancement, and HiRes120 using current steering and temporal feature enhancement to enhance the accuracy of stimulus delivery in spatial terms. The novel coding strategy used in the Neubio full spectrum continuous stimulation (FSCS) system involves converting a digital signal into an electric analog signal, which is then sent to the internal receiving unit (IRU) consistently at a continuous rate, preserving the temporal and spectral characteristics of the sound. Manufacturers typically prioritize speech in the coding process, ensuring that patients can clearly hear spoken words in quiet situations. However, cochlear implant recipients still face difficulties when it comes to hearing in noisy environments despite the enhanced hearing capabilities they may experience in quiet settings. The ultimate goal for prelingual pediatric patients is to achieve not only hearing but also clear and effective speech. Speech audiometry is commonly used to assess a person's ability to recognize speech, both in quiet environments and in the presence of background noise (Boisvert *et al*., 2020). Various types of speech materials, including phonemes, individual words, and complete sentences, are employed to thoroughly assess a person's speech recognition skills. However, traditional audiometric tests do not fully address the challenges individuals face in everyday communication, especially in situations where the acoustic conditions are unfavorable (e.g., when there are people talking nearby, environmental sounds, or reverberation). In such situations, peripheral hearing alone is not sufficient for speech understanding, and other cognitive abilities may come into play.

Research has highlighted the role of "working memory capacity" (WMC) in speech understanding for individuals with "normal hearing" or "mild to moderate" hearing loss (Akeroyd, 2008; Dryden *et al*., 2017). The speed at which information is processed and specific areas of executive functioning, such as the ability to control impulses, may also influence the situation (Dryden *et al*., 2017). While less is known about the influence of cognitive factors on speech recognition in cochlear implant (CI) users, recent studies have shown associations between speech recognition in CI users and cognitive factors such as WMC, non-verbal reasoning, inhibitory control, and processing speed "(Rosemann *et al*., 2017, Volter *et al*., 2021)."

The Ease of Language Understanding (ELU) model posits that cognitive abilities play a significant role in comprehending speech in challenging conditions. It proposes that speech comprehension becomes easy and natural when the auditory signal is easily understandable. (Ronneberg *et al*., 2017). However, any distortions in the signal, such as noise, signal processing issues, or hearing loss, can disrupt this automatic process and place a strain on cognitive resources, particularly working memory. This increased cognitive load can make speech understanding in these situations more effortful due to the limited capacity of cognitive resources (Kahneman 1973).

The other tests, such as the Revised Categories of Auditory Performance (CAP) score, offer a hierarchical evaluation of auditory perception, ranging from basic awareness of environmental sounds to complex tasks such as telephonic conversations. The evaluation of "speech perception" abilities in children with cochlear implants is crucial for their speech and language development. While there are subjective tests available, they require cooperation from the child being tested. This study aims to measure "speech perception" objectively in these children to better understand their abilities.

MATERIALS AND METHODS

- This was a prospective observational study of clinical outcomes that evaluated the validated Habilitation scores of 19 children having severe to profound hearing loss. Children have received cochlear implantation with BOLD 18 CI system & BOLD 22 with 15 mm of active length covering the entire spiral ganglion. The BOLD 18 CI system is 9 electrodes system that is used in the case of cochlear ossification and other cochlear anatomical abnormalities.
- The Revised CAP data were retrieved from patients' records and were selected for speech audiometry testing whose Revised CAP score was 4 or greater. 19 Children with age range 2 to 17 years and out of which one case of cochlear stage III ossification who underwent unilateral cochlear implantation were included.
- The study took place at the "Cochlear Implant" clinic in Delhi/NCR region. We collected data on the demographics, implantation details, and duration of standard validated outcome measures for the pre-and sequential post-implantation "Revised CAP" scores. The impact of continuous electric analog signals on auditory perception outcomes of late implanters was observed in the study.

Participants

The research involved children aged between 2 and 17 years who had undergone cochlear implantation. These children had been born with "bilateral severe to profound sensorineural hearing loss" but had normal cognitive abilities.

