# Multidisciplinary Cognitive Function Assessment of Good versus Poor Performance in Children with Cochlear Implants: An Observational Cross-Sectional Study

Ola A. Ibraheem[1] Mohamed Abdelghani[2] Elham M. Hassan[3] Nadia El-Nebtity[1] Nahlah H. Gad[1]

[1] Audio-Vestibular Medicine Unit, Department of Otolaryngology-Head and Neck Surgery, Faculty of Medicine, Zagazig University, Egypt
[2] Department of Neuropsychiatry, Faculty of Medicine, Zagazig University, Egypt
[3] Phoniatrics Unit, Department of Otolaryngology-Head and Neck Surgery, Faculty of Medicine, Zagazig University, Egypt

**Address for correspondence** Ola Abdallah Ibraheem, MD, Department of Otolaryngology, Audio-Vestibular Medicine Unit, Zagazig University Hospitals, Zagazig, Egypt (e-mail: ola_medvoice@yahoo.com).

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## Abstract

**Introduction** Despite the developing technology of cochlear implants (CIs), implanted prelingual hearing-impaired children exhibit variable speech processing outcomes. When these children match in personal and implant-related criteria, the CI outcome variability could be related to higher-order cognitive impairment.

**Objectives** To evaluate different domains of cognitive function in good versus poor CI performers using a multidisciplinary approach and to find the relationship between these functions and different levels of speech processing.

**Methods** This observational, cross-sectional study used the word recognition score (WRS) test to categorize 40 children with CIs into 20 good (WRS/65%) and 20 poor performers (WRS < 65%). All participants were examined for speech processing at different levels (auditory processing and spoken language) and cognitive functioning using (1) verbal tests (verbal component of Stanford-Binet intelligence [SBIS], auditory memory, auditory vigilance, and P300); and (2) performance tasks (performance components of SBIS, and trail making test).

**Results** The outcomes of speech processing at different functional levels and both domains of cognitive function were analyzed and correlated.

Speech processing was impaired significantly in poor CI performers. This group also showed a significant cognitive function deficit, in which the verbal abilities were more affected (in 93.5%) than in the good performers (in 69.5%). Moreover, cognitive function revealed a significant correlation and predictive effect on the CI speech outcomes.

**Conclusion** Cognitive function impairment represented an important factor that underlies the variable speech proficiency in cochlear-implanted children. A multidisciplinary evaluation of cognitive function would provide a comprehensive overview to improve training strategies.

**Keywords**
- cochlear implantation
- cognitive function
- P300
- trail making test
- children
- auditory processing

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## Introduction

Cochlear implants (CIs) represent promising management to improve speech and language development in children with severe-to-profound sensorineural hearing loss. In a group of children with CIs, variable speech processing outcomes were obtained despite having comparable personal, implantation, and rehabilitation circumstances.[1] Several factors may interact to determine the proficiency of speech processing in CI recipients, including auditory deprivation,[2] preimplant mode of communication,[3] cross-modal reorganization of the auditory cortex,[4] genetic effect,[5] and cognitive abilities.[6]

To explain speech processing variability in CI users, it is important to describe higher-order processes that interact with speech processing in a top-down manner. Accurate speech processing requires directing attention to the relevant acoustic features, selective inhibition of the ambient interference,[7] preserving acoustic information in memory (verbal cognitive function),[8] and integrating it with other non-acoustic sources of information (executive functions).[9]

The higher-order verbal-related cognitive function provides a top-down control of these processes that, in turn, enhances the bottom-up processing of speech. Verbal cognitive function can be estimated behaviorally using the auditory memory and vigilance tests[10] and verbal resonance component of Stanford-Binet intelligence scale (SBIS) (4th edition),[11] and electrophysiologically using P300 auditory evoked potentials.[12] Performance cognitive domain, such as executive functions (e.g., visual-spatial processing, memory, controlled attention and inhibition, processing speed) could integrate the processing of non-verbal sensory input.[13] It can be assessed using performance components of the SBIS[11] and trail making test (TMT).[14] Both categories of cognitive function are supposed to be interdependent and fundamental to speech processing.[15]

The knowledge is developing regarding the role of cognitive function that arises beyond and interacts with speech processing in a complex manner. The variability in speech proficiency in cochlear-implanted children could be attributed to the individual differences in the global or particular cognitive development while matching personal and device-related factors. We hypothesized that using a multidisciplinary test battery to estimate different domains of cognitive function (verbal and performance) would be of great value in targeting the affected ability and determining CI benefits. Therefore, the current study was designed to examine variable domains of cognitive function in cochlear-implanted children exhibiting different speech processing outcomes and to estimate the relationship between cognitive function and different levels of speech processing in these children. Identification of the cognitive deficit would guide the development of personalized intervention strategies to overcome inter-individual variations and improve speech recognition in children with CI.

