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Neural markers of attention processing in pediatric cochlear implant users: an ERP study

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The current study examined the neural mechanisms underlying auditory outcomes in pediatric cochlear implant (CI) users using event-related potentials, focusing on the frontocentral Novelty P3 (indexing automatic attention) and the parietal Target P3 (reflecting controlled attention). By comparing CI children with normal-hearing peers, we aimed to elucidate how these attention mechanisms contribute to post-implantation auditory performance variability. Prelingually deaf children with early bilateral CIs (*n* = 25) and normal-hearing (NH) controls (*n* = 28), matched for gender and age (7–13 years), completed an oddball paradigm during ERP recording and performed speech-in-noise and memory tasks. CI users showed reduced Novelty P3 amplitudes compared to NH peers, suggesting impaired automatic attention mechanisms, while Target P3 amplitudes were comparable between groups, indicating preserved controlled attention. CI users demonstrated poorer performance on speech-in-noise recognition and forward digit span tasks. Larger Novelty P3 and Target P3 amplitudes both correlated positively with speech-in-noise performance across all participants. In contrast, in CI users specifically, Target P3 amplitudes showed positive associations with short-term memory performance. This study provides novel evidence that pediatric CI users exhibit reduced automatic attention shifting in response to acoustic changes while maintaining intact controlled attention processes that may serve as a compensatory mechanism. The neural markers' associations with behavioral performance suggest potential intervention targets: rehabilitation efforts might focus on strengthening automatic attention shifting while leveraging preserved controlled attention pathways.

Keywords Cochlear implants, Event-related potentials, P3 components, Attention mechanisms, Speech perception, Short-term memory

Cochlear implants (CIs) have transformed the management of severe-to-profound sensorineural hearing loss, with more than one million recipients worldwide[1,2]. Despite this remarkable success, CIs remain fundamentally limited by reduced processing capacity: while the normal cochlea conveys thousands of frequencies through ~ 3,500 inner hair cells[3], CIs provide only 12–22 electrodes, resulting in diminished temporal and spectral resolution that constrains speech perception and sound detection[1,2].

Although many CI recipients achieve near-normal communication, outcomes remain highly variable and cannot be explained solely by classical predictors such as implantation age, duration of use, or socioeconomic factors[4,5]. In children implanted before 3.5 years of age, neural plasticity is generally greater[6], yet performance varies substantially in complex listening situations, particularly in noise or with competing speakers[7–9]. This variability has shifted attention toward cognitive mechanisms, especially auditory attention, as key contributors to functional outcomes.

Auditory attention operates through two complementary processes: automatic, bottom-up orienting to unexpected sounds and controlled, top-down focus on task-relevant inputs[10,11]. In CI users, degraded auditory input disrupts the balance between these processes, leading to greater reliance on effortful controlled processing and working memory[12]. Meta-analyses indicate that about one-third of pediatric CI users experience executive function delays, particularly in verbal short-term memory and auditory attention[13–15]. These difficulties become most evident in noisy or unpredictable environments.

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Event-related potentials (ERPs) provide a powerful method for probing such mechanisms with millisecond precision[16]. The P3 complex, elicited 300–700 ms after stimulus onset[17,18], includes two subcomponents: the frontal Novelty P3 (P3a), which indexes automatic attention reorienting to unexpected events[19–22], and the parietal Target P3 (P3b), which reflects controlled attention allocation and working memory updating[23]. To maintain clarity, we refer to these components throughout as the Novelty P3 and Target P3. These processes are commonly studied using the novelty oddball paradigm, which presents frequent standard tones (~ 80%), rare target tones (~ 10%), and unexpected novel sounds (~ 10%), enabling simultaneous assessment of both automatic and controlled attention[22,24].

Adult CI studies consistently report alterations in these components. A systematic review of 20 studies found that ~ 60% of adult CI users exhibit prolonged P3b latency and ~ 35% show reduced amplitudes, with effects stronger for speech than for pure tones[25]. Post-lingually deaf CI users often show attenuated Novelty P3 alongside preserved Target P3, suggesting that automatic attention is more vulnerable than controlled attention[26–28]. However, most studies were limited by small samples ($n < 15$) and task designs that included only standard and novel sounds without target detection[26]. In contrast, Schierholz et al. (2021)[24], using a more comprehensive novelty oddball task with a larger sample ($n = 40$), found enhanced N1 modulation but only a trend toward reduced Novelty P3. The N1, an early auditory ERP component peaking around 100 ms, reflects initial sensory encoding of sound. These findings suggest that, in adults, CI-related attention differences may primarily affect earlier auditory processing stages rather than later attentional reorienting.

In children with pre-lingual CIs, attention-related ERPs have also been linked to functional outcomes[29]. Target P3 responses distinguish between good and poor performers: children with strong speech recognition (> 65%) show amplitudes and latencies comparable to their normal-hearing peers, whereas weaker performers demonstrate delayed and diminished responses[30,31]. Henkin et al. (2008)[32] showed that P3 latency increases with phonetic complexity, underscoring its sensitivity to linguistic demands. More recently, Deroche et al. (2023)[18] found that CI children with age-appropriate language presented preserved P3 responses, while those with language delays exhibited reduced amplitudes. Beyond speech perception, Target P3 has been associated with literacy, auditory memory, and processing efficiency[31,33–35].

Despite these promising findings, pediatric research remains underpowered (typically $n < 15$)[30,32–36], with only a few larger cohorts published[18,31]. Importantly, the Novelty P3 has scarcely been studied in children with CIs, despite its critical role as a marker of automatic orienting and adaptation[19,24,26]. Since automatic attention to unexpected sounds is essential for communication in noisy, unpredictable environments, this represents a major gap in our understanding of pediatric outcomes.

The present study addresses this gap by examining both automatic and controlled attention in early-implanted bilateral CI children compared with age-matched normal-hearing peers. We focused on the Novelty P3 and Target P3 components to clarify how early implantation influences attention networks and how these markers relate to speech perception and working memory. Specifically, the study addressed three key questions. First, we asked whether frontal Novelty P3 responses to novel versus standard distractors would differ between CI and NH children, with the hypothesis that CI users would show attenuated responses despite early implantation, consistent with adult findings[24,26–28]. Second, we examined whether parietal Target P3 responses to rare target stimuli would be preserved in CI users, predicting intact responses in line with evidence from high-performing pediatric groups[18,30,31]. Third, we investigated whether P3 markers would predict functional outcomes, expecting larger amplitudes to correlate positively with speech-in-noise performance and short-term memory, and longer latencies to show inverse associations that may reflect neural mechanisms of successful auditory rehabilitation in pediatric CI users,

Results

Normality checks showed that several variables deviated from a normal distribution. These included two neural parameters (standard stimulus latency at FCz and Pz), two demographic measures (age and implant age), and two behavioral outcomes (speech-in-noise scores and accuracy rate). For these variables, non-parametric tests were applied, consistent with the statistical approach described in the Methods.

Demographic outcomes

The demographic analysis revealed well-matched characteristics between the CI and NH groups across all key variables. No significant differences were found in age (CI: $M = 9.79$, $SD = 1.81$; NH: $M = 9.19$, $SD = 1.8$; $t(51) = 1.24$, $p = 0.22$), gender distribution (CI: 9 F/16 M; NH: 10 F/18 M; $\chi^2(1) = 0.26$, $p = 0.610$), or native language distribution (CI: 7 Hebrew/18 Arabic; NH: 10 Hebrew/18 Arabic; $\chi^2(1) = 0.32$, $p = 0.574$). Similarly, socioeconomic status (CI: 14 medium/11 high; NH: 12 medium/16 high; $\chi^2(1) = 0.73$, $p = 0.392$) and estimated IQ (CI: $M = 119.00$, $SD = 25.21$; NH: $M = 125.00$, $SD = 21.94$; $t(51) = 0.93$, $p = 0.359$) showed no significant differences between groups.

