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Speech Perception in Noise and Auditory Temporal Processing in Pediatric Hearing Aid Users

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Abstract

Introduction:

Children with sensorineural hearing loss (SNHL) may experience difficulty understanding speech in noisy environments despite appropriate hearing aid (HA) fitting. The underlying contributions of temporal processing, cognitive factors, and the timing of rehabilitation remain poorly understood. The study aimed to evaluate speech perception in noise among children with SNHL and rehabilitated with HAs and to assess its relationship with temporal processing and other factors, including cognitive abilities, language abilities, and age of rehabilitation with HAs.

Materials and Methods:

This cross-sectional study included a cohort of 40 children (20 hearing-impaired children using HAs and 20 age- and sex-matched normal-hearing controls). All participants underwent basic audiological evaluation, cognitive evaluation, language assessment, speech-in-noise (SIN) test, and temporal processing tests, including the pitch discrimination test, pitch pattern sequence test, and auditory fusion test-revised.

Results:

The hearing-impaired group showed poorer performance than the control group across all measures of the SIN test and temporal processing. In the hearing-impaired group, SIN test scores demonstrated significant correlations with temporal processing measures, as well as with cognitive and language scores. Earlier HA fitting and longer HA use were associated with better performance.

Conclusion:

Despite adequate amplification, children with SNHL demonstrate reduced speech perception in noise performance, which appears to be related to temporal processing. These findings suggest that functional listening outcomes may extend beyond peripheral audibility and that early and sustained HA use may contribute to improved auditory performance. The study indicates the potential importance of incorporating central auditory processing assessment in pediatric HA users.

Keywords: Sensorineural hearing loss; Speech perception in noise; Auditory Temporal processing; Hearing aids; Cognitive ability; Language abilities

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Introduction

Hearing loss (HL) is the most prevalent sensory impairment in the world. A significant percentage of people suffering from disabling HL are the pediatric population (1). HL in children, based on its etiology, can be classified as either genetic or non-genetic. Genetic HL may be present at birth or developed later in life and is further classified into syndromic and non-syndromic forms. Acquired non-genetic HL causes include infections, ototoxic medications, prematurity, and others (2,3).

Sensorineural hearing loss (SNHL) can adversely affect a child's overall quality of life, particularly by hindering speech and language acquisition. Children with impaired hearing often show slower language development and reduced communication skills compared to those with normal hearing (2,4).

Early identification and management of HL are essential to support proper developmental outcomes in children, as timely intervention promotes the development of speech, language, and auditory skills. Newborn hearing screening programs are now used to detect infants who may have hearing impairment and who need counseling, hearing amplification devices, or cochlear implants (2).

Children classified as hard of hearing, typically having a pure tone average between 25 and 75 dBHL in their better ear, are generally not considered candidates for cochlear implants. With appropriate support such as hearing aids (HAs) and speech-language therapy, these children are usually able to develop language skills (5). Most human communication occurs through spoken language across diverse everyday listening environments. Individuals with HL frequently report difficulty understanding speech, especially in situations where there is competing background noise (6).

Speech-in-noise assessments can accurately assess hearing ability and the benefit of amplification in settings that simulate real-world listening situations (7). Although many children using appropriately fitted HAs may comprehend speech in quiet conditions at a level comparable to their normal-hearing peers, only a small number can perform similarly in noisy backgrounds (8). The persistence of speech-perception difficulties in noisy environments despite amplification highlights the need to explore the factors that influence speech recognition in challenging listening environments.

Understanding speech in noisy conditions is influenced by multiple factors, including the listener's ability to accurately extract the spectral and temporal acoustic cues within the speech signal. Distortion of spectral and temporal processing sensitivity is one of the mechanisms by which HL affects speech recognition, especially in noise, even when the speech is clearly heard. Because HA signal processing can substantially modify the acoustic cues in speech, individuals may require a period of adjustment to adapt to these alterations (9,10). Nevertheless, the extent to which HA use promotes adaptive neuroplasticity underlying speech understanding in noise remains uncertain (11). In addition to auditory factors, linguistic and cognitive abilities play a critical role in how effectively a listener can interpret speech in complex acoustic environments (8).