## Method

### Subjects

Forty children with unilateral CI, ranging in age from 5 to 10 years old, of both sexes, participated in this observational, cross-sectional study. They were attended at the tertiary care CI unit, where they went for follow-up with the CI program. Prior to surgery, children had a prelingual profound hearing loss. They revealed age-inappropriate language development despite wearing bilateral hearing aids and receiving speech therapy regularly for at least 6 months. Children relied on uttering single words with lip reading or pointing and gestures as a preimplant mode of communication. The preoperative selection for CI candidacy followed the guidelines of the department of health of Western Australia.[16] The national health insurance protocol considers only unilateral cochlear implantation per child. In addition, the socioeconomic status (SES) of most families does not support CI surgery for the other ear at their expense. Therefore, there were no participants with bilateral implants.

All children exhibited the following: a prelingual heredofamilial hearing loss; unilateral implantation before the end of the sensitive period for language development with an age of implantation ranging from 2 to 5 years old[17]; an average intelligence quotient (IQ); an implant usage for 36 to 60 months; regular CI programming and auditory training; monolingual hearing parents, providing a language-rich environment that encourages an auditory-oral communication; and aided CI-thresholds not higher than 25 dB HL in the frequency range of 0.5 to 4 kHz. Children were excluded from the study if they had any neurological disorders or radiological anomalies determined by computerized tomography or magnetic resonance imaging, for example, marked cochlear deformity, cochleovestibular nerve hypoplasia, or narrowing of the internal auditory canal.

Among 160 children with unilateral CI visiting the CI unit, 55 fulfilled the inclusion criteria. They were divided into two groups according to their auditory and speech performance, using a clinically warranted criterion.[18] The Arabic phonetically balanced kindergarten (PBKG) words[19] were applied, and children with word recognition score (WRS)/65% were considered good CI performers ($n = 30$), whereas children with WRS $< 65\%$ represented poor CI performers ($n = 25$). Forty children were chosen as a sampling population: 20 good CI performers (G group) and 20 poor CI performers (P group). ►**Fig. 1** shows a flow chart representing the included sample in this study. Both study groups had matched personal and implantation characteristics (►**Table 1**).

### Procedure

The study was performed from March 2020 to June 2021 by expert examiners in the audio-vestibular medicine (AVM), phoniatrics, and psychology at university hospitals. Three sessions over three separate days were needed to complete the investigations so the children would not get bored. The first session was held in the audio-vestibular unit and lasted for 2 hours. During this session, parents provided a signed informed written consent and detailed history before testing. The AVM examiner assessed SES, using the SES scale[20]; aided CI threshold in the frequency range from 0.5 to 4 kHz (representing the primitive level of speech processing), using a calibrated two-channel audiometer (Orbiter 922 v. 2; Madsen, Taastrup, Denmark); auditory processing tests

 

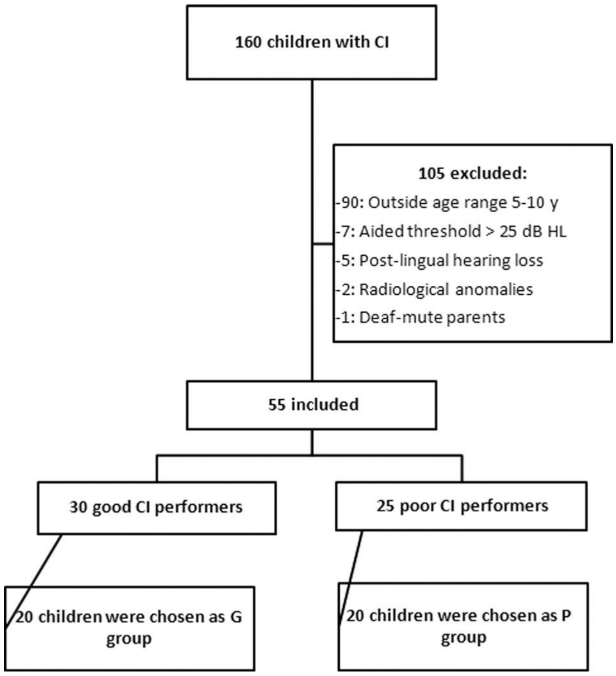


**Fig. 1** A flowchart of the included sampling population. Abbreviations: CI, cochlear implant; G, good performers; P, poor performers.

that assess the next levels of speech processing (WRS test to examine speech discrimination and recognition, and the Arabic-translated meaningful auditory integration scale [MAIS] to explore listening skills); and verbal cognitive tests involving auditory memory tests, auditory vigilance tests, and P300.

The second session was performed in the phoniatrics unit and required an hour, in which a phonetician examined the level of speech processing (spoken language) using the Arabic-translated and modified preschool language scale, fourth edition (PLS-4). The third session was completed within an hour in the psychology clinic. An expert psychologist further assessed the verbal cognitive function using the verbal subcomponent of the Arabic version of SBIS (4th edition) as well as the performance cognitive function using the non-verbal subcomponent of SBIS and the TMT. Study procedures followed the international review board guidelines (ID: 5931–9-3–2020).