Behavioral outcomes

Speech in noise

The Mann-Whitney U test revealed significantly poorer performance in the CI group (Mean Rank = 13.38) compared to the NH group (Mean Rank = 39.16; $U = 9.500$, $p < 0.001$; Fig. 5).

Digit span

A 2 × 2 mixed-design ANOVA with Task (forward vs. backward digit span) as a within-subjects factor and Group (CI vs. NH) as a between-subjects factor revealed a significant main effect of task ($F(1, 51) = 5.76$, $p = 0.020$, $\eta^2 p = 0.10$), indicating higher scores on forward than backward digit span overall. A significant main effect of group was also observed ($F(1, 51) = 23.88$, $p < 0.001$, $\eta^2 p = 0.32$), showing that NH participants outperformed

Effect / Task	Group	Mean (SD)	F-value	df	*p*-value	Mean Difference (95% Confidence Interval)	Partial η^2
Main Effect: Memory Task	–	–	5.76	1, 51	0.020	–	0.10
Main Effect: Group			23.88	1, 51	< 0 0.001	–	0.31
Interaction: Group × Memory Task	–	–	10.66	1, 51	0.002	–	0.17
Forward Digit Span	CI	9.08 (1.91)	23.88	1, 51	< 0 0.001	−2.67 [−3.767, − 1.573]	0.31
	NH	11.75 (2.05)					
Backward Digit Span	CI	9.32 (2.56)	1.87	1, 51	= 0.177	−0.86 [−2.119, 0.402]	0.04
	NH	10.18 (2.00)					

Table 1. Comparison in memory tasks across the CI and NH groups: Results of mixed ANOVA, including main Effects, Interaction, and pairwise comparison across memory tasks (forward and backward digit span).

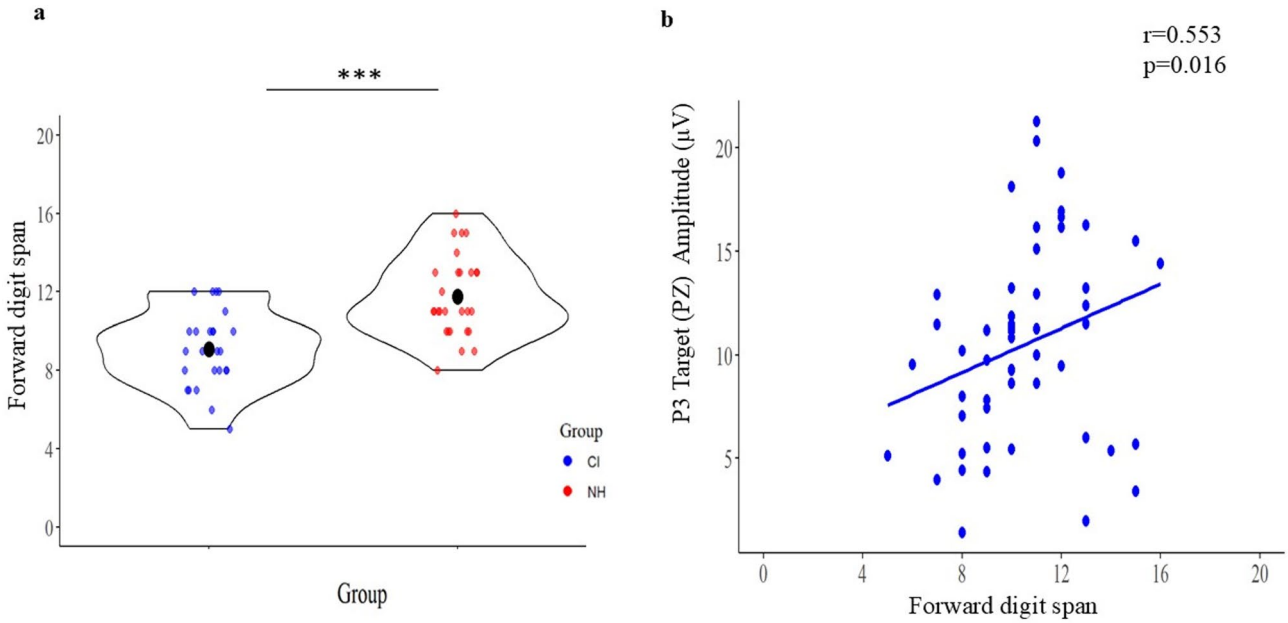

Fig. 1. (**a**) Violin plot showing significant difference in forward digit span between cochlear implant (CI) users (blue dots) and normal hearing (NH) participants (red dots) (***$p < 0.001$), with NH individuals demonstrating superior short-term memory capacity. (**b**) Scatter plot demonstrating positive correlation between forward digit span and P3 Target amplitude at PZ electrode ($r = 0.553$, FDRp = 0.016).

CI users across tasks. Importantly, the group × task interaction was significant ($F(1, 51) = 10.66$, $p = 0.002$, $\eta^2 p = 0.17$), suggesting that group differences varied by task.

Follow-up comparisons confirmed that the group effect was specific to forward digit span: NH participants (M = 11.75, SD = 2.05) scored significantly higher than CI users (M = 9.08, SD = 1.91), $F(1, 51) = 23.88$, $p < 0.001$, $\eta^2 p = 0.31$, mean difference = 2.67, 95% Confidence.

Iinterval [1.57, 3.77]. In contrast, no group difference was found for backward digit span ($F(1, 51) = 1.87$, $p = 0.177$, $\eta^2 p = 0.04$; NH: M = 10.18, SD = 2.00; CI: M = 9.32, SD = 2.56). Detailed in Table 1; Fig. 1.

Response times

An independent samples t-test revealed slower reaction times in the CI group (M = 0.73 **s**, SD = 0.11) compared to the NH group (M = 0.67 **s**, SD = 0.12), though this difference did not reach statistical significance, $t(51) = 1.913$, $p = 0.061$. The analysis yielded a medium effect size (d = 0.54, 95% Confidence Interval = [−0.003, 0.129]), suggesting a practically meaningful difference between groups. The mean difference of 63 ms (SE = 0.033) indicates a trend toward slower responses in CI users.

Accuracy rates between groups were compared using a Mann-Whitney U test, which showed no significant difference (U = 319.500, $p = 0.569$). The NH group demonstrated a higher mean rank (28.09) compared to the CI group (25.78).

Electrophysiological measures

Amplitude measures

Descriptive statistics are presented in Table 2. Across groups, amplitudes were largest for novel stimuli, followed by target and standard conditions. Consistent with prior evidence that Novelty P3 effects are maximal at FCz,

Electrode Site	Effect Type	Source	NH ($n = 28$) Mean (SD)	CI ($n = 25$) Mean (SD)	F (dfh, dfe)	P	η^2p
FCz	Within-Subjects	Stimuli (Main Effect)	—	—	77.498*** (2, 47)	< 0.001	0.766
	Between-Subjects	Group (CI vs. NH)	—	—	1.356 (1, 48)	0.25	0.028
	Interaction	Stimuli × Group	—	—	13.554*** (2, 47)	< 0.001	0.366
	Pairwise Comparisons (stimuli × Group)	CI vs. NH at Novel Stimuli	10.55 (4.40)	6.40 (4.93)	—	< 0.001	—
		CI vs. NH at Target Stimuli	2.80 (3.89)	3.56 (3.40)	—	0.463	—
		CI vs. NH at Standard Stimuli	2.02 (1.79)	2.61 (1.59)	—	0.221	—
PZ	Within-Subjects	Stimuli (Main Effect)	—	—	71.937*** (2, 49)	< 0.001	0.746
	Between-Subjects	Group (CI vs. NH)	—	—	0.190 (1, 50)	0.665	0.004
	Interaction	stimuli × group	—	—	1.736 (2, 49)	0.181	0.066
	Pairwise Comparisons (Stimuli × Group)	CI vs. NH at Novel Stimuli	8.468 (5.28)	8.861 (4.44)	—	0.774	—
		CI vs. NH at Target Stimuli	11.366 (5.28)	9.509 (4.46)	—	0.163	—
		CI vs. NH at Standard Stimuli	2.134 (1.75)	2.594 (1.49)	—	0.315	—

Table 2. Comparison in amplitude measurements at the PZ and FCz electrode sites across the CI and NH groups: Results of ANOVA repeated measures, including main Effects, Interaction, and pairwise comparison across stimuli reactions (novel, target, and standard). ***$p < 0.001$.

and in line with our pre-specified analysis plan, the main group differences were observed at the FCz electrode. At this site, analyses revealed marked differences between NH and CI groups, particularly for novel stimuli, with large effect sizes for both stimulus type ($\eta^2p = 0.766$) and the stimulus × group interaction ($\eta^2p = 0.366$). In contrast, analyses at Pz showed no significant group effects or interactions, indicating largely preserved posterior target-related processing in CI users relative to NH controls (see Supplementary Tables 2 and Fig. 2).