This study involved nineteen children who had received a cochlear implant. Among these children, one case showed stage

Table 1: Participants age distribution in the study

Age range	*No. of males*	*Mean age*	*Standard deviation*	*No. of females*	*Mean age*	*Standard deviation*
2- 5 yrs.	03	4.6	+/-0.47	05	4.3	+/-0.6
6-10 yrs.	03	7.3	+/-1.24	03	6.3	+/-0.47
11-17 yrs.	01	-	-	04	13.5	+/-2.2

III ossification. The participants had been using a unilateral cochlear implant for at least 6 months. They did not have amplification in the other ear and had normal intelligence. Their average aided response with the cochlear implant was 39.58 dB ± 5.8 SD and 54.2 dB ± 8.7 SD for speech recognition threshold. All parents were actively involved in the listening exercises during the tests. Children with auditory neuropathy, nerve deficiency in MRI, "ADHD", or "autism" were excluded from the study.

Procedure

All of the participants underwent the following procedure:

Ethical considerations in research

Following the information provided to parents regarding the study's objectives, written consent was obtained. The study was conducted adhering to the ethical guidelines established by the World Medical Association's Code of Ethics (Declaration of Helsinki) for conducting human experiments.

Medical evaluation

This involved a thorough otologic examination, as well as a general examination to exclude any potential underlying medical issues. Speech Audiometry testing was done through picture identification. The speech recognition threshold and word recognition scores were measured using 50 monosyllabic & di-syllabic familiar words, respectively. Aided thresholds in the Sound Field were obtained during the test prior to speech audiometry.

Aided CI response

Done in a sound-treated room (ANSI 3X 76)."

- Aided pure tone audiometers were measured using a calibrated Maico MA clinical audiometer. Aided sound field thresholds were measured for frequencies from 500 to 4000 Hz using a loudspeaker.
- Aided Speech audiometer: Speech recognition threshold (SRT)" was measured using Hindi words consisting of monosyllable and disyllable. The tool was developed using common 50 familiar words list validated by 5 speech-language pathologists and Audiologists.

Speech Perception Tests

Setting of the experiment

The study was conducted in a quiet, two-room environment with minimal distractions. The lighting in the room was sufficient for clear visibility of the images used in the test. The test was administered using a loudspeaker with a live voice, positioned at a 45-degree angle to the subject's cochlear implant."

Seating arrangement

The child was given five presentations at a time through flashcards from a developed common Hindi word list. The examiner sat to the next room to give the presentation. The patient had to identify from the pictures presented him whenever the examiner utter word in the sound field.

Speech material

Hindi words consisting of monosyllables and disyllables. The tool was developed using common 50 familiar word list and validated by 5 speech language therapists `and Audiologists.

Presentation level

"Speech stimuli were delivered at a usual conversational volume (approximately at 70 dB SPL)."

Speech stimuli

Hindi monosyllabic and disyllabic, which consists of categories such as Kinship terms, Fruits, Animals, vegetables, and common familiar words.

Components of the Test

The first phase

A set of items containing two-syllable words was used to determine the threshold at which speech recognition occurs. Each word was repeated twice, and if a word was not recognized at a certain level, the threshold was increased by 5 dB.

The second part of the test involved assessing the child's ability to recognize and identify words, which included both simple and complex sounds. The words were presented randomly and repeated twice, with the child pointing to the corresponding image. A plus sign was given for correct answers and a negative sign for incorrect responses.

Statistical Analysis

Descriptive statistics, including the mean, standard deviation, and median, were calculated. The Shapiro-Wilk test was conducted to assess the normality of the data, which indicated a significant deviation from a normal distribution ($p < 0.05$). Consequently, Spearman's Coefficient of correlation, a non-parametric method, was utilized. The significance levels were evaluated at 0.05 and 0.01. All statistical analyses were performed using SPSS.

RESULTS

This study focused on 19 children with "bilateral severe to profound hearing loss" who underwent "unilateral cochlear implantation." The findings provide valuable insights into the impact of cochlear implants with FSCS on the "speech perception" abilities of these children.