## Speech Processing

Speech processing was examined at different levels using a group of tests:

### Auditory Processing

- The WRS test is used to assess recognition of 25 PBKG monosyllabic words in an open set manner.[19] These words are appropriate for children's vocabulary. They were presented at 40 dB SL to children in a sound-treated booth through a loudspeaker placed one meter, zero azimuths from the head. The percentage of correct word recognition was calculated for each child.
- The Arabic-translated MAIS questionnaire estimated auditory processing and listening skills.[21] The parents

**Table 1** Personal and implantation data of good (G) versus poor (P) cochlear implant performers

| Personal and implantation data | | G $n = 20$ | P $n = 20$ | Test value ($p$) | df |
|---|---|---|---|---|---|
| Age (mean ± SD years) | | 7.32 ± 1.61 | 7.41 ± 1.25 | 0.193 (0.48)[a] | 38 |
| Sex (n) | Male | 11 | 8 | 0.902 (0.34)[b] | 1 |
| | Female | 9 | 12 | | |
| SES (mean ± SD%) | | 63.00 ± 7.28 | 61.63 ± 7.06 | 0.580 (0.57)[a] | 38 |
| IQ (mean ± SD) | | 101.41 ± 5.48 | 98.56 ± 4.41 | 1.785 (0.082)[a] | 38 |
| Preimplant mode of communication (n) | Single word | 13 | 9 | 1.616 (0.20)[b] | 1 |
| | Gestures | 7 | 11 | | |
| Duration of HA use (mean ± SD years) | | 2.21 ± 0.84 | 1.81 ± 0.67 | 1.650 (0.11)[a] | 38 |
| Age at implantation (mean ± SD years) | | 3.50 ± 0.98 | 3.86 ± 0.97 | 1.157 (0.26)[a] | 38 |
| Duration of implant use (mean ± SD years) | | 3.81 ± 0.90 | 3.49 ± 0.72 | 1.219 (0.23)[a] | 38 |
| Side of implant (n) | Right | 11 | 10 | 0.100 (0.75)[b] | 1 |
| | Left | 9 | 10 | | |
| CI device (n) | AB | 10 | 11 | 0.248 (0.88)[b] | 2 |
| | MedEl | 7 | 7 | | |
| | Cochlear | 3 | 2 | | |
| Average aided response (mean ± SD dB HL) | | 22.33 ± 2.71 | 23.40 ± 1.76 | 1.448 (0.16)[a] | 38 |

Abbreviations: CI, cochlear implant G, good performers; IQ, intelligence quotient; P, poor performers; SD, standard deviation; SES, socioeconomic status.
[a]Independent sample *t*-test [t(*p*)]; [b] Chi-square test [$X^2(p)$].

 

answered 10 questions. Each item scored from 0 to 4, so the child receives 0 for the answer never, 1 for rarely, 2 for occasionally, 3 for frequently, and 4 for always. Therefore, the maximum score would be 40, and the total score for each child was calculated out of the 40.[21,22]

### Spoken Language

- The Arabic translated and modified PLS-4[23] examined three scales: receptive, expressive, and total-language age (TLA), with an upper limit of language age evaluation of 83 months.[23,24] This limit is the ceiling value that represents the highest level of language development. Therefore, older children who achieved the ceiling would be considered to have appropriate language age. The assessment involved: gesture, play, attention, vocal maturation, social interaction, vocabulary, language composition, integrative language skills, phonological awareness, and concepts.

## Cognitive Function

A multidisciplinary framework included audiological, phoniatric, and psychological test battery for a comprehensive evaluation of the cognitive function. It involved both *verbal* (auditory) and *performance* (non-auditory) tests based on the underlying processing skill:

### Verbal Cognitive Tests

The verbal tests were used to drive the cognitive function related to auditory processing:

- **Verbal reasoning (VR) portion of the Arabic version of the SBIS (4th edition)**
  This test examines the 'child's ability to think, reason, and solve problems.[11]
- **Auditory memory tests**
  Memory tests for content and sequence were used to estimate short-term memory (STM) that describes the storage and consecutive recall of information within a temporary period.[8,10] In addition, a memory test for recognition was used to examine verbal working memory (VWM) that expresses further processing and alteration of information while retaining a sequence of verbal stimuli in STM.[10,13] Familiar words within the children's vocabulary were utilized in these tests. The CI users were instructed to repeat the words in no specific order in the content-memory test, while keeping their order in the sequential memory test. The recognition-memory test involved word repetition in a particular order, such as repetition of only first, third, and fifth words. The percentage of correct repetitions was calculated.[10]
- **Auditory vigilance test**
  This test estimates concentration-vigilance-inhibition, VWM, selective attention, sustained attention, categorization, and decision-making. These functions require auditory alertness, maintaining a focus on the relevant information, the ability to respond correctly to auditory stimuli and to withstand disturbing cues over a long period.[12] 'The children's task was to identify the target word while sustaining attention for an age-appropriate auditory article. The target was a particular word, a word starting with a defined phoneme, or words having specific meaning. The score was the percentage of correct identifications.[10]
- **P300**
  The P300 is a cortical auditory evoked potential that reflects cognitive activities, including VWM and sustained and selective attention.[12] It was recorded in a sound-treated booth using the following auditory evoked-potential systems: OtoAccess v 1.3 and Eclipse 25 (Interacoustics A/S, Assens, Denmark). A speech oddball paradigm was used as a stimulus that consisted of a frequent /ga/ stimulus (80% probability) and a rare /da/ stimulus (20% probability). This paradigm arose through a loudspeaker placed one meter in front of the subject's head at an intensity of 70 dB nHL. The recording was collected by a non-inverting electrode on the mid-forehead, inverting electrode on the mastoid of the non-implanted side, and the ground electrode on the forehead below the non-inverting one. The P300 response was identified as a positive peak at latency around 300 milliseconds and analyzed for the latency and peak amplitude.

### Performance-cognitive Tests

The performance tests examine the cognitive function that is related to non-auditory processing, for example, visual memory and attention. Non-verbal instruction, such as simple demonstration, was used to prevent the effect of audibility on performance. Therefore, the variability in the non-verbal cognitive results was ensured to be independent of the impaired audibility.[25] The examined performance-cognitive abilities include:

- **Performance components of the Arabic version of the SBIS**
  Abstract and quantitative reasoning (AR and QR) were investigated to entail the ability to analyze information, create a coherent representation of the problem, and solve problems on a complex, insensible level. In addition, performance STM was examined as a part of the SBIS.[11]
- **Trail Making Test (TMT)**
  It is a motor-based task that measures visual scanning, speeded processing, multitasking, attention, and executive functions.[26] Executive functions include the non-verbal STM, working memory, attention, visuospatial processing, sensorimotor coordination, inhibition, organization, self-monitoring, flexible-shifting, and goal direction. The test involved a rapid drawing of lines to connect a set of 25 encircled successive numbers (trail A) and alternative numbers and letters randomly distributed on a page (trail B).[14] The time required to complete the drawing was recorded in seconds.

## Statistical Analysis

The IBM SPSS Statistics for Windows, version 22.0 (IBM Corp., Armonk, NY, USA) and social science statistics were applied for the analyses. Study variables exhibited normal distribution with a significance value /0.05, using the Shapiro-Wilk test. The parametric statistics (independent sample *t*-test and one-way ANOVA test) were used to compare continuous data presented as a mean ± standard deviation (SD). Arcsine transformation was performed before the analysis of percentages. The Chi-squared test was applied to compare the distribution of the categorical variables.

The Pearson correlation coefficients were used to assess the relationships between variables. Furthermore, the linear regression analysis estimated the predictor effect of both cognitive domains on different levels of the CI speech processing outcomes. The significance level ($p$) was set at $< 0.05$. The statistical validity and significance of strength were ensured by estimating the degrees of freedom (DFs) and effect size (ES), respectively.

## Results

### Speech Processing in Good versus Poor CI Performers

The average aided response, representing the initial level of speech processing (detection), exhibited a non-significant difference among the 2 study groups, $t(38) = 1.448, p = 0.16$. ►**Table 2** shows the outcomes of speech processing at higher levels using WRS, MAIS, and PLS-4 and reveals statistically significant higher scores in the good versus poor CI performers with a large ES.

### Cognitive Function in Good versus Poor CI Performers

Generally, there were reduced verbal and performance outcomes in the P versus G group, with the verbal cognitive function being the most affected. In ►**Fig. 2**, the scores of all subcomponents of the SBIS were lower in the P group, but the VR score was the only one that was significantly impaired, $t(38) = 2.048$, $p = 0.04$, with a medium ES = 0.65. Hence, the subcomponent representing the verbal cognitive function (VR) was the most impaired in poor CI performers. Moreover, the one-way analysis of variance (ANOVA) was used to compare the four subcomponents in each study group. They revealed statistically significant differences in the VR, which had the lowest scores among the four subcomponents [G group: $F$ (3,84) = 6.413, $p = 0.001$; P group: $F$ (3,68) = 10.784, $p < 0.001$].

►**Fig. 3** illustrates the outcomes of the remaining verbal and performance cognitive function tests. Poor performers exhibited significantly lower auditory memory, lower auditory vigilance, longer P300 latency, smaller P300 amplitude, and longer TMT values ($p < 0.001$), with a large ES (> 0.8). ►**Fig. 4** shows examples of P300 potentials with longer latency and smaller amplitude in traces recorded from a poor versus a good CI performer. The percentage of children in the P group with impaired cognitive function is presented in ►**Fig. 5,** revealing a higher total prevalence of impairment in verbal (93.5%) versus performance (69.5%) tests.