Analyses of the N1–P2 complex at FCz revealed no significant differences between groups, indicating comparable early auditory processing (see Figure S2 and Table 2 in the Supplementary Materials). Grand-average ERPs, topographical maps, and waveform plots illustrating these effects are presented in Figs. 3 and 4.

FCz electrode

Analysis revealed a significant main effect for stimulus type (Wilks' Lambda = 0.278, F(2, 47) = 61.001, $p < 0.001$), indicating significant amplitude variations across novel, target, and standard stimuli. A significant stimulus type × group interaction was also observed (Wilks' Lambda = 0.676, F(2, 47) = 11.288, $p < 0.001$), demonstrating distinct amplitude patterns between NH and CI groups. Pairwise comparisons revealed that the NH group showed significantly higher amplitudes for novel stimuli compared to the CI group (mean difference = 4.144 µV, $p = 0.003$, 95% Confidence Interval [1.405, 6.883]), while no significant differences emerged for target stimuli (mean difference = -0.768 µV, $p = 0.463$, 95% Confidence Interval [-2.399, 0.863]) or standard stimuli (mean difference = -0.595 µV, $p = 0.221$, 95% Confidence Interval [-1.682, 0.492]). Analysis of difference waves at the FCz electrode showed highly significant group differences for Novel-Standard comparisons (t(50) = 4.84, $p < 0.001$), with NH children exhibiting substantially larger amplitudes (M = 14.75 µV, SD = 5.56) compared to CI users (M = 7.34 µV, SD = 5.47), representing a large effect size (d = 1.34).

Pz electrode

Analysis revealed a significant main effect of stimulus type (Wilks' Lambda = 0.161, F(1.65, 49) = 71.937, $p < 0.001$, Greenhouse-Geisser corrected). However, neither the main effect of group (F(1, 50) = 0.190, $p = 0.665$, $\eta^2p = 0.004$) nor the stimulus × group interaction (F(2, 49) = 1.736, $p = 0.181$, $\eta^2p = 0.066$) reached significance. Pairwise comparisons between groups showed no significant differences for novel stimuli (mean difference = -0.393 µV, SE = 1.359, $p = 0.774$, 95% Confidence Interval [-3.088, 2.302]), target stimuli (mean difference = 1.857 µV, SE = 1.311, $p = 0.163$, 95% Confidence Interval [-0.741, 4.456]), or standard stimuli (mean difference = -0.459 µV, SE = 0.453, $p = 0.315$, 95% Confidence Interval [-1.362, 0.444]). Analysis of difference waves Target-Standard differences at the Pz electrode showed non-significant differences (t(49) = 1.83, $p = 0.074$), where NH children (M = 10.32 µV, SD = 4.53) demonstrated slightly larger amplitudes than CI users (M = 8.32 µV, SD = 3.05), with a medium effect size (d = 0.51).

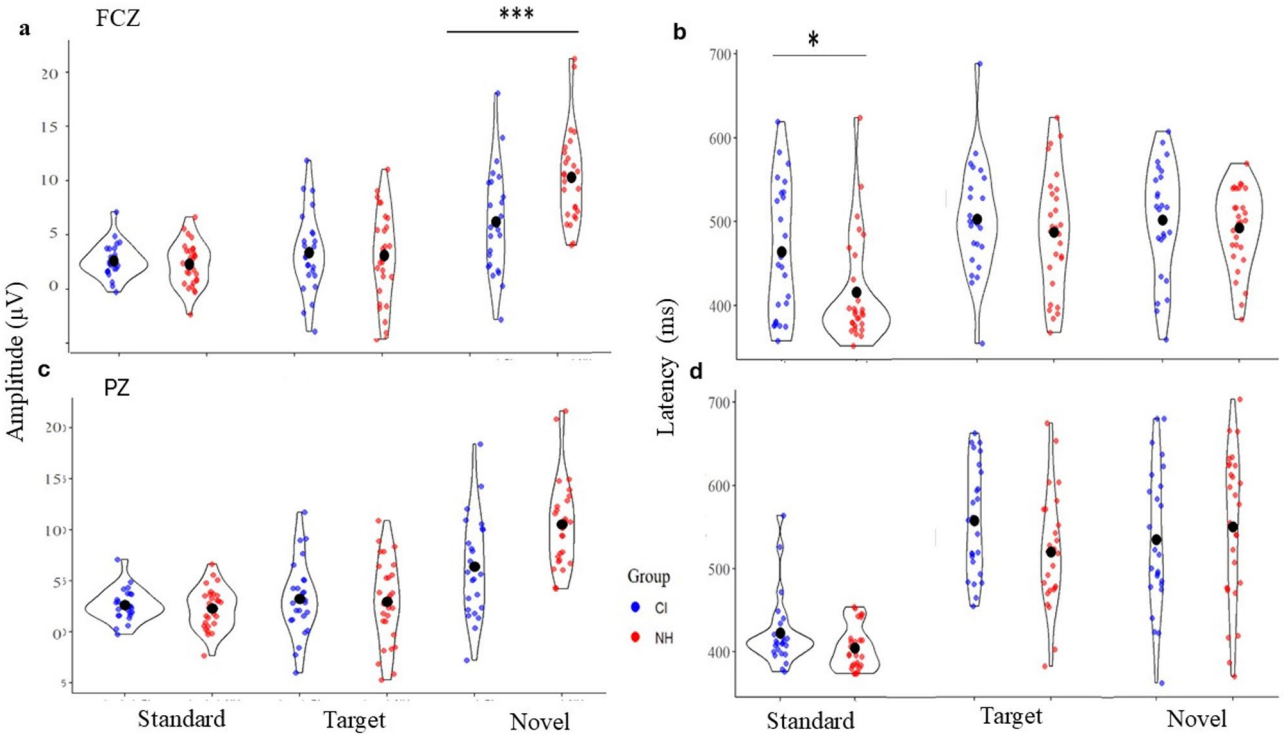

Fig. 2. shows violin plots comparing ERP responses between cochlear implant users (CI, blue) and normal hearing individuals (NH, red) across stimulus types (Standard, Target, and Novel) at two electrode sites. Panels (**a**) and (**c**) display P3 amplitude (μV) at FCZ and PZ electrodes respectively, with significantly higher responses to novel stimuli (***$p < 0.001$) at FCZ. Panels (**b**) and (**d**) present P3 latency (ms) at the same electrode sites, with a significant difference (*$p < 0.05$) for standard stimuli. Black dots represent group means, while individual participant data points are shown within each distribution, revealing response variability between groups across different stimulus conditions.

