



Auditory cortical processing in cochlear-implanted children with different language outcomes

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Abstract

Purpose Behavioral evaluation of language development is an important index for the usefulness of cochlear implantation. However, it could not apply to infants and very young children. It is useful to adopt an objective measure to examine speech discrimination in this population. Thus, the current study aimed to predict the different behavioral language performance (good versus poor) in cochlear implant (CI) recipients through the auditory cortical assessment of speech discrimination with mismatch negativity (MMN).

Methods The study comprised 40 CI children who were divided into two groups according to their behavioral language evaluation outcomes: 20 good and 20 poor CI performers. They were age, gender, and socioeconomically matched. The MMN was examined and compared between both groups with finding out the relationship between MMN and different variables.

Results MMN existed in all good performers and 87.5% of the poor performers. There were significantly shorter latency, larger amplitude, and a larger area of MMN in the good performers. The MMN results correlated with a significant predictive effect on the behavioral measures of language evaluation.

Conclusion The MMN is a clinically applicable objective measure of speech discrimination proficiency. Hence, it could be useful in CI programming and auditory cortical monitoring during rehabilitation.

Keyword Cochlear implantation · Auditory cortical processing · Mismatch negativity · Language development · Children

Introduction

It has been clearly shown that longstanding congenital deafness is difficult to reverse into normal hearing performance. Sensory deprivation causes a permanent effect on the development of the entire central auditory system [1]. However, early cochlear implantation represents a dramatic solution to children with severe hearing impairment. The primary goal of cochlear implantation is to permit speech perception and production [2].

Speech abilities in cochlear implant (CI) recipients are variable and questionable, with the same device and same

circumstances [3, 4]. The recovery of auditory abilities after implantation shows a considerable individual variability. In particular, speech intelligibility is extremely variable across individuals [5]. Speech performance scores can reach 70–80% for sentence recognition in a quiet environment but for some CI users, speech perception may remain challenging [6].

Variance in CI outcomes could be attributed to multiple factors. Duration of hearing deprivation and residual hearing was reported to be highly predictive factors related to the variability in speech perception [3, 7]. In addition, hearing aid (HA) use, age of implantation, intelligence quotient (IQ), preoperative radiological assessment showing the survival of spiral ganglion cells, device-related factors, and surgical factors [7, 8]. However, these factors were found to represent only a limited portion of CI outcome variability. A great proportion (up to 80%) could be related to central factors beyond these personal and behavioral features [4, 7]. A comprehensive study of these central factors could provide a thorough understanding of mechanisms underlying the variability in CI outcomes.

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Auditory cortical processing of the CI recipients revealed an association with auditory performance outcomes [9]. Clinically, event-related potentials can be used to assess the central mechanisms underlying speech perception in those individuals objectively. Mismatch Negativity (MMN), in particular, may provide insight into the fine discrimination abilities of the central auditory pathway [10]. The measures of MMN were found to have a correlation with psychometric test scores of language development in children [11]. It was reported that MMN amplitude in CI users with good language performance was similar to that of adults with normal hearing [12, 13].

Moreover, psychoacoustic measures may not be suitable for difficult-to-test subjects such as infants and very young children especially with the tendency for early implantation. Using an objective electrophysiological method to evaluate cortical auditory processing of speech would be more appropriate to cope with this population. Restricted data are available about the MMN as an objective tool for speech evaluation in CI children with different behavioral language performance [14].

Consequently, the current study aimed to explore the results of MMN in CI children with good versus poor behavioral outcomes to find out the contributing role of auditory cortical processing to individual variability in CI performance. In addition, the study aimed to find out the relationship between both MMN and behavioral measures, yielding some declarative data for the objective evaluation of variable speech discrimination abilities to be applied for CI children who cannot administer behavioral tests.

Methods

Subjects

This comparative cross-sectional study included 40 Arabic-speaking monaural CI children of both genders with an age range of 5–10 years old and variable behavioral performance. The CI recipients were selected pre-operatively following the CI candidacy criteria of the Department of Health, Western Australia [15]. There were absent response on the tonal free field, speech free field audiometry, otoacoustic emissions, and auditory brainstem response. Aided thresholds were higher than the average normal speech spectrum with poor spoken language development despite proper amplification and adequate auditory training over at least 6 months of hearing aid fitting. In addition, high-resolution imaging was studied to determine any anatomical deformities and to examine the patency of the cochlear turns that could interfere with electrode insertion.