### Relationship between Cognitive Function and Speech Processing

The Pearson's correlation coefficient revealed moderate-to-strong statistically significant correlations between speech

**Table 2** Comparison of speech processing measures between both study groups using independent sample *t*-test [*t* (*p*)]

| Speech measures | | G<br>$N = 20$<br>Mean ± SD | P<br>$N = 20$<br>Mean ± SD | $t$ ($p$) | ES |
|---|---|---|---|---|---|
| WRS | | 75.45 ± 6.79 | 42.89 ± 17.67 | 7.974 (< 0.001)* | 2.53 |
| MAIS | | 34.27 ± 2.37 | 29.06 ± 2.34 | 6.961 (< 0.001)* | 2.21 |
| PLS-4 | Receptive | 4.36 ± 0.83 | 2.90 ± 0.81 | 6.539(< 0.001)* | 2.08 |
| | Expressive | 3.64 ± 0.66 | 2.45 ± 0.68 | 5.584(< 0.001)* | 1.77 |
| | TLA | 3.95 ± 0.7 | 2.63 ± 0.75 | 5.795 (< 0.001)* | 1.84 |

Abbreviations: G, good performers; P, poor performers; WRS, word recognition score; MAIS, meaningful auditory integration scale; PLS-4, preschool language scale (fourth edition); TLA, total-language age; ES, effect size.
* Significant value.

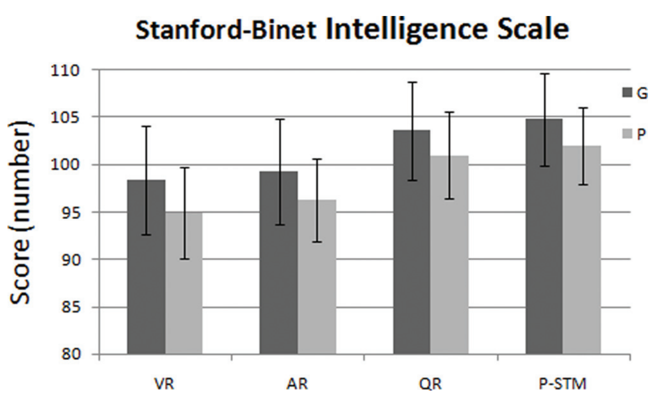


**Fig. 2** Bar charts of the results of cognitive function assessed by Stanford-Binet Intelligence Scale (4th edition) subcomponents (VR, verbal reasoning; AR, abstract reasoning; QR, quantitative reasoning; P-STM, performance short-term memory) in good (G) versus poor (P) cochlear implant performers.

 

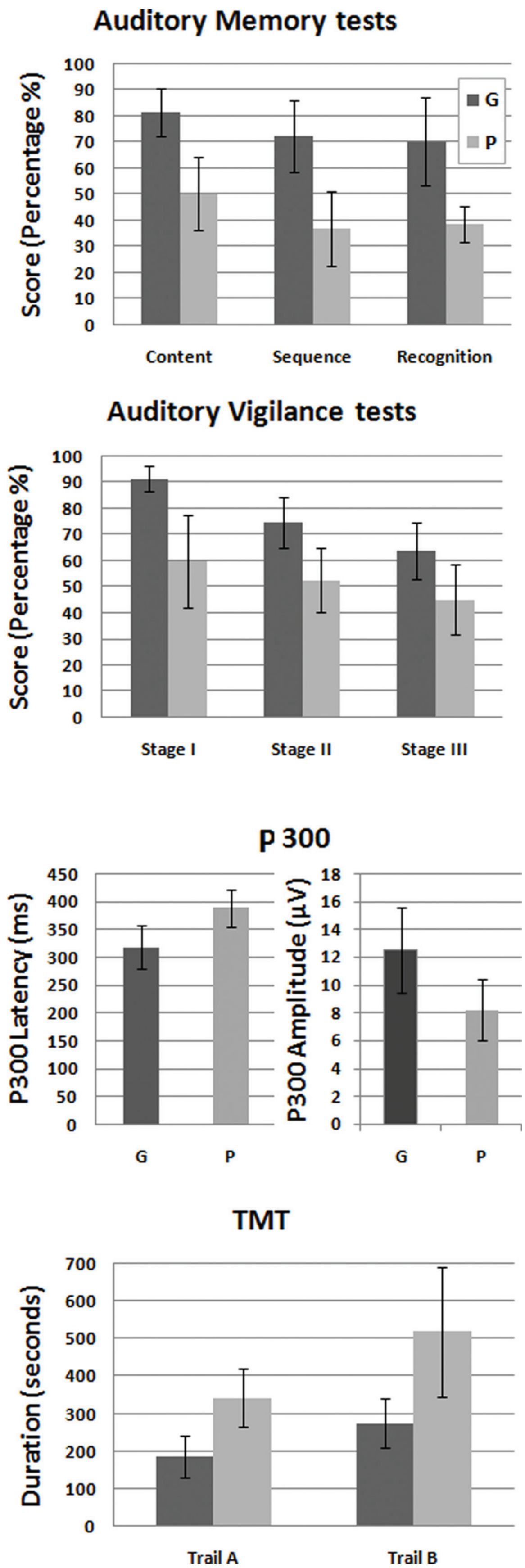


**Fig. 3** Bar charts of the results of verbal and performance cognitive function tests in good (G) versus poor (P) cochlear implant performers. Abbreviations: TMT, trail making test.