Latency measures

Descriptive statistics, summarized in Table 3, indicated that latency differences between CI and NH groups were most pronounced at the FCz electrode during standard stimulus processing, yielding a moderate effect size ($\eta^2 p = 0.19$). In contrast, analyses at the Pz electrode did not reveal significant between-group differences. These findings are detailed in Table 3 and illustrated in Fig. 2.

FCz electrode

Between-group comparisons revealed significant latency differences during standard stimulus processing ($U = 224.50$, $p = 0.025$, $\eta^2 p = 0.19$), with CI users showing longer peak latencies ($M = 464.32$ ms, $SD = 79.58$) than NH participants ($M = 415.81$ ms, $SD = 63.68$). No significant differences were found for novel (CI: $M = 501.80$ ms, $SD = 67.27$; NH: $M = 492.07$ ms, $SD = 48.19$; $U = 297.00$, $p = 0.345$) or target stimuli (CI: $M = 502.72$ ms, $SD = 65.58$; NH: $M = 486.79$ ms, $SD = 70.82$; $U = 305.50$, $p = 0.428$).

PZ electrode

between-group comparisons showed no significant differences in latencies for novel (CI: $M = 492.07$ ms, $SD = 48.19$; NH: $M = 501.80$ ms, $SD = 67.27$; $U = 318.00$, $p = 0.569$, $\eta^2 p = 0.10$), target (CI: $M = 486.79$ ms, $SD = 70.82$; NH: $M = 502.72$ ms, $SD = 65.58$; $U = 250.00$, $p = 0.075$, $\eta^2 p = 0.11$), or standard stimuli (CI: $M = 415.81$ ms, $SD = 63.68$; NH: $M = 464.32$ ms, $SD = 79.58$; $U = 245.50$, $p = 0.063$, $\eta^2 p = 0.15$).

Correlation analysis of P3 components, clinical, and behavioral measures

Speech-in-noise performance positively correlated with both Novel P3 amplitude at FCz ($r = 0.368$, $p = 0.025$, Confidence Interval [0.091, 0.592]) and Target P3 amplitude at Pz ($rs = 0.400$, $p = 0.0125$, Confidence Interval [0.134, 0.612]), indicating that stronger P3 responses are associated with better speech perception in noise (Fig. 3). In CI users, Forward Digit Span demonstrated a strong positive correlation with Target P3 amplitude at Pz ($r = 0.553$, $p = 0.004$, $pFDR = 0.001$) (Fig. 5). A moderate positive correlation was found between forward digit span and speech-in-noise performance ($rs = 0.512$, $p = 0.009$,95% Confidence Interval [0.147, 0.757]). No significant correlations emerged between RTs and Target P3 latency at the Pz electrode, either in the overall sample ($r = 0.06$, $p = 0.671$) or within the CI group ($r = 0.043$, $p = 0.839$).

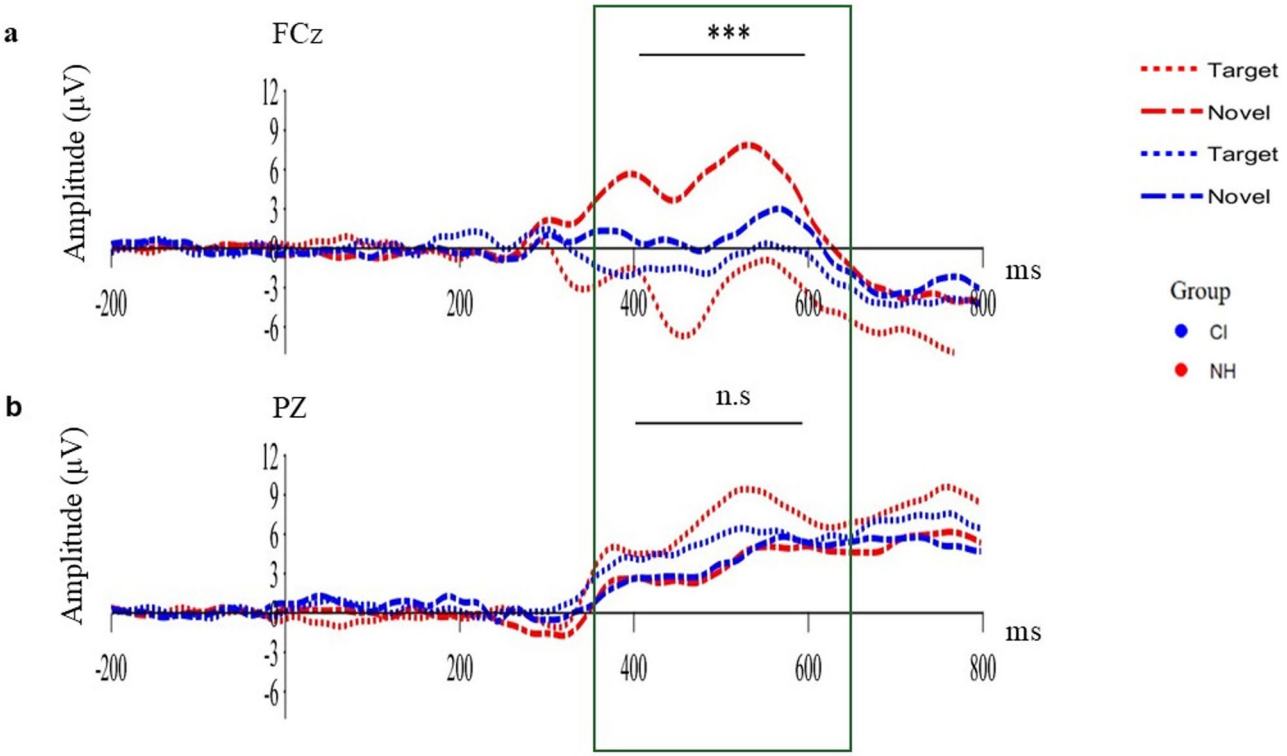

Fig. 3. Event-related potential (ERP) waveforms comparing cochlear implant (CI) users and normal-hearing (NH) individuals during an auditory oddball paradigm. (**a**) At FCz, NH participants (red dashed lines) exhibited substantially larger Novel P3 amplitudes than CI users (blue dashed lines) (***$p < 0.001$). (**b**) At Pz, Target P3 responses (dotted lines) were robust and comparable across groups, indicating preserved controlled attention. Green boxes highlight the time window of interest (350–650 ms) corresponding to the P3 component.

Discussion

Early-implanted bilateral CI children exhibit a distinct neurocognitive profile characterized by preserved controlled attention alongside impaired automatic attention mechanisms. This is the first study to investigate automatic attention processes in pediatric CI users, showing a selective reduction in Novelty P3 despite intact Target P3 responses. These findings complement persistent difficulties in speech-in-noise perception and provide new insight into the neurocognitive consequences of auditory restoration.

Our analysis of unexpected stimulus processing revealed preserved detection but reduced Novelty P3 amplitudes at frontocentral sites, a key marker of involuntary attention capture[17,19,21]. This impairment persisted despite early bilateral implantation, consistent with the notion that automatic attention switching requires intact early auditory input (Kamal et al., 2022[37]. Consequently, CI users may perform adequately in structured settings but struggle in dynamic listening environments. Although absolute sensation levels may differ between CI and NH participants, the preserved Target P3 responses, alongside reduced Novelty P3 amplitudes, indicate that the observed effects are unlikely to stem from audibility differences and instead reflect selective alterations in attention mechanisms.

While our findings provide the first evidence of Novelty P3 responses in pre-lingually implanted children, differences from adult CI studies[26,27,38] should be interpreted cautiously. Such discrepancies may reflect developmental timing as well as methodological factors (task demands, stimulus parameters, or duration of CI use). For instance, Schierholz et al. (2021)[24] showed that post-lingual adults exhibit enhanced N1 and subtle Novelty P3 reductions, suggesting compensatory reallocation at earlier processing stages, a pattern absent in our pediatric cohort. In contrast, our CI group demonstrated intact early N1–P2 responses but attenuated Novelty P3, pointing to selective impairment at later stages. Delayed P3 latencies for standard tones further suggest that predictable input requires greater frontal resources, raising the threshold for automatic attention capture.