Speech understanding in noise is a complex task that relies heavily on central auditory processing (CAP) mechanisms, which encompasses the efficiency with which the central nervous system utilizes auditory information. Within CAP, auditory temporal processing—the processing of acoustic stimuli over time—is fundamentally critical. However, temporal processing is not a single skill; it comprises distinct sub-profiles (12). To capture these varying dimensions comprehensively, this study utilized three specific behavioral measures, each serving a distinct diagnostic rationale. The pitch discrimination test (PDT) was selected to evaluate basic acoustic frequency discrimination. The pitch pattern sequence (PPS) test was utilized to assess temporal ordering and pattern recognition, tasks that uniquely require intact interhemispheric transfer via the corpus callosum for linguistic labeling. The Auditory Fusion Test-Revised (AFT-R) was employed to isolate temporal resolution (specifically gap detection thresholds), reflecting the auditory system's capacity to resolve rapid acoustic envelope changes. Despite its clinical significance for social and academic integration, limited data are available regarding the interaction between speech perception in noise and these specific, multi-dimensional temporal processing abilities

in pediatric HA users, particularly within the phonological and lexical constraints of the Arabic language. Therefore, the aim of this study was to evaluate speech recognition abilities in noise in children with SNHL rehabilitated with HAs and to analyze their relationship with distinct temporal processing sub-profiles while accounting for contributing cognitive and linguistic factors. We hypothesized that children with SNHL, despite achieving adequate peripheral audibility via HAs, would exhibit deficits in specific temporal processing domains and that these underlying temporal deficits would independently predict reduced speech perception performance in noisy environments.

Materials and Methods

Study Design and Participants

This cross-sectional study included 20 children with SNHL using HAs (study group) and 20 age- and sex-matched children with normal hearing (control group).The study group included 20 hearing-impaired children using HAs. Children with mild to severe SNHL who were fitted with HAs and who demonstrated a satisfactory aided pure tone average response, speech perception in quiet above 60% on a monosyllabic word list, and an intelligence quotient (IQ) ≥ 80 were included in the study. Children with conductive or mixed HL, those with known neurological, psychological, or cognitive disorders, any history of otologic surgery, or delayed language development were excluded. The study was carried out between December 2024 and December 2025.

Ethical Considerations

This study was carried out at tertiary-level healthcare facility outpatient clinics after ethical approval. The Ethics Committee of our institution (IRB NO: 00012098 - FWA NO: 00018699) approved this study (Approval serial number: 0108659). The approval process followed the guidelines set out in the Declaration of Helsinki and the Belmont Report. We secured informed consents from all study participants' guardians.

Procedures and Measures

All participants were subjected to the following:

Phoniatric assessment:

- Language Abilities Assessment: The Arabic Language Test was used to evaluate each child's expressive and receptive skills, semantics, prosody, and pragmatics, ensuring age-appropriate language development, with each child's total score used in the analysis (13).
- Phonology Test: Children named pictures to assess speech sound production. Errors were analyzed by word position (initial, medial, and final), and each child's total errors and phonological processes were recorded (14).
- Psychometric Evaluation: The Stanford-Binet Intelligence Scales was used to assess intellectual functioning across verbal, quantitative, abstract/visual reasoning, and short-term memory domains (15).

History taking:

History taking included collecting personal data such as age and sex, followed by a detailed review of prenatal and natal factors, including hypoxia, low birth weight, hyperbilirubinemia, intrauterine infections, prematurity, consanguinity, and any family history of HL. Information about the etiology of HL (when known), the age of diagnosis of HL, the age at amplification, and the duration of HA use were also obtained.

Otoscopic examination was done to ensure normal external auditory canal and tympanic membrane.

Basic audiological evaluation:

- Immittancemetry: Immittancemetry was conducted using the AT235 tympanometry (Interacoustics, Denmark).
- Pure tone audiometry (PTA): Peripheral hearing sensitivity was evaluated for all participants in a sound-treated chamber using the AD629 diagnostic audiometer (Interacoustics, Denmark) to obtain air- and bone-conduction thresholds. For children with hearing loss, aided free-field thresholds were measured at 250–4000 Hz using loudspeaker presentation at 0° azimuth and 1 m distance to assess HA performance.
- Speech audiometry: It was done for all participants. Speech audiometry included measurement of speech reception thresholds (SRT) using Arabic disyllabic lists and speech recognition scores (SRS) using monosyllabic word lists presented at suprathreshold levels. For children with hearing loss, aided speech audiometry was conducted in a free field using loudspeaker presentation at 0° azimuth and 1 m distance.