All CI recipients fulfilled the following criteria to be involved in the study: a pre-lingual hearing loss with no

other disabilities; an average IQ as tested by Stanford-Binet Intelligence Scale; 4th edition [16]; surgery was performed within the critical period for language development [17]; an average aided CI-threshold not exceeding 25 dB HL in the frequency range 0.5–4 kHz; and an implant use duration of 36–60 months with proper CI programming and speech therapy.

Psychoacoustic speech performance scores were used as an index to divide the CI children into good and poor performers following a clinically accepted criterion [13]. Individuals with correct scores equal to or better than 65% using PBKG were considered as good performers (G1: $n = 20$). Poor performers (G2: $n = 20$) were defined as having less than 65% correct Word Recognition Score (WRS) on the Arabic Phonetically Balanced Kindergarten (PBKG) words [18] or when they gave no response except on other speech measures including the Arabic Word Intelligibility by Picture Identification (WIPI) test [19] or simple verbal command using simple orders as pointing to body parts, raising a hand, or opening the mouth.

Procedure

The study started with obtaining a detailed history; the socio-economic status (SES) of both CI subgroups using the Socioeconomic Status Scale [20]; the Arabic translated Meaningful Auditory Integration Scale (MAIS) inventory [21, 22]; the aided CI-threshold in the frequency range 0.5–4 kHz, using a calibrated audiometer (Orbiter 922 v. 2; Madsen, Taastrup, Denmark); psychoacoustic speech evaluation; and objective evaluation of speech discrimination using MMN. Other tests were performed including the Stanford-Binet Intelligence Scale (4th edition) to assess IQ and the Arabic edition of “Modified Preschool Language Scale-fourth” (PLS-4) for language evaluation [23].

The Arabic translated Meaningful Auditory Integration Scale (MAIS) questionnaire

This scale included ten questions examining the listening behavior and speech skills of the CI recipients in real-life situations. The parents answered these questions that were modified by the examiner. Each question scored from 0 to 4 where: 0 indicates never; 1 indicates rarely; 2 indicates occasionally; 3 indicates frequently; and 4 indicates always with a 40 total score [21].

Psychoacoustic speech evaluation

Behavioral evaluation of speech discrimination proceeded according to the child performance using the WRS test, the Arabic WIPI test, and then responding to simple verbal order:

- The WRS is an open set speech test of 25 PBKG monosyllabic words suitable for children vocabulary [18]. The child seated in a sound-treated booth facing a loudspeaker located one meter, zero azimuths from the child's head and conducted speech at 40 dB SL. Correct word recognition was given a score of 4% with total correct responses were added together.
- The Arabic WIPI test [19] is formed of six lists of 25 monosyllabic words within the child's vocabulary. Each word is represented graphically in one of 25 pages. Each page contained six pictures from which the child selected the picture representing the target word. A test list was presented at an average conversational level in a face-to-face condition, outside a sound-booth. The children were asked to point to the correct picture. The examiner turned the pages as the child made a selection. A practice item was presented before testing to ensure that each child understood the task. Correct picture identification was scored by 4%. Number of correct identification were added together to calculate the final score.
- Responding to the simple verbal command using simple orders as pointing to body parts, raising a hand, or opening the mouth.

Mismatch negativity (MMN)

The auditory evoked system, OtoAccess (v 1.3; Eclipse 25; Assens, Denmark) was used to examine the MMN cortical response in a sound-treated room. Two stimuli were presented as an odd-ball paradigm with a frequent tone-burst of 750 Hz and a deviant tone-burst of 1000 Hz, with a probability of 80% and 20%, respectively. The sound was delivered through a loudspeaker located one meter at zero azimuth from the subject's head, at a level of 70 dB nHL. Responses were obtained with a non-inverting electrode placed in the middle of the forehead, an inverting electrode placed over the mastoid of the non-implanted ear to avoid electric artifact from the CI and a ground electrode placed on the forehead just below the non-inverting one.