Table 2: below displays data for six different variables: Duration of device post switch on of device, Revised CAP score, Aided Average threshold, Speech Recognition Threshold, Speech Awareness Threshold, & Word Recognition Score %. For each variable, the data consists of 19 observations or data points. These statistics provide information on the range, central tendency, and dispersion of the data for each variable

	Duration of device post switch on	*Revised CAP score*	*Aided threshold (dBHL)*	*Speech Recognition threshold (dBHL)*	*Speech Awareness Threshold (dBHL)*	*Word Recognition Score (%)*
N	19	19	19	19	19	19
Minimum	6	4	26	45	35	30
Maximum	20	9	50	70	60	90
Median	12	4	38	50	40	65
Mean	12.79	5.26	39.58	54.21	43.68	62.11
St. Deviation	4.354	1.628	5.815	8.702	8.794	18.129

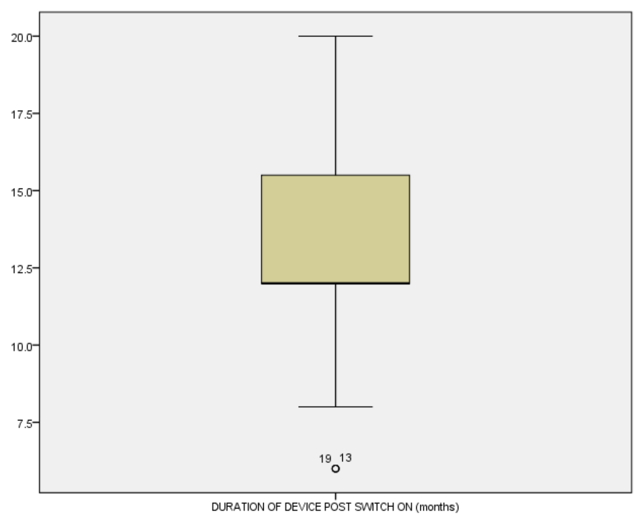

Fig. 1: Duration of device post switch on (months)

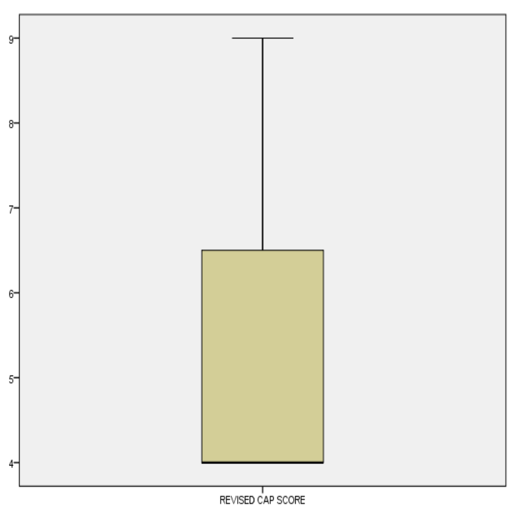

Fig. 2: Revised cap score

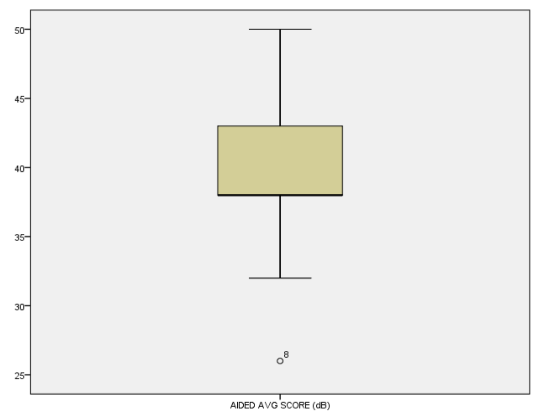

Fig. 3: Aided avg score (dB)

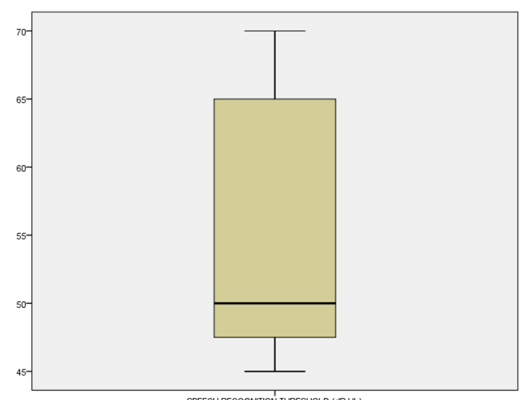

Fig. 4: Speech awareness thresold (dBHL)

DISCUSSION

Children with "bilateral severe to profound hearing loss" can benefit from cochlear implants, which improve their ability to perceive speech through auditory cues. However, studies have shown that the outcomes of cochlear implant recipients can vary greatly. Consequently, it is essential for audiologists to assess the speech perception skills of children with cochlear implants. In our research, we employed subjective assessments to evaluate the speech perception capabilities of Neubio cochlear implant users utilizing full spectrum continuous stimulation. All the children were between the ages of 2 and 17 years of age, with one of the cases of ossification stage III.