In contrast to this impairment in automatic attention, controlled attention mechanisms remained intact. Both groups exhibited robust Target P3 responses at parietal sites, consistent with the typical P3b distribution[18,32]. This provides strong evidence that goal-directed attentional control is preserved in pediatric CI users. Our results extend earlier findings of preserved target processing in smaller CI samples (Beynon et al., 2002[30]; Abrahamse et al., 2021[35] by demonstrating this pattern in a larger, well-matched cohort. Language proficiency may modulate this effect: Deroche et al. (2023)[18] reported that CI users with strong language skills showed parietal P3 responses comparable to NH peers, while those with weaker skills showed reduced responses. Our cohort's preserved

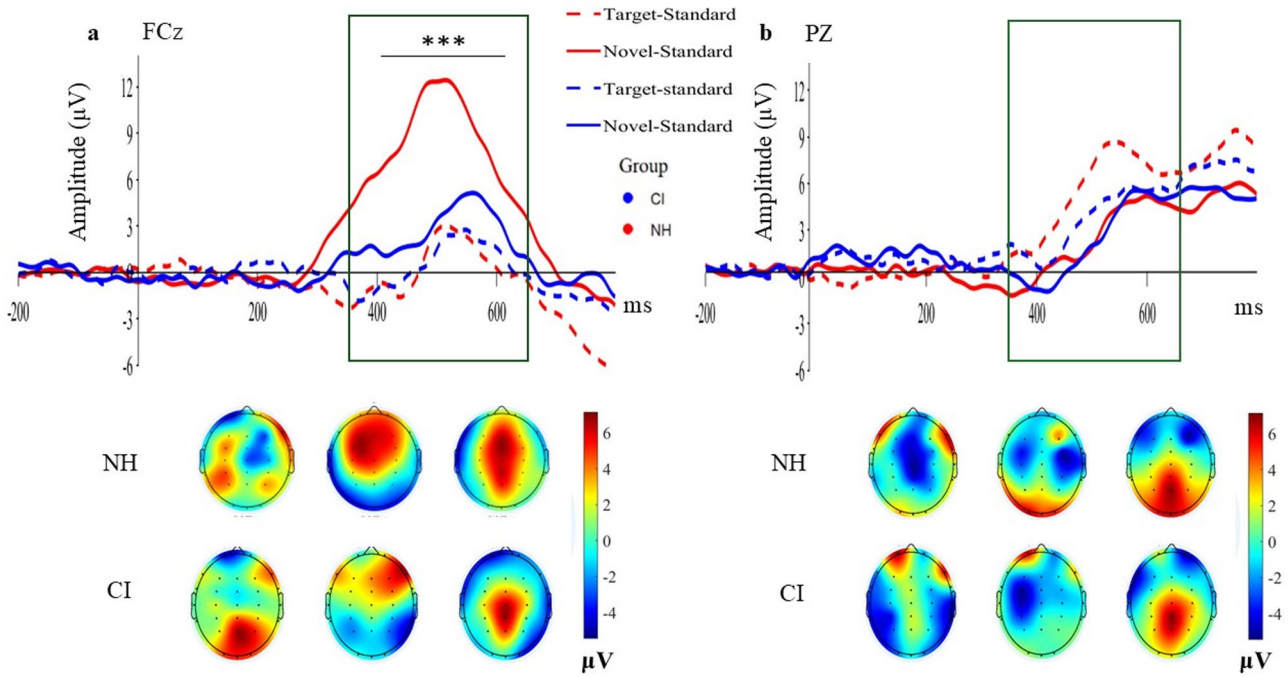

Fig. 4. Event-related potential (ERP) difference waveforms and scalp topography maps comparing cochlear implant (CI) users and normal hearing (NH) individuals during an auditory oddball paradigm. (**a**) FCz electrode recordings showing NH participants (red lines) exhibiting substantially larger amplitude responses than CI users (blue lines) (*** $p < 0.001$), for novel stimuli (~ 12 μV vs. ~5 μV peak). Scalp maps below reveal more pronounced frontocentral activation patterns in NH individuals. (**b**) PZ electrode recordings demonstrating a different pattern where target responses (dashed lines) become more prominent than novel responses (solid lines), with scalp distributions indicating stronger parietal activation. Green boxes highlight the time windows of interest (350–650 ms) corresponding to the P3 component.

Electrode site	Stimuli type	Group	*n*	Mean Rank	Mean (ms)	Sd	Mann-Whitney U	*p*-value	Effect Size $\eta^2 p$
FCz	Novel	NH	28	2.38	492.07	48.19	297.00	0.345	0.14
		CI	25	2.28	501.80	67.27			
	Target	NH	28	2.23	486.79	70.82	305.50	0.428	0.13
		CI	25	2.00	502.72	65.58			
	Standard	NH	28	1.39	415.81	63.68	224.50	0.025*	0.19
		CI	25	1.72	464.32	79.58			
Pz	Novel	NH	28	2.61	547.11	88.8	318.00	0.569	0.10
		CI	25	2.44	532.16	83.97			
	Target	NH	28	2.32	517.59	65.80	250.00	0.075	0.11
		CI	25	2.40	554.72	65.04			
	Standard	NH	28	1.07	404.50	26.07	245.50	0.063	0.15
		CI	25	1.16	422.72	42.66			

Table 3. Descriptive statistics and Mann-Whitney U test Results for latency measurements (novel, target, and standard) at the FCz electrode for both cochlear implant (CI) and normal hearing (NH) groups. *$p < 0.05$.

Target P3, combined with comparable IQ scores, suggests reliance on similar controlled attention resources as high-performing CI groups. Importantly, the inclusion of novel stimuli allowed us to demonstrate a dissociation between controlled and automatic attention, an effect that would be missed in standard oddball paradigms.

The dissociation observed between impaired automatic attention (Novelty P3) and preserved controlled attention (Target P3) is consistent with theoretical models that differentiate stimulus-driven ventral mechanisms from goal-directed dorsal networks[11,39–41]. This framework suggests that CI children compensate for weakened automatic attention by recruiting controlled attention resources. While our study does not provide direct evidence for network-level organization, these interpretations align with compensatory accounts of attentional