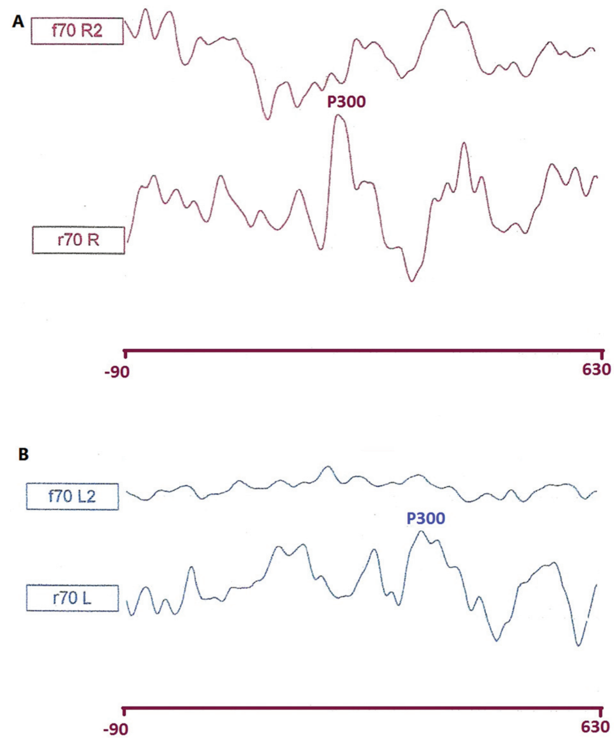


**Fig. 4** P300 recorded from (A) good performer, an 8-year-old child with a cochlear implant in the right ear (R) (upper trace) versus (B) poor performer, a 7-year-old child with a cochlear implant in the left ear (L) with longer latency and smaller amplitude (lower trace). Each trace has two waves: the upper (f) is the response to a frequent stimulus, and the lower (r) is the response to a rare stimulus (showing the P300 potential).

processing measures and the entire verbal and performance-cognitive function tests (►**Table 3**). The correlations were positive with the SBIS subcomponents, auditory memory tests, auditory vigilance tests, and P300 amplitude, and they were negative with the P300 latency and both TMT subtests. a linear regression analysis was applied and revealed that both verbal and performance-cognitive functions statistically significantly predicted CI speech processing outcomes in both groups ($p < 0.001$).

## Discussion

Speech recognition demands the processing of acoustic information at multiple levels in a bottom-up manner. The processing proceeds through sound detection, speech discrimination without semantic intelligibility, and semantic clarification to elicit listening skills, comprehension, and spoken language.[27] In children with prelingual hearing loss, there is a considerable disruption of different speech processing stages. Cochlear implantation helps overcome this disturbance and restore the progress of speech processing.

In this study, different levels of speech processing were assessed in children with good versus poor CI performance. The average aided hearing response, representing the initial stage of auditory processing (sound detection), was the sole comparable measure among the two study groups. This

 

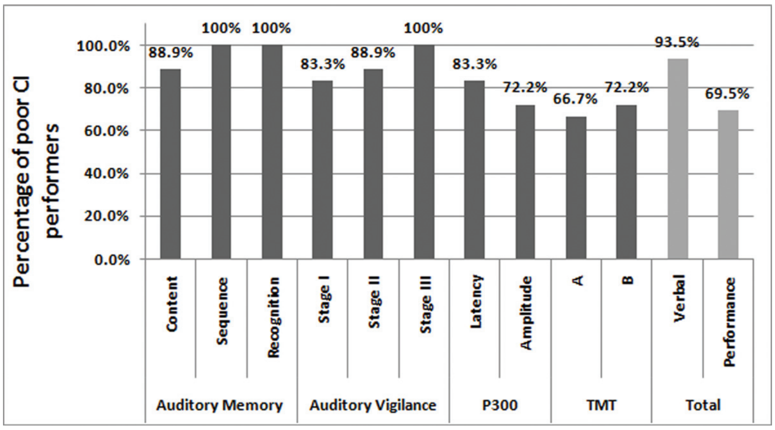


**Fig. 5** Percentage of poor cochlear implant performers for the verbal and performance cognitive function tests. Abbreviations: CI, cochlear implant; TMT, trail making test.