Children had used Neubio (BOLD) cochlear implants for at least 6 months. The pioneering nature of this study lies in its original exploration of the Full spectrum Continuous Stimulation (FSCS) strategy, a novel and innovative approach to cochlear implantation. It is crucial to understand the implications of FSCS in a broader context and its effect on

Fig. 5: Speech recognition threshold (dBHL)

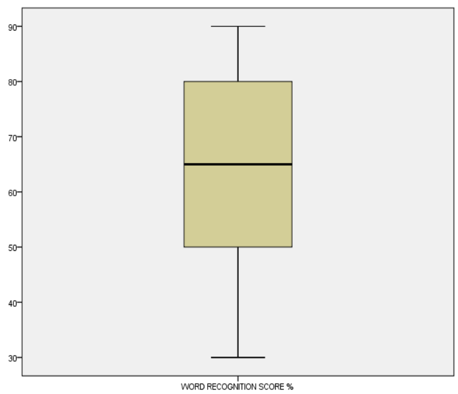

Fig. 5: Word recognition score %

speech perception outcomes in children. The study findings have important implications for our understanding of speech perception in patients and the correlation of time duration post-cochlear implantation.

The results provide a comprehensive insight into the speech perception of children who underwent cochlear implantation, with a focus on various key variables. These variables include Speech Recognition threshold, speech Awareness threshold, Aided threshold, word Recognition Score & most important factor, the time duration post cochlear implantation. Together, these variables contribute to a detailed understanding of speech perception in a quiet environment in children with cochlear implants and enhance our knowledge of effective intervention strategies across diverse settings and age groups. Through this study, our goal was to assess the correlation of time duration on the above-described variables.

The data provided in Table 2 displays information for six different variables: Duration of device post switch-on of device, Revised CAP score, Aided Average threshold, Speech Recognition threshold, Speech Awareness Threshold, and Word Recognition Score. Each variable has 19 observations or data points, allowing for the calculation of various statistics, including the range, central tendency, and dispersion. The duration of the device post-switch-on ranges from a minimum of 6 to a maximum of 20, with a median of 12 and a mean of 12.79. This suggests that the majority of the observations fall within the range of 6-20, with an average duration of around 12.79. For the Revised CAP score, the range is from 4 to 9, with a median of 4 and a mean of 5.26. This indicates that the majority of the observations have a score of 4, with a slightly higher average score of 5.26. The aided average threshold ranges from 26 to 50 dBHL, with a median of 38 and a mean of 39.58. This suggests that the majority of the observations fall within the range of 26-50 dBHL, with an average threshold of around 39.58. The speech recognition threshold ranges from 45 to 70 dBHL, with a median of 50 and a mean of 54.21. This indicates that the majority of the observations fall within the range of 45 to 70 dBHL, with an average threshold of around 54.21. The speech awareness threshold ranges from 35 to 60 dBHL, with a median of 40 and a mean of 43.68. This suggests that the majority of the observations fall within the range of 35-60 dBHL, with an average threshold of around 43.68. The word recognition score ranges from 30 to 90%, with a median of 65% and a mean of 62.11%. This indicates that the majority of the observations fall within the range of 30 to 90%, with an average score of around 62.11%. In summary, the data in Table 2 provides information on the range, central tendency, and dispersion of the six variables. This information supports understanding the distribution and characteristics of the data for each variable.