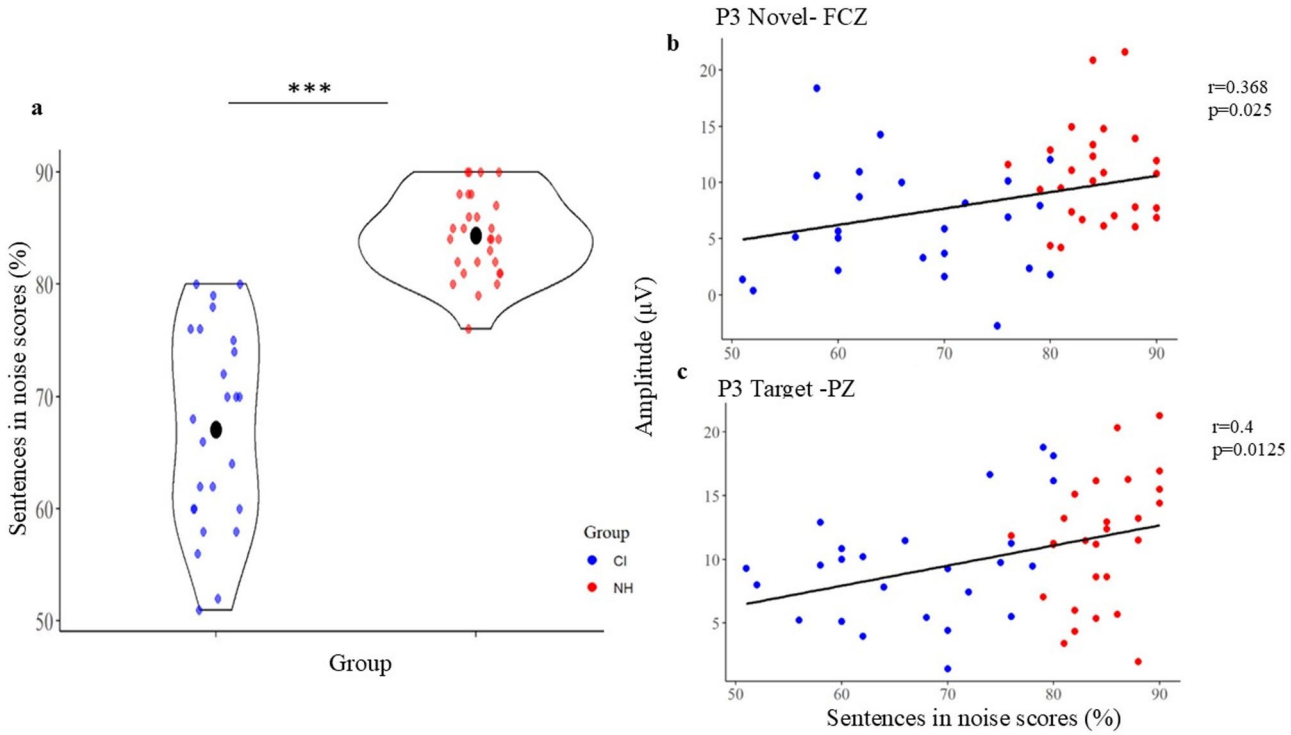

Fig. 5. Correlation between speech in noise and neural responses in cochlear implant (CI) users and normal hearing (NH) individuals. Panel (**a**) displays violin plots showing significantly higher sentences-in-noise scores for NH participants (red, ~ 85%) compared to CI users (blue, ~ 65%), marked with three asterisks indicating strong statistical significance ($p < 0.001$). Panels (**b**) and (**c**) demonstrate positive correlations between speech perception scores and ERP amplitudes: panel (**b**) shows P3 Novel responses at FCz electrode ($r = 0.368$, FDR $p = 0.025$), while panel (**c**) depicts P3 Target responses at Pz electrode ($r = 0.4$, FDR $p = 0.0125$) In NH subjects (red dots) AND CI users (blue dots).

control. Future studies using source localization, fMRI, or connectivity analyses will be needed to directly test this hypothesis.

These neural findings translated into meaningful functional outcomes. Behaviorally, CI children performed significantly worse than NH peers in speech-in-noise, reflecting both device limitations and altered attention. CIs provide limited spectral and temporal resolution[2,7], which interacts with disrupted automatic attention to impair performance in adverse conditions. Importantly, outcome variability was substantial: some CI children performed near-normally, while others continued to struggle despite similar clinical profiles. This heterogeneity likely reflects differences in working memory, neural plasticity, intervention timing, and rehabilitation quality[42–44].

Memory results supported this interpretation. Reduced forward digit span (short-term memory), while backward span (working memory) was preserved, indicated intact central executive processes but compromised phonological encoding[45–47]. Earlier implantation appears to enhance compensatory strategies (Köse et al., 2022[48], which may explain the relative resilience of working memory in our cohort.

Crucially, ERP markers predicted functional outcomes. Larger Novelty P3 responses correlated with better speech-in-noise performance, consistent with the role of this frontal component in indexing attentional resource allocation under degraded input[49,50]. Target P3 amplitudes also correlated with both speech perception and short-term memory, **consistent with findings from** pediatric CI users[34], bimodal users[51], and post-lingually deaf adults[52]. Within the CI group, larger parietal Target P3 amplitudes predicted stronger digit span scores (Vanaja & Sarda, 2019[33], underscoring the interdependence of attention and working memory in supporting speech perception.

A developmental perspective further contextualizes these findings. Unlike post-lingually deaf adults, where Target P3 latency correlates with reaction times (Schierholz et al., 2021[24], our pre-lingually implanted children showed no such relationship, suggesting distinct developmental trajectories of auditory–cognitive integration. These findings should be interpreted cautiously given the narrow age range (7–13 years) and homogeneous early-implantation sample, but they highlight important developmental distinctions in adaptation.

Taken together, our findings establish a coherent neurocognitive profile for early-implanted bilateral CI children. This profile is marked by preserved controlled attention and working memory, but impaired automatic attention capture, alongside persistent challenges in speech-in-noise perception and short-term memory. This dissociation directly addresses the central aim of our study: characterizing auditory attention mechanisms in pediatric CI users. By showing that neural markers of both involuntary and controlled attention predict

functional outcomes, the results bridge laboratory measures with real-world listening difficulties. More broadly, the findings suggest that rehabilitation should move beyond language development and device optimization to also strengthen automatic attention processes, thereby improving speech perception in everyday environments. In this way, our study advances an integrated framework linking neural adaptation, cognitive compensation, and functional outcomes in children growing up with cochlear implants.

Conclusion

The present study demonstrates a clear dissociation in early-implanted bilateral CI children: impaired automatic attention, reflected in reduced Novelty P3, alongside preserved controlled attention, indexed by intact Target P3b. This selective reorganization underscores how early auditory deprivation reshapes attention networks while still allowing compensatory adaptations. Robust correlations between ERP components and behavioral measures further validate P3 responses as sensitive cognitive markers in this population. Despite the benefits of early implantation, certain auditory-dependent cognitive processes remain vulnerable, emphasizing the need for targeted interventions and ongoing monitoring.

Clinical implications

Our findings carry several important implications for clinical practice and technology development. First, rehabilitation programs should incorporate strategies that strengthen automatic attention capture, such as training under dynamic and unpredictable listening conditions. Second, cochlear implant design should prioritize improvements in temporal and spectral resolution to support more efficient automatic attention mechanisms. Third, assessment of pediatric CI outcomes should combine neural and behavioral indices to provide a more comprehensive picture of communicative function and cognitive load. Together, these implications highlight the importance of moving beyond language and audibility alone, toward approaches that also target attentional processes critical for successful everyday listening.

Limitations

Several limitations should be considered when interpreting these findings. The sample size was modest ($n = 25$ CI users) and restricted to a narrow age range (7–13 years), which may limit generalizability. The study employed a single SNR level in the speech-in-noise task, preventing assessment across a range of listening difficulties. EEG was recorded with a 32-channel system, which provided sufficient coverage for ERP analyses but limited spatial resolution for source-level inference. CI device type and processor varied across participants, potentially introducing heterogeneity, and the cross-sectional design did not allow examination of developmental trajectories. Finally, sensation levels were not equated across groups; although converging evidence suggests that audibility alone cannot explain our results, future studies should employ matched sensation-level paradigms for greater control.

Materials and methods

Study population

A total of 56 children were initially recruited through the Pediatric Cochlear Implant Program at Hadassah Medical Centre (CI group) and public recruitment flyers (NH group) in Jerusalem, Israel. Strict inclusion criteria for the CI group required bilateral implantation before age 3.5 years, aided hearing thresholds between 20 and 30 dB HL with both implants, Word Recognition Scores above 75% in quiet with bilateral implants, consistent device use, oral language communication, regular mainstream education placement, and medium to high socioeconomic status (based on maternal education).

General exclusion criteria for all participants (CI and NH) included developmental disorders, neurological disorders, genetic syndromes, cognitive impairments, and non-native speaker status. For the CI group, additional exclusions included device failures and ear pathology. For the NH group, unaided hearing thresholds above 20 dB HL were exclusionary. After applying these criteria (three CI children excluded: two due to technical issues, one due to cochlear malformation), the final sample comprised 53 participants (a 94.6% participation rate), aged 7.04–13.26 years ($M = 9.56$, $SD = 1.86$).