Recording was carried out while the child was watching a movie on a laptop placed above the loudspeaker to distract his/her attention to the stimulus. The picked-up potentials were filtered with a band-pass filter of 0.83–33 Hz and presented in a time window of 600 ms with a pre-stimulus interval of – 50 ms. The MMN was presented as a negative trough in the difference wave obtained by subtracting the frequent from the deviant responses. Response parameters involved latency, amplitude, duration, and area of the negative trough located nearly after 250 ms [22].

The modified Preschool Language Scale fourth (PLS-4); Arabic edition

The modified PLS-4 was used to examine several aspects of the receptive and expressive language skills were evaluated, including attention, play, gesture, vocal development, social communication, vocabulary, concepts, language structure, integrative language skills, and phonological awareness. Scoring involved age-related subscales: receptive, expressive, and total language age (TLA) with an upper limit of language development of 6 years and 11 months (83 months) [23].

Statistical analysis

The data were analyzed using the SPSS 22.0 software. The normality of different variables was assessed using Shapiro–Walk test. The continuous data were presented as mean \pm Standard deviation (SD) while the categorical data were presented as frequencies and percentages. The normally distributed data were compared using the parametric tests (*t* test and one-way ANOVA test) whereas the abnormally distributed data were compared using the non-parametric test (Mann–Whitney (*U*) test and Kruskal–Wallis *H* test). The distribution of categorical variables was compared using χ^2 or Fisher's exact tests when appropriate.

Correlation coefficient was performed with Person's correlation test for parametric testing and with Spearman's correlation test for non-parametric testing. Linear regression analysis was applied to find out the predictor effect of different significantly correlated variables on MMN. The level of significance (*p*) was set at <0.05. To ensure the validity of the statistical analysis and the strength of significance, the degrees of freedom (*df*) and Effect size (ES) were evaluated, respectively.

Results

Table 1 represents the personal and CI device criteria of both study groups. The good and poor CI performers were matching in age, sex, and SES. Chi-square test revealed a significantly different distribution of the causes of hearing loss, but with a small ES (0.03). The hereditary etiology was the commonest among the two groups. Other etiologies such as meningitis and hypoxia dominated in the poor CI performers. Both groups had a comparable duration of HA usage, age at implantation, duration of implant, and distribution of the CI devices and speech strategies.

As shown in Table 2, the two groups exhibited equivalent average aided response and IQ. Other behavioral measures including WRS, MAIS, and language age were significantly higher with *df*=38 and large ES in the G1 group. In both

Table 1 Personal data of good (G1) versus poor (G2) CI performers

Personal data	G1 <i>n</i> =20	G2 <i>n</i> =20	Test value (<i>p</i>)	<i>df</i>
Age (mean ± SD years) (months)	7.22 ± 1.60 (86.66 ± 19.19)	7.45 ± 1.29 (89.38 ± 15.45)	0.471 (0.64)	38
Gender [<i>n</i> (%)]				
Male	14 (58.33)	7 (43.75)	0.520 (0.37)	1
Female	10 (41.66)	9 (56.25)		
SES (mean ± SD%)	57.8 ± 6.48	55.75 ± 6.24	1.019 (0.16)	38
Causes of hearing loss [<i>n</i> (%)]				
HF	22	8	11.389 (0.01)*	3
Meningitis	0	4		
Hypoxia	0	2		
Neuropathy	2	2		
Duration of HA use (mean ± SD years) (months)	2.21 ± 0.81 (26.54 ± 9.68)	1.75 ± 0.68 (21.00 ± 8.20)	1.946 (0.06)	38
Age at implantation (mean ± SD years) (months)	3.50 ± 0.94 (42.04 ± 11.32)	3.90 ± 1.00 (46.88 ± 12.10)	1.270 (0.21)	38
Duration of implant use (mean ± SD years) (months)	3.74 ± 0.89 (44.88 ± 10.63)	3.55 ± 0.75 (42.50 ± 9.00)	0.760 (0.45)	38
CI device [<i>n</i> (%)]				
AB	13	8	0.079 (0.961)	2
MedEl	8	6		
Cochlear	3	2		
Speech strategy [<i>n</i> (%)]				
HiRes	0	4	8.460 (0.13)	5
HiRes 120	9	2		
HiRes Optima	4	2		
FS4	6	4		
FS4P	2	2		
ACE	3	2		