Table 3 focuses on the results between the duration of device post-switch-on and various audiological outcomes. The variables examined include the Revised CAP score, Aided Avg Score (dB), Speech Recognition Threshold (dB HL), Speech Awareness Threshold (dB HL), and Word Recognition Score (%). The Revised CAP score is a measure of auditory performance, which assesses the ability to perceive and understand speech in daily communication. The positive correlation between the duration of the device post-switch-on and the Revised CAP score suggests that as individuals use the device for a longer duration, their auditory performance in speech perception and understanding improves. This finding is highly significant, indicating that there is a reliable relationship between longer device use and higher Revised CAP scores. In summary, the correlation analysis results demonstrate that there are significant relationships between the duration of the device post-switch-on and various audiological outcomes. Longer device use is associated with improved auditory performance, speech recognition and awareness abilities, and word recognition skills. These findings highlight the importance of long-term device use in achieving better audiological outcomes. The results of our study are in concurrence with the previous study reported by (Kasper *et al.*, 2022) majority of patients included in their study experienced positive outcomes in terms of their ability to perceive speech and their overall quality of life after receiving a cochlear implant. These improvements were most notable during the first follow-up appointment and remained stable by the time of the second follow-up. Our prospective study focused on a group of patients with sensorineural hearing who underwent

Table 3: below shows the duration of the device post switch on (months) and Revised CAP Score: There is a "significant positive correlation" (r = 0.561, *p* = 0.012), indicating that as the duration of device use increases, there is an improvement in the Revised CAP Score. Duration of device post switch on (months) and Aided Avg Score (dB): There is no significant correlation found between these variables (r = -0.141, *p* = 0.565), suggesting that the duration of device use does not have a significant impact on the Aided Avg Score. Duration of device post switch on (months) and Speech Recognition Threshold (dB HL): There is a "significant negative correlation" (r = -0.300, *p* = 0.212), indicating that as the duration of device use increases, there is a decrease in the Speech Recognition Threshold, suggesting an improvement in speech recognition ability. Duration of device post switch on (months) and Speech Awareness Threshold (dB HL): There is a significant negative correlation (r = -0.375, *p* = 0.114), suggesting that as the duration of device use increases, there is a decrease in the Speech Awareness Threshold, indicating an improvement in the ability to perceive speech. Duration of device post switch on (months) and Word Recognition Score %: There is a "significant positive correlation" (r = 0.317, *p* = 0.187), indicating that as the duration of device use increases, there is an improvement in the Word Recognition Score. It is important to note that the correlation coefficients indicate the strength and direction of the relationship between the variables. Additionally, significance levels (*p-values*) provide information about the reliability of the observed correlations.

			Duration of device post switch on	*Revised CAP score*	*Aided Avg Score (dB)*	*Speech Recognition threshold (dBHL)*	*Speech Awareness Threshold (dBHL)*	*Word Recognition Score %*
Spearman's rho	Duration of device post switch on	Correlation coefficient	1.000	.561*	-.141	-.300	-.375	.317
		Sig.(2-tailed)		.012	.565	.212	.114	.187
		N	19	19	19	19	19	19
	Revised CAP score	Correlation coefficient	.561*	1.000	-.420	-.709**	-.676**	.829**
		"Sig.(2-tailed)"	.012		.074	.001	.001	.000
		N	19	19	19	19	19	19
	Aided Avg Score (dB)	"Correlation coefficient"	-.141	-.420	1.000	.472*	.506*	-.436
		Sig.(2-tailed)	.565	.074		.042	.027	.062
		N	19	19	19	19	19	19
	Speech Recognition threshold (dBHL)	"Correlation coefficient"	-.300	-.709**	.472*	1.000	.977**	-.718**
		"Sig.(2-tailed)"	.212	.001	.042		.000	.001
		N	19	19	19	19	19	19
	Speech Awareness Threshold (dBHL)	"Correlation coefficient"	-.375	-.676**	.506*	.977**	1.000	-.666**
		"Sig.(2-tailed")	.114	.001	.027	.000		.002
		N	19	19	19	19	19	19
	Word Recognition Score %	"Correlation coefficient"	.317	.829**	-.436	-.718**	-.666**	1.000
		Sig.(2-tailed)	.187	.000	.062	.001	.002	
		N	19	19	19	19	19	19

*Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

cochlear implantation and completed their six-month post-device switch-on. Through the use of audiometric tests such as Dantale I and HINT, as well as patient-reported outcome measures like the NCIQ and SSQ, their study were able to observe significant advancements in speech perception and quality of life.