A priori power analysis using G*Power (Version 3.1;[53], based on maximal effect sizes reported in prior auditory processing studies of CI users[24,54], indicated that our sample size was sufficient to detect medium-to-large effects ($f = 0.39$) at $\alpha = 0.05$ with 80% power.

Among the CI group ($n = 25$), 22 received simultaneous implantation and 3 underwent sequential implantation with short inter-implant intervals (0.49, 0.6, and 2.08 years). These brief delays during peak auditory plasticity effectively represent "near-simultaneous" implantation, consistent with evidence showing comparable outcomes to simultaneous procedures[55,56]. The mean age at first implantation was 1.44 years (SD = 0.72; range: 0.47–3.01) and at second implantation was 1.57 years (SD = 0.72; range: 0.61–3.02).

The distribution of cochlear implant systems in our cohort comprised Cochlear™ (Cochlear Ltd., Sydney, Australia; 72%, $n = 18$), MED-EL™ (MED-EL GmbH, Innsbruck, Austria; 24%, $n = 6$), and Advanced Bionics™ (Advanced Bionics LLC, Valencia, CA, USA; 4%, $n = 1$). While the manufacturer distribution was uneven, recent reviews[57] and earlier work (Harris et al., 2011[58] indicate no significant performance differences among current-generation CI systems regarding speech outcomes.

Study procedures

The current study was approved by the Institutional Review Board (IRB) of Hadassah—Hebrew Medical Center in Jerusalem, Israel (approval # HMO-0881-20), and written informed consent was obtained from

all parents or guardians of the participants. The procedure lasted approximately three hours, with breaks provided upon the participants' request. Families received $40 in compensation for their time and effort.

Upon arrival, all participants were given a detailed explanation of the experimental tasks. Demographic and background data were collected through a questionnaire. For the NH group, pure-tone audiometric thresholds were assessed to confirm normal hearing levels in both ears. The following tests were administered during the study: three subscales of the Wechsler Intelligence Scale for Children, 4th edition (WISC-IV;[59], a speech-in-noise test, and EEG recordings.

Outcome measures

The Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV;[59] was administered to assess cognitive functioning in children aged 6 to 16 years. Three key subtests were administered: (i) Vocabulary subtest, measuring verbal knowledge and crystallized intelligence through word definition tasks; (ii) Block Design subtest, evaluating visuospatial organization and fluid intelligence through pattern construction; and (iii) Digit Span subtest, comprising Digits Forward (auditory short-term memory) and Digits Backward (working memory). An estimated Full-Scale IQ was calculated using Block Design and Vocabulary subtests, showing a strong correlation (r = 0.88) with complete WISC-IV administration[60]. Digit Span scores were analyzed separately as measures of memory performance. All assessments were conducted by the primary researcher in a quiet room, with CI participants tested using optimally functioning devices.

Speech perception measures

To assess the perception of spoken sentences, either the Hebrew or the Arabic everyday sentences test for children was utilized ("MELE Sentences")[61,62]. This test comprises 11 lists of 12 sentences each, selected based on criteria from the Central Institute for the Deaf (CID)[63]. The sentences utilize common words, include statements and questions, cover concrete topics, avoid proper names, and vary in length from two to six words. Each list contains yes/no questions, declarative phrases, and imperative sentences. The sentences were recorded by a female native speaker, ensuring authenticity.

Testing was conducted individually in a soundproof room, with participants seated one meter from a loudspeaker at 0 degrees azimuth. Prior to testing, children received a brief training session to ensure they understood the task. Sentences in noise tests were delivered via an Asus laptop connected to the monitor view meter of a GSI audiometer. The sentences were recorded in a female voice using a 44.1 kHz sampling rate and 16-bit resolution. To ensure precision, sentence intensity was calibrated to 65 dB SPL at the participant's location using a sound-level meter and a 1000 Hz calibration tone.

The testing environment simulated challenging listening conditions with a signal-to-noise ratio (SNR) of 0, chosen to avoid floor and ceiling effects based on pilot data from five children with CIs and five NH peers. Subjects were instructed to repeat everything they heard, even if they only understood portions of the sentence. For the everyday sentences test, scoring was based on the number of correct words in each sentence. Each correct word was awarded 2 points, while definitive morphemes in Hebrew/Arabic received 1 point. All responses were scored in real time by the researcher.

EEG recording

Task and stimuli

Participants were seated one meter from the monitor and instructed to remain as still as possible to minimize motion-related artifacts, with an experimenter present to monitor attentiveness. The auditory oddball paradigm consisted of two blocks, each containing approximately 200 stimuli, presented in a randomized order with predetermined probabilities (70% standard tones, 15% target tones, and 15% novel sounds). All stimuli lasted 200 milliseconds with 10-millisecond rise/fall times, while the inter-stimulus interval varied randomly between 800 and 1000 milliseconds. The standard (1000 Hz) and target tones (2000 Hz) were delivered as sinusoidal bursts, while novel stimuli comprised 60 different environmental sounds (e.g., dog barking, door creaking, telephone ringing) that were digitally recorded, low-pass filtered at 10,000 Hz, and normalized to match the tonal stimuli[19,21,24]. All sounds were presented through speakers at 65 dB SPL, with novel sounds appearing only once per block to maintain their unexpected nature.

Both target tones and novel sounds were always preceded by at least one pair of standard tones. Each condition began with a sequence of 10 initial standard tones to establish a stable sensory memory trace of the standard. Prior to the experimental blocks, participants completed a short training session to ensure that children with CI could distinguish between standard and deviant sounds. During the task, participants were instructed to focus on a small fixation cross in the center of the screen and press the space bar on the keyboard with their dominant hand in response to target tones, while ignoring standard tones and novel sounds. Each block lasted approximately five minutes, making the protocol suitable for potential clinical implementation if the necessary equipment was available. The experimental paradigm was implemented using PsychoPy (https://www.psychopy.org/).

Data recording and analysis

Behavioral analysis For behavioral analysis, a correct trial was defined as a button press occurring between 100 and 1200 ms after target presentation. Mean response time (RT) was calculated for each participant based on their correct trials only. Accuracy rates were determined by calculating the percentage of correct responses relative to total target presentations, incorporating both successful target detection (hits) and correct rejection of non-target stimuli (standard tones and novel sounds). Both response times and accuracy rates were subsequently compared between CI and NH groups.

Electrophysiological data A high-density 32-electrode sensor array net was placed on the scalp using the Micromed™ SD 64 system (Mogliano Veneto, Italy), following the 10–20 system (Spes Medica™, Battipaglia, Italy). Data were collected from 32 scalp locations: Fp1, Fp2, F7, F3, Fz, F4, F8, FT7, FC3, FCz, FC4, FT8, T7, C3, Cz, C4, T8, TP7, CP3, CPz, CP4, TP8, P7, P3, Pz, P4, P8, O1, Oz, and O2. The right earlobe (A2) was used as a reference, while the left earlobe (A1) served as the ground. The impedance was maintained below 5 kΩ throughout the recording. Raw data were sampled at a rate of 1024 Hz (EGI net amps 300 system) and stored for offline analysis.

Preprocessing

EEG data analysis was conducted using custom MATLAB (2022) Version R2022b scripts in conjunction with EEGLAB (version 14.0.0)[64]. During the preprocessing phase, channels located near the speech processor and transmitter coil (P7, P8) were excluded, following the same protocol applied to NH participants. Continuous EEG data were downsampled to 500 Hz[65] and re-referenced offline to the average of 28 electrodes. Subsequently, a finite impulse response (FIR) bandpass filter was applied, set between 0.1 and 30 Hz, while preserving the original sampling rate. Following the recommendations by Widmann et al. (2015), FIR filtering was chosen for its zero-phase distortion capability and guaranteed stability, ensuring optimal signal preservation[24,64,66].