*Significant value

Table 2 Comparison of behavioral measures between both study groups

	G1	G2	Test value (<i>p</i>)	ES
Average aided response (mean ± SD) dB HL	22.52 ± 2.78	22.50 ± 2.50	191 (0.98)	0.01
IQ (mean ± SD)	101.46 ± 5.32	99.13 ± 2.09	1.278 (0.07)	0.5
WRS% (mean ± SD)	75.83 ± 5.59	35.71 ± 22.10	8.513 (<0.001)*	2.76
MAIS (mean ± SD)	34.17 ± 2.32	28.63 ± 2.00	7.822 (<0.001)*	2.52
PLS-4 (mean ± SD) (months)				
Receptive	52.88 ± 10.24	32.25 ± 10.80	6.090 (<0.001)*	1.97
Expressive	44.21 ± 8.29	30.13 ± 9.47	4.971 (<0.001)*	1.60
TLA	47.96 ± 8.94	32.63 ± 10.34	4.993 (<0.001)*	1.61

*Significant value

study groups, the different behavioral measures of language evaluation and IQ revealed significant inter-correlations (Table 3).

Figure 1 represents the MMN incidence in both groups and revealed a non-significant difference (Fisher's exact = 0.154, $p > 0.05$). There were significantly shorter latency, larger amplitude, and a larger area of MMN with $df = 38$ and large ES in G1 as compared to the G2 group,

but the MMN duration did not differ significantly (Table 4). Figure 2 illustrates examples of MMN response from a good CI performer with shorter latency (panel a) versus a poor CI performer (panel b).

On studying the relationship between different factors and MMN outcomes (Table 5); personal and implantation features did not show any significant relationship in both groups; aided response had a significant correlation with all

Table 3 Correlation matrix [*r*(*p*)] of different behavioral language evaluation and IQ measures in both study groups

	G1			
	IQ	WRS%	MAIS	TLA
IQ		0.822 (<0.001)*	0.481 (0.02)*	0.790 (<0.001)*
WRS%	0.913 (<0.001)*		0.419 (0.04)*	0.877 (<0.001)*
MAIS	0.588 (<0.001)*	0.916 (<0.001)*		0.544 (0.006)*
TLA	0.846 (<0.001)*	0.875 (<0.001)*	0.883 (<0.001)*	
G2				

*Significant value

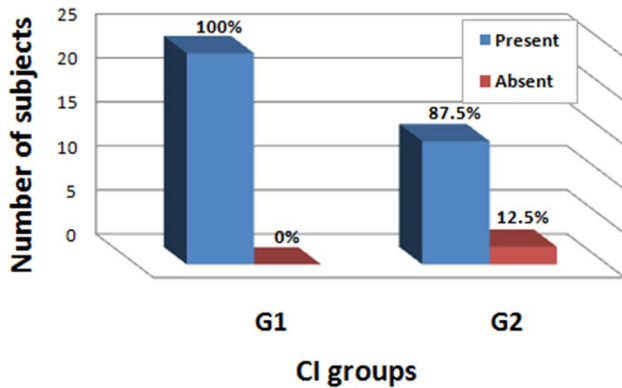


Fig. 1 Incidence of MMN in good (G1) versus poor (G2) CI performers

MMN measures except the duration in G1 group; and other behavioral measures (WRS, IQ, MAIS, and language age) exhibited significant correlations with most of the MMN measures in the two groups. Linear regression analysis was applied to the significant correlations and revealed an overall significant predictive effect of the MMN outcomes on the aided response (in G1) and behavioral measures (in both groups) (*p* < 0.001).

Discussion

Psychoacoustic language evaluation in CI children

The behavioral measures of language development are the fundamental modalities that provide a comprehensive description of linguistic skills and auditory performance.

Despite the comparable age, audibility, auditory experience, intelligence, and SES of the study groups, the behavioral measures of language evaluation were significantly lower in poor than good performers. Previous behavioral studies showed similar findings in CI users [24, 25]. The significant inter-correlation among these measures reflects the parallel central auditory maturation integrated with the peripheral auditory stimulation through CIs.