**Table 3** Correlation [*r* (*p*)] between the speech processing and the verbal and performance cognitive function in both cochlear implant groups ($n = 40$)

| Cognitive tests | Speech processing measures | | | | |
|---|---|---|---|---|---|
| | WRS | MAIS | Receptive | Expressive | TLA |
| Verbal cognitive tests | | | | | |
| SBIS | | | | | |
| VR | 0.649 (< 0.001) | 0.758 (< 0.001) | 0.553 (< 0.001) | 0.519 (0.001) | 0.544 (< 0.001) |
| Auditory memory | | | | | |
| Cont. | 0.890 (< 0.001) | 0.851 (< 0.001) | 0.807 (< 0.001) | 0.785 (< 0.001) | 0.783 (< 0.001) |
| Seq. | 0.836 (< 0.001) | 0.841 (< 0.001) | 0.796 (< 0.001) | 0.770 (< 0.001) | 0.788 (< 0.001) |
| Recog. | 0.697 (< 0.001) | 0.744 (< 0.001) | 0.690 (< 0.001) | 0.644 (< 0.001) | 0.658 (< 0.001) |
| Auditory vigilance | | | | | |
| Stage I | 0.962 (< 0.001) | 0.859 (< 0.001) | 0.821 (< 0.001) | 0.787 (< 0.001) | 0.809 (< 0.001) |
| Stage II | 0.867 (< 0.001) | 0.858 (< 0.001) | 0.782 (< 0.001) | 0.742 (< 0.001) | 0.765 (< 0.001) |
| Stage III | 0.830 (< 0.001) | 0.824 (< 0.001) | 0.758 (< 0.001) | 0.717 (< 0.001) | 0.889 (< 0.001) |
| Performance tests | | | | | |
| SBIS | | | | | |
| AR | 0.621 (< 0.001) | 0.736 (< 0.001) | 0.524 (0.001) | 0.497 (< 0.001) | 0.530 (< 0.001) |
| QR | 0.602 (< 0.001) | 0.711 (< 0.001) | 0.518 (0.001) | 0.506 (0.001) | 0.523 (0.001) |
| P-STM | 0.654 (< 0.001) | 0.734 (< 0.001) | 0.546 (< 0.001) | 0.531 (< 0.001) | 0.556 (< 0.001) |
| TMT | | | | | |
| Trail A | -0.876 (< 0.001) | -0.833 (< 0.001) | -0.848 (< 0.001) | -0.815 (< 0.001) | -0.824 (< 0.001) |
| Trail B | -0.893 (< 0.001) | -0.849 (< 0.001) | -0.799 (< 0.001) | -0.775 (< 0.001) | -0.793 (< 0.001) |

Abbreviations: AR, abstract reasoning; Cont., content; MAIS, meaningful auditory integration scale; P-STM, performance short-term memory; P-STM, performance-short term memory; QR, quantitative reasoning; Recog., recognition; SBIS, Stanford-Binet intelligence scale; Seq., sequence; TLA, total-language age; TMT, trail making test; VR, verbal resonance; WRS, word recognition score.

 

could be attributed to the fact that sound detection represents the primitive level of auditory processing, which does not require top-down interference.[27] On the other hand, there was an enormous variability at the higher levels of CI auditory processing and spoken language. The poor CI performers showed significantly lower scores compared with the good performers, which is in line with previous studies.[1,4] Both groups had matched personal criteria, intelligence, communication mode, social circumstances, implantation-related factors, and rehabilitative measures. Therefore, these factors were unrelated to speech processing. Since this higher-level perceptual framework demands top-down enrollment, a higher-order cognitive dysfunction may contribute to the speech processing variability.

Therefore, the current study aimed to use a comprehensive multidisciplinary approach for testing different domains of cognitive function in children with prelingual hearing loss and variable CI speech proficiency. Overall, poor CI performers revealed lower scores on verbal and performance-cognitive function tests, with the verbal domain being the most affected. Intelligence measure is a crucial indicator for the development of cognitive function in children.[28] In this study, the scores of SBIS subcomponents were lower in the poor performers, with the verbal subcomponent (VR) being the most impaired in comparison to the performance subcomponents. Similarly, researchers reported a reduction of both verbal[29] and performance[28] intelligence scores, with the tendency of the performance task to be less affected or even normal.[30]

The other behavioral, verbal cognitive tests (auditory memory and vigilance tests) scored lower in the poor CI performers. These results suggested deficits in verbal STM, VWM, sequential processing, vocabulary development, inhibition-concentration, attention, and categorization. Several research outcomes agreed with our results regarding verbal STM and verbal rehearsal in prelingual CI users.[31] Moreover, the electrophysiologic evaluation showed longer latency and smaller amplitude of P300 in the poor CI performers, suggesting impaired inhibition-concentration, selective attention, sustained attention, categorization, and decision-making verbal abilities. Earlier studies also reported prolongation of P300 latency or absent response in poor-performing children.[32]