The study reported by Ursina Ruegg *et al*., 2021, tested speech in quiet environments and reported the goal of their study was to establish a connection between routinely collected data from a large number of cochlear implant clinics rather than relying on speech tests conducted in more complicated sound environments. Additionally, the advantages of having some hearing ability after surgery extend beyond just better speech recognition. Their research has shown that residual hearing can lead to an overall higher quality of life in various ways, including increased self-confidence, improved safety, heightened awareness of sounds when the cochlear implant is turned off, enhanced music perception, and greater feelings of well-being and security. In our present study by using both audiometric evaluations and patient-reported outcome measures, we were able to provide detailed evidence of the benefits of cochlear implantation in Neubio Bold Implant users. This information can assist healthcare providers in advising patients on their treatment options and managing their expectations. Additionally, our study, maybe combined with other recent research on cochlear implant benefits, aids in the development of new selection criteria for cochlear implant patients.

Our study showed positive outcomes in speech perception through FSCS coding strategy is analogous to the study done by (Manrique *et al*., 2005) with Nucleus devices using "ACE" and "SPEAK" coding strategies. The results showed that cochlear implantation provides significant advantages for speech perception in children who were deaf before learning language. Both the "SPEAK" and "ACE" speech coding strategies show positive outcomes. Children using the ACE strategy initially make faster progress in speech perception improvement. However, after 2 years of using the cochlear implant, there is no notable difference in performance. The study reported by (Muller *et al*., 2012) included a total of 46 adults who had at least six months of experience with cochlear implants. The aim was to compare the effectiveness of three different speech perception tests (Continuous Interleaved Sampling+, "High-Definition Continuous Interleaved Strategy," and "Fine Structure Processing" in noisy environments, pitch scaling, and through questionnaires. The tests were randomly conducted twice: once at the beginning of the study (interval 1) and again after three months of FSP experience (interval 3). In the comparison between "FSP and CIS+", it was found that "FSP" performed at least as well as "CIS+" in all speech perception tests. Additionally, "FSP" outperformed "CIS+" specifically in vowel and monosyllabic word discrimination. On the other hand, when comparing "FSP" and "HDCIS," both systems performed equally well in all speech perception tests. The FSCS coding strategy showed analogous results with speech in a quiet environment from the above study. FSCS strategy showed that as the duration of device use increases, the CAP score also increases. The CAP score measures speech perception in quiet and noisy environments, so this correlation suggests that individuals who have been using the device for a longer period of time tend to have better speech perception abilities. Children have better sensitivity with the prolonged usage of the device as the aided average score decreases to a normal hearing threshold, which measures the sensitivity/audibility of the device. This indicates that the duration of device use may have a significant impact on overall sound quality and audibility. The ability to detect and understand speech at different threshold levels is better with prolonged usage. Indicating the children can perceive the speech stimulus at lower presented threshold levels. Also showed that individuals who have been using the device for a longer period of time tend to have better word recognition abilities. Overall, the results of the FSCS coding strategy suggest that the children are performing better with prolonged device usage with respect to speech perception in the real-world scenario.

CONCLUSION

This research indicates that cochlear implants in children have improved speech perception in quiet settings. The implementation of full spectrum continuous stimulation (FSCS) as an electric analog signal for cochlear implant stimulation represents a promising advancement in pediatric cochlear implantation. The length of time the device has been active after being switched on is a crucial factor for children with cochlear implants, as those who used the Neubio CI device for over six months demonstrated significantly better speech perception outcomes.

LIMITATIONS & FUTURE RESEARCH

The potential limitation of our research studies is a small sample size, which can limit the generalizability of the findings. Future research directions could involve conducting studies with larger sample sizes to increase the reliability and validity of the results. This could involve recruiting participants from multiple centres to increase diversity and reduce the risk of bias.

Another potential limitation of our study is single centric, which may not fully capture the variability that exists across different populations or settings. Future research directions could involve conducting multi-centre studies to compare results across different geographic regions, populations, or healthcare systems. This could provide a more comprehensive understanding of the topic being studied and help to identify any potential factors that may influence outcomes.

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COMPETING INTEREST

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

ETHICAL APPROVAL

Institutional ethical approval is taken to conduct this research.

INFORMED CONSENT

Written informed consent was obtained from the patients.

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