Auditory cortical processing in good versus poor-performing CI children

This study aimed to investigate the cortical auditory processing of speech in CI children with different behavioral language outcomes. The inclusion criteria of the participants of both study groups established analogous personal and implantation factors. Therefore, it would be possible to estimate a confined contribution of central auditory processing to language development in CI children. In this study, MMN recorded in all good CI performers and 87.5% of poor CI performers. The literature presented the incidence of MMN with considerable variability.

Some investigators used tonal contrasts to elicit MMN in good versus poor CI performers to examine the auditory cortical processes consistent with their speech discrimination. In postlingual hearing-impaired adults with CI, the MMN existed in five out of six ears (83.3%) with good performance and in only one out of six ears (16.7%) with moderate-to-poor performance [26]. Kelly [27] reported a reduced or absent MMN in poor (*n* = 4) as compared to good performers (*n* = 8) using a two-deviant tonal paradigm in 12 adults with CI.

Table 4 MMN test results in both CI groups

MMN measures	Good	Poor	<i>U</i> (<i>p</i>)	ES
Latency	347.54 ± 59.47	427.21 ± 27.81	39.5 (<0.001)*	1.61
Amplitude	18.44 ± 6.62	6.40 ± 3.27	12 (<0.001)*	2.17
Duration	109.13 ± 39.02	89.79 ± 24.34	120 (0.15)	0.57
Area	1993.10 ± 957.94	630.08 ± 462.60	25 (<0.001)*	1.70

*Significant value

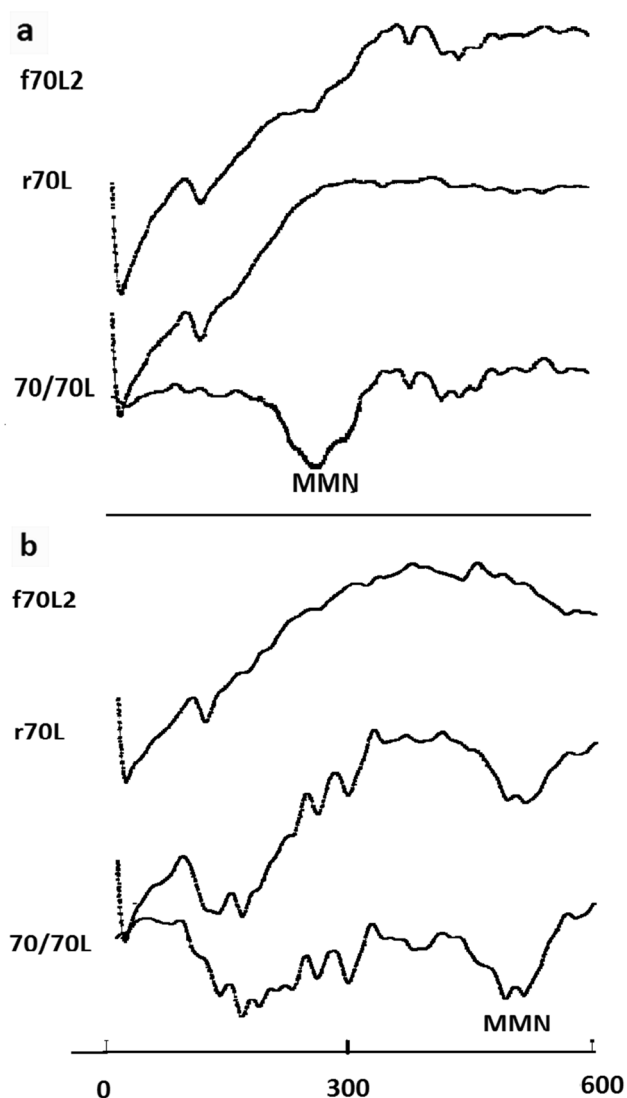


Fig. 2 Example of (a; upper trace) MMN from a 7-year-old boy with right-sided CI and good language results, and (b; lower trace) MMN from a 10-year-old girl with right-sided CI and poor language results. Each trace contains three waves: the upper (f) is a response to a frequent stimulus; the middle (r) is a response to rare stimulus; the lower is a difference wave (MMN)

More complex stimulus paradigms were also used to record MMN in CI users with different behavioral speech outcomes. Kraus et al. [10] and Groenen et al. [12] presented a speech paradigm that elicited MMN in all adult CI participants with preferable speech outcomes but not in any of the poor performers. In 35 CI children (7–17 years), speech stimuli produced MMN in 80–85% of good performers and in 15–20% of poor performers [28]. Using a two-deviant speech paradigm, Turgeon et al. [13] recorded MMN from all adults with CI, either good ($n = 10$) or poor ($n = 10$) performers; however, the MMN in the poor performers had smaller amplitude and longer latency.