Speech-in-noise (SIN) test:

The test was based on the Speech Intelligibility

in Noise test for children, using 20 semantically meaningful Arabic sentences designed to match the vocabulary level of the target pediatric age group (16). The test was carried out while using the HAs in the hearing-impaired group. The first ten sentences were presented with white noise and the remaining ten with cafeteria noise, with both speech and noise delivered at 40 dB SL (sensation level) through a loudspeaker positioned 1 meter in front of the listener at 0° azimuth in a sound-treated room. The signal-to-noise ratio (SNR) was 0 dB. Performance was calculated as the percentage of correctly identified words per sentence, and the final score for each noise type was obtained by averaging the percentages across its ten sentences. To minimize potential examiner bias during behavioral testing and scoring, behavioral CAP assessments were administered and scored by an audiologist blinded to the children's specific language test results, IQ scores, and exact metrics of HA history.

Temporal processing tests:

Children wore their HAs during testing. Each child received training before the test to ensure task familiarity, and this training was not included in scoring. Test materials were presented at 40 dB SL through a loudspeaker positioned 1 meter away at 0° azimuth. To reduce fatigue and maintain optimal attention and performance, children were given a 10-minute break between assessments.

- Pitch discrimination test (PDT): The test comprised twenty pairs of 500-ms tones separated by a 300-ms interval, using two frequencies—880 Hz (low) and 1122 Hz (high)—to form four combinations (LH, LL, HL, HH). Participants were instructed to judge whether each pair contained the same or different tones, and responses were scored as the percentage of correct identifications (17).
- Pitch pattern sequence Test (PPS test): The test included 60 frequency patterns, each consisting of three 500-ms tones separated by 300-ms intervals, using two frequencies: 880 Hz (low) and 1122 Hz (high). Each pattern contained two identical tones and one different tone, forming six possible combinations (LLH, LHL, LHH, HLH, HLL, HHL) (18). Children were asked to verbally identify the pattern they heard (e.g., "fat–thin–fat" to represent a low–high–low pattern). Scores were calculated as the percentage of correctly identified patterns.
- Auditory fusion test-revised (AFT-R): To evaluate the temporal resolution (gap detection), AFT-R was used. Pairs of tonal stimuli were given at five frequencies (250 to 4000 Hz) with the interpulse interval varying between 0 and 40 msec. Participants were asked to detect the perception of either one or two tones. The auditory fusion threshold was taken as the mean inter-pulse interval at which 2 tones were judged to be 1 during ascending and descending runs (19).

Statistical analysis of the data:

Data analysis was carried out using the IBM SPSS software package (version 20.0; Armonk, NY: IBM Corp., 2011 release). Normality of distribution was assessed with the Shapiro-Wilk test. The Chi-square test was used to compare categorical variables. Continuous variables were compared between the two groups by student t-test for parametric data and Mann–Whitney U-test for non-parametric data. For correlation analyses, the Pearson correlation coefficient was used for parametric variables, and Spearman's rank correlation coefficient was used for non-parametric variables. Partial correlation analyses were conducted to assess the independent relationships between primary study variables while statistically controlling potential confounding factors. Statistical significance was set at $p < 0.05$. Bonferroni correction was applied where appropriate to account for multiple comparisons. Effect sizes were computed to assess the magnitude of between-group differences.

Results

The sample comprised 20 children in the hearing-impaired group and 20 children in the control group. Males constituted 60% of cases and 65% of controls, while females represented 40% and 35%, respectively. Sex distribution was comparable between both groups ($\chi 2 = 0.107$, $p = 0.744$).

Participants in both groups ranged in age from 9 to 15 years. The mean age of the hearing-impaired group was 11.50 ± 2.01 years, and that of the control group was 11.55 ± 1.76 years. No significant difference in age was observed between the two groups ($p = 0.934$). The mean age at HL diagnosis was 2.90 ± 1.67 years. At the time of the study, the mean duration of HA use was reported as 7.03 ± 2.91 years. The HAs utilized were distributed among three main

models: Oticon Dynamo SP4 behind-the-ear (BTE) (35.0%, N=7) and Oticon Xceed 3 Up BTE (35.0%, N=7) represented the most common devices, followed by Danalogic Ambio 88 BTE (20.0%, N=4), with a minority using Beltone TST CIC6 UP Completely-in-Canal (CIC) device (10.0%, N=2). CIC users' average age was 13.5 years. The hearing-impaired group showed significantly higher PTA thresholds in both ears than controls ($p < 0.001$), with mean values of approximately 57 dB HL for the hearing-impaired group versus 13.5 dB HL in controls. The distribution of HL degrees in the hearing-impaired group was primarily concentrated in the moderate (30%) to moderately severe range (52.5%); the mild degree of HL represents 15%, and the severe degree of HL represents 2.5%. Comparison of the SRS between the two groups using the Student t-test demonstrated a highly significant difference ($p < 0.001$) for both ears.