Artifacts were identified in a semi-automated manner, with sections of data exceeding 200 μV being automatically removed. Then, a visual inspection was made to identify and exclude sections of EEG traces containing substantial artifacts. Independent components associated with ocular and muscular artifacts were identified using the runica algorithm (via the pop_runica function), informed by visual inspection of scalp topography, power spectra, and time courses[67]. On average, 2.16 ± 0.36 (NH) and 2.12 ± 0.33 (CI) eye-related components were removed, with no significant difference between groups ($t(51) = 0.43$, $p = 0.672$, $d = 0.12$, 95% Confidence Interval [-0.15, 0.23]), facilitating further analysis of the remaining components. The data were then epoched from − 200 to 800 ms relative to sound onset, with baseline correction applied from − 200 to 0 ms. To mitigate electrical artifacts from the CI, we performed independent component analysis (ICA) using the Infomax algorithm on the epoched, sampled data, utilizing the ADJUST plugin[68,69]. CI artifact components, which are several orders of magnitude larger than neural signals, present as systematically occurring amplitude peaks that are independent of brain processes[70–72]. These artifacts were identified based on three key features: localized topographical distribution near the implant site, periodic patterns synchronized with device stimulation, and high-amplitude electrical transients[24,65]. On average, a total of 0 to 2 ICA components were removed during this process. Noisy channels were spherically interpolated, averaging 13 electrodes (SD: 0.89; range: 0–3 electrodes). Further artifact rejection was conducted automatically, excluding trials with voltages exceeding ± 120 μV using ERPLAB. After completing all artifact rejection steps and excluding these trials, we found no significant differences between groups in terms of the number of accepted trials for ERP analysis. 93.55 ± 5.05% (NH) and 94.43 ± 3.94% (CI) of trials were accepted for analysis, with no significant difference between groups ($t(51) = -0.70$, $p = 0.486$, $d = 0.19$, 95% Confidence Interval [-3.40, 1.64]).

EEG data analysis

ERP analyses were conducted using the ERPLAB toolbox, an open-source plugin for EEGLAB[73], at both individual and group levels for Standard, Target, and Novel stimuli. Although EEG was recorded using a 32-electrode montage, statistical analyses focused on two midline sites, selected on both theoretical and empirical grounds. FCz (frontocentral) was used for Novel P3 analysis, reflecting maximal responses to unexpected sounds and automatic attention orientation. In contrast, Pz (parietal midline) was used for Target P3 analysis, reflecting maximal responses to task-relevant detection. This selection was supported by prior work showing strongest Novel P3 effects at FCz[27] and maximal Target P3b effects at Pz[32], as well as by visual inspection of our grand-average waveforms. Restricting analyses to these well-established midline maxima reduced the number of multiple comparisons and enhanced interpretability, while the full 32-electrode array remained essential for high-quality data acquisition, artifact rejection, and topographic verification. In pediatric and CI populations, such an approach is particularly important, as it mitigates noise from inter-individual variability and increases sensitivity to group-level effects. At the same time, recording with a full array ensured robust preprocessing (e.g., artifact rejection, ICA), confirmed expected scalp distributions, and preserved flexibility for future analyses or data sharing. This approach strikes a balance between methodological rigor and reproducibility, aligning with best practices in developmental ERP research. For P3 quantification, a 350–650 ms post-stimulus time window was applied, consistent with prior literature[19,24,27,32]. Amplitudes were extracted as mean activity within ± 10 ms around local maxima, with automatic peak detection performed in the defined window. Difference waves (novel minus standard) were calculated for Novelty P3.

Earlier auditory components were also analyzed at FCz, where the N1–P2 complex is typically maximal[18]. The N1 was measured in the 150–250 ms window and the P2 in the 250–350 ms window, based on established literature and visual inspection of our waveforms. Baseline correction was applied, and averages were computed separately for each stimulus type and participant to ensure adequate trial counts.

Statistical analysis

All analyses were conducted using IBM SPSS Statistics version 29 (IBM Corp., Armonk, NY). Outliers were identified using the interquartile range (IQR) method[74], defined as values outside [Q1–1.5 × IQR, Q3 + 1.5 × IQR]. This procedure identified approximately 1% of values as outliers across both CI and NH groups. Missing data rates were minimal (< 1%).

Normality was assessed with Shapiro–Wilk tests and Q–Q plots. Most neural and demographic variables were normally distributed ($p > 0.05$), but non-normal distributions were detected for two neural parameters (standard stimulus latencies at FCz and Pz), two demographic variables (age and implant age), and two

behavioral measures (speech-in-noise scores and accuracy rate). Log_{10} and Yeo–Johnson transformations were attempted, but several measures remained non-normal. Accordingly, analyses combined parametric and non-parametric tests as appropriate.

Demographic comparisons between groups were performed using independent-samples *t*-tests for age and IQ, and chi-square tests for sex and socioeconomic status. For behavioral measures, reaction times (RT) for target stimuli were analyzed with independent-samples *t*-tests, while non-normal variables (speech-in-noise and accuracy rates) were assessed with Mann–Whitney U tests. Working memory was examined using a 2×2 mixed ANOVA with group (NH, CI) as the between-subjects factor and memory task (forward vs. backward digit span) as the within-subjects factor, enabling tests of both main effects and interactions.

Neural responses were analyzed separately for amplitudes and latencies. Amplitude analysis used repeated-measures ANOVA with electrode site (Pz, FCz) and stimulus type (novel, target, standard) as within-subject factors, and group (CI, NH) as the between-subject factor. Multivariate tests (Pillai's Trace, Wilks' Lambda) were reported, with Mauchly's test used to verify sphericity. Significant effects were followed by pairwise comparisons. Latency analyses employed non-parametric methods: within-group effects were tested using Friedman tests for each electrode site, and between-group differences with Mann–Whitney U tests. Partial eta-squared (ηp^2) was calculated from chi-square values using $\eta p^2 = \chi^2 / (\chi^2 + (n - 1))$[75]. Difference waveforms were computed by subtracting ERP responses to standard distractors from those elicited by novel distractors (FCz) and by target distractors (Pz), and these were compared between groups using independent-samples *t*-tests.

For the N1–P2 complex, amplitudes (peak-to-peak P2–N1) and latencies were compared between CI and NH groups at the FCz electrode using independent-samples *t*-tests. Correlations between neural measures (Novelty P3 at FCz and Target P3 at Pz) and behavioral outcomes were examined with Pearson's correlations for normally distributed variables (RT, digit span, implant duration) and Spearman's rho for non-normal variables (age, implant age, speech-in-noise, accuracy rate). To control for multiple comparisons across neural parameters (Pz target amplitude and latency, FCz novel amplitude and latency), a False Discovery Rate (FDR) correction was applied.

Effect sizes were reported using Cohen's *d* for *t*-tests, *r* for Mann–Whitney U tests, and partial eta-squared (ηp^2) for ANOVAs. Statistical significance was set at $p < 0.05$ (two-tailed).

Data availability

The original contributions presented in the study are included in the article; further inquiries can be directed at the corresponding authors.

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Author contributions
O.B.-Z. designed the research, collected the data, analyzed the data, and wrote the manuscript. O.D.-K. contributed to conceptualizing the project and methodology, analyzed the data, wrote, reviewed, and edited, and supervised. H.M. contributed to conceptualizing the project and methodology. J.A. contributed to project conceptualization, methodology, writing, review and editing, data interpretation, and supervision. C.A. contributed to data collection and supervision, and writing, review and editing.

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Declarations

Competing interests
The authors declare no competing interests.

Conflict of interest
The authors declare no conflicts of interest.

Institutional review board statement
The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (IRB) of Hadassah—Hebrew University Medical Center in Jerusalem, Israel (approval # HMO-0881-20, 8 February 2021).

Informed consent
was obtained from all subjects involved in the study.

Additional information

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