The different findings in these studies may be due to the variability in age, sample size, stimulus parameters, and equipment used. Despite the different outcomes, there was a general agreement that the CI users with proficient behavioral speech results showed a prevalent MMN response. Those with poor behavioral results presented a degraded or even absent MMN. Consequently, the incidence of MMN represents the underlying neurophysiologic mechanisms responsible for speech discrimination that reflect and go parallel with the outcomes of psychoacoustic speech evaluation.

Additional findings in this study were significantly shorter latency, larger amplitude, and a larger area of MMN in good versus poor CI children. These data are consistent with previous studies, which have shown a tendency of good CI performers to exhibit larger MMN amplitude, approximating that of normal-hearing individuals [15, 26, 27, 29]. The significant differences of MMN measures between good and poor performers suggest different pre-attentive speech discrimination capabilities that are impaired in the poor performers. Hence, MMN can be used as an objective measure to categorize speech discrimination dexterity in CI subjects especially in those who are difficult to test behaviorally [28, 30].

Factors determining the proficiency of language development in CI children

Despite the comparable personal and implantation criteria, CI users in the current study had variable language skills (good versus poor) as revealed with the behavioral and MMN measurements. Researchers suggested several factors that determine the proficiency of language development in CI individuals. Longstanding hearing impairment prior to cochlear implantation causes auditory deprivation with a negative impact on language development, especially in the pediatric population [31, 32]. The auditory deprivation interferes with proper auditory cortical maturation [26] and cognitive function evolution [33–35]. Previous studies provided evidence of cross-modal auditory cortical reorganization following a prolonged auditory deprivation where other sensations such as vision [4, 29, 36] and touch [37] replace the hearing sensation. Thus, the ability to process auditory cues provided with the CI is markedly impaired within the reduced auditory temporal cortex [38].

Eppsteiner et al. [39] suggested that the gene mutations in genetic hearing loss could affect the proficiency of language outcomes in CI recipients. They reported TMRSS3 gene mutations in the spiral ganglion of a poor performer and LOXHD1 gene mutations in the membranous labyrinth of two good performers. Further, bacterial meningitis can impair the auditory performance in CI individuals due to different cochlear and central auditory lesions, depth of electrode insertion, and number of active electrodes [40]. It

Table 5 Relationship between both personal and behavioral measures and the MMN measures