The hearing-impaired group showed significantly lower SRS, with mean values of 77.0 ± 6.07% in the right ear and 76.80 ± 6.30% in the left ear, compared with 98 ± 2.05% for both ears in the control group. The hearing-impaired group demonstrated functional aided performance, with mean aided PTAs of approximately 28 dB HL in both ears and a mean aided SRT of 28.75 ± 3.58 dB HL. Aided SRS in quiet was excellent, with a mean aided score of 91.60 ± 4.28%.

SIN test scores were significantly lower in the hearing-impaired group than in the control group under both white noise and cafeteria noise conditions ($p < 0.001$) (Table 1). Moreover, performance in cafeteria noise was poorer than that in white noise in both groups ($p < 0.05$), indicating greater difficulty in a fluctuating, real-world noise environment. Independent samples t-tests revealed large effect sizes for SIN deficits in the hearing-impaired cohort.

Table 1. Comparison of speech-in-noise (SIN) test scores between the hearing-impaired group and control group

		Hearing-impaired (n = 20)	Control (n = 20)	t	p
White noise (%)	Min. – Max.	57.0 – 92.0	92.0 – 99.0	7.507*	<0.001*
	Mean ± SD.	74.18 ± 12.82	95.90 ± 1.79		
Cafeteria noise (%)	Min. – Max.	56.0 – 90.0	90.0 – 96.0	7.236*	<0.001*
	Mean ± SD.	72.35 ± 12.50	92.73 ± 1.49		

SD: Standard deviation; t: Student t-test; p: p value for comparing between the two studied groups; *: Statistically significant after Bonferroni correction (adjusted significance threshold $p \leq 0.025$)

Comparison of the PDT and PPS tests between the two groups revealed highly significant differences ($p < 0.001$) for both measures. For the PDT, the mean score for the hearing-impaired group was 89.25±4.94%, which was significantly lower than the control group's mean score of 96.25±3.58 (Mann Whitney U = 55.500) (Figure 1). The Mann-Whitney U test indicated a large effect size.

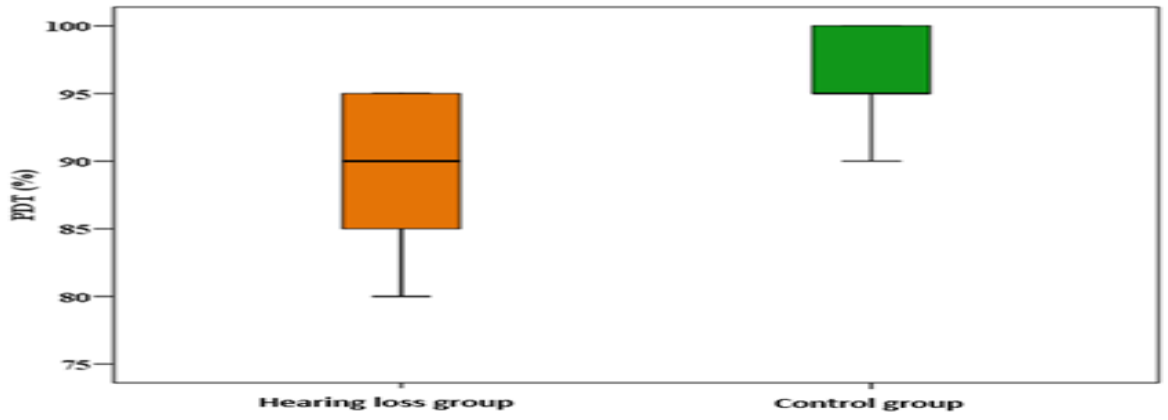

Fig 1. Comparison of pitch discrimination test (PDT) between the hearing-impaired group and control group

Similarly, on the PPS test, the mean score for the hearing-impaired group was 79.25 ± 5.23, which was significantly lower than the control group's mean (91.41 ± 3.79) (Student t = 8.421, $p < 0.001$). The Student's t-test demonstrated a large effect size, with a Cohen's d of 2.66. The Student's t-test comparison of the AFT-R between the hearing-impaired group and the control group revealed a highly significant difference ($p < 0.001$) for all frequencies tested (Figure 2). The post-hoc effect sizes were large.

In the hearing-impaired group, SIN test scores showed strong positive correlations with PDT and PPS test performance as well as moderate to strong negative correlations with AFT-R thresholds across all frequencies (Table 2). Following Bonferroni correction (adjusted $p \leq 0.0036$), the control group SIN test scores retained significant associations with PDT, PPS, and high-frequency AFT-R measures, although these correlations were generally weaker than those observed in the hearing-impaired group.