In the same manner, TMT showed longer durations in the poor CI performers. The poor test results were found in $\sim$ 69.5% of these children, reflecting impaired executive functions. The present findings were in-line with a study that reported poorer non-verbal cognitive outcomes in 46% of children implanted at 2 to 6 years old.[33] In postlingually-implanted elders, TMT-performance was impaired in 57%.[26] Nevertheless, children implanted before the age of 2.5 years exhibited age-appropriate non-verbal cognitive results. It was suggested that earlier age at implantation might develop adequate non-verbal cognitive abilities.[31]

An explanation of the variable cognitive function outcomes in the CI users was provided. The prefrontal cortex is thought to integrate various sensory cues (verbal and non-verbal) with cognitive function that works orderly to encode, store, recall, and organize these cues.[25,34] In children with prelingual hearing loss, preimplant auditory deprivation, and less perfect sound presentation through CIs appear to delay maturation of the auditory cortex with reduced neural connectivity to the prefrontal cortex. Consequently, there will be a considerable effect on the development of different domains of cognitive abilities needed for speech processing.[25,35]

Verbal tests were applied to investigate the auditory processing-related cognitive function. They impaired markedly in poor CI performers. Consequently, this study suggested that the preimplant auditory deprivation,[6] and the relatively unnatural stimulation provided by the CI[31] affected the ability to encode, store, recall, and manipulate verbal representations, a phenomenon known as "linguistic coding."[36]

On the other hand, performance tests were applied to examine the cognitive function elicited with non-verbal stimuli to confirm that their outcomes are not dependent on audibility. However, these functions showed an essential role in speech processing, evidenced by activity recorded over visual regions (occipital lobe) using auditory stimulation in postlingually hearing-impaired CI users.[37] Such activities provide another form of information (e.g., visual cues) to compensate for auditory deprivation in poor CI performers.[4,38] This mechanism was described as cross-modal reorganization that could explain the less affected non-verbal cognitive function in the poor CI performers in the current study.[4]

In summary, the auditory deprivation during the critical period for language development and the partially altered auditory inputs via CIs impaired verbal cognitive function. In addition, there was an adverse impact on the non-verbal domain. In the literature, there is controversy about whether the difficulties in the non-verbal abilities are caused by auditory deprivation itself[13,25] or by delayed language that often coincides with hearing loss.[39] The current findings support the combined effect of disrupted auditory and language access on non-verbal functions due to lower scores on speech perception (WRS and MAIS) and spoken language (PLS-4) testing in poor CI performers. Moreover, the non-verbal functions were less affected than the verbal ones (69.45% versus 93.5% of poor CI performers, respectively) because of the cross-modal organization that integrated the non-auditory central cortex in children with hearing loss.

Differences in cognitive function between the cochlear-implanted groups were suggested to contribute to the variability in speech processing outcomes. Moreover, the current results revealed a potency of different cognitive aspects to correlate with and predict CI speech processing outcomes. All subcomponents of the intelligence procedure represented valid indicators of CI proficiency. Similar findings were reported for both verbal[29] and performance[28] IQs. The behavioral measures of verbal cognitive function predicted speech processing efficiency, corresponding to verbal STM and VWM results that have been obtained from prelingually implanted children[15,34] and postlingually implanted adults.[40] Also, the P300 latency and amplitude represented indices that could predict speech perception abilities, in agreement with existing findings.[41] Likewise, the non-verbal cognitive testing modality predicted speech performance as supported by available data.[25,26,39]

Generalized cognitive function impairment in poor CI performers requires a broad diagnostic framework of verbal and performance tests. Multidisciplinary approaches provide a comprehensive assessment to determine all aspects implicated with hearing impairment. Hence, cognitive training can be implemented within the management plan and personalized for the CI users, not only depending on the auditory and speech training. In this way, early intervention would enhance underlying core cognitive function and top-down streaming. Expertise obtained through cognitive training can be conveyed to speech processing skills.

## Limitations

The study represents preliminary findings obtained from a small sample with unilateral CI; thus, a larger sample of bilaterally implanted children might better explain the relative contribution of cognitive function measures to the prediction of speech proficiency. Moreover, to investigate the causal relationship between the verbal and performance cognitive functions and the CI speech outcomes, a prospective longitudinal study involving a preoperative multidisciplinary cognitive and speech evaluation of children with CI should be explored.

## Conclusion

Children with prelingual hearing loss revealed variable CI speech proficiency. Despite being matched in personal and implant-related criteria, the poor CI performers exhibited impaired speech processing at different levels when compared with the good performers. The current study extended the available research on cognitive function assessment in children with CIs, using a multidisciplinary approach to explore the underlying factor causing variability in speech processing. Both aspects of cognitive function showed lower scores in poor CI performers. The verbal cognitive function was more impaired than the non-verbal one. The results of the cognitive tests correlated with and predicted CI-performance outcomes. These findings offer valuable clinical guidance to develop new personalized intervention methods necessary to improve overall functioning.

Conflict of Interests
The authors have no conflict of interests to declare.

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