Factors	MMN in G1				MMN in G2			
	Latency	Amplitude	Duration	Area	Latency	Amplitude	Duration	Area
Gender	0.642 (0.63)	1.942 (0.06)	1.191 (0.25)	0.040 (0.97)	1.800 (0.10)	1.833 (0.10)	1.023 (0.33)	1.548 (0.15)
Causes of hearing loss	1.091 (0.31)	0.549 (0.467)	3.534 (0.07)	2.880 (0.10)	0.728 (0.56)	2.324 (0.14)	2.137 (0.16)	3.493 (0.06)
Duration of HA use	-0.310 (0.14)	0.309 (0.14)	-0.122 (0.57)	0.078 (0.72)	0.459 (0.10)	-0.192 (0.51)	-0.338 (0.24)	-0.196 (0.50)
Age at Implantation	-0.228 (0.28)	0.300 (0.015)	-0.097 (0.65)	0.084 (0.70)	-0.220 (0.45)	0.238 (0.41)	-0.015 (0.96)	0.180 (0.54)
Duration of implant use	-0.313 (0.14)	0.242 (0.25)	-0.307 (0.15)	-0.120 (0.58)	-0.099 (0.74)	0.094 (0.75)	0.111 (0.71)	0.111 (0.70)
CI device	1.674 (0.21)	1.625 (0.22)	0.671 (0.52)	0.909 (0.42)	0.003 (0.99)	0.280 (0.76)	0.012 (0.99)	0.227 (0.80)
Speech strategy	1.230 (0.33)	0.954 (0.46)	1.497 (0.243)	2.039 (0.13)	0.457 (0.80)	1.221 (0.38)	0.471 (0.79)	1.408 (0.32)
Aided response	0.706 (0.001)*	-0.414 (0.04)*	-0.180 (0.40)	-0.445 (0.03)*	0.126 (0.67)	-0.333 (0.25)	-0.119 (0.69)	-0.297 (0.30)
IQ	-0.783 (<0.001)*	0.668 (<0.001)*	0.081 (0.71)	0.542 (0.006)*	-0.911 (<0.000)*	0.641 (0.01)*	0.547 (0.04)*	0.617 (0.01)*
WRS	-0.909 (<0.001)*	0.852 (<0.001)*	0.004 (0.99)	0.680 (<0.001)*	-0.973 (<0.001)*	0.626 (0.01)*	0.540 (0.04)*	0.596 (0.02)*
MAIS	-0.574 (0.003)*	0.529 (0.008)*	0.064 (0.77)	0.321 (0.13)	-0.895 (<0.001)*	0.646 (0.01)*	0.549 (0.04)*	0.627 (0.01)*
Receptive	-0.974 (<0.001)*	0.839 (<0.001)*	-0.124 (0.56)	0.486 (0.02)*	-0.963 (<0.001)*	0.605 (0.02)*	0.540 (0.04)*	0.582 (0.03)*
Expressive	-0.913 (<0.001)*	0.728 (<0.001)*	0.088 (0.68)	0.593 (0.002)*	-0.872 (<0.001)*	0.485 (0.08)	0.357 (0.21)	0.458 (0.09)
TLA	-0.951 (<0.001)*	0.791 (<0.001)*	-0.022 (0.92)	0.540 (0.006)*	-0.770 (0.001)*	0.412 (0.14)	0.204 (0.483)	0.374 (0.19)

*Significant value

is the case in this study where the meningitis is among the causes of hearing loss in the poor CI performers.

Relationship between different variables and auditory cortical processing in the CI subgroups

Another important aim of this study was to find out the relationship between different subjective criteria and MMN. The different personal and implantation data showed no significant association with the outcomes of MMN recording. This could be attributed to the inclusion criteria of the studied CI children involving a limited range of implantation age, implantation duration, and appropriate rehabilitation. Some investigators found significant relationships between the MMN latency and subjects' age [41], MMN latency and age at implantation [32], and MMN latency and amplitude and duration of HA use [42]. These differences in outcomes relative to that of the current study could be attributed to the recording of MMN early after implantation [41, 42] and to different stimulus parameters (e.g. smaller frequency deviance [32]).

The aided response correlated with MMN parameters in good performers but not in poor ones. This indicates the presence of factors contributing to impaired performance other than the impaired cortical auditory processing in poor performers as mentioned in the previous section. The MMN results correlated with a significant predictive effect on IQ and behavioral measures of language evaluation. Similar findings were also reported in the previous studies [13, 41, 43, 44]. Thus, MMN could provide an objective indicator of speech discrimination for proper CI programming, central auditory plasticity monitoring, and follow-up during auditory rehabilitation.

Conclusion

This study showed that the assessment of cortical auditory processing could reflect the behavioral language outcomes in CI children. There was a tendency of good CI performers to have a shorter latency, larger amplitude, and a larger area of MMN than the poor ones. These results suggested that the electrophysiological MMN recording provided an objective assessment of speech discrimination. Hence, it could be an easily applied determinant of CI proficiency in difficult-to-test subjects such as infants and young children. Given the predictive effect of MMN on the behavioral tests of a language evaluation, it could be a clinically useful tool in CI programming, monitoring, and follow-up during rehabilitation programs.

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Compliance with ethical standards

Conflict of interest The authors declared that there was no conflict of interest.

Ethical approval All the study procedures were performed using non-invasive testing, following the guidelines of the International Review Board of Zagazig University with an ID: 5613-29-9-2019.

Informed consent Study took place after explaining the procedures to the participants/parents and obtaining informed consent the parents of the participants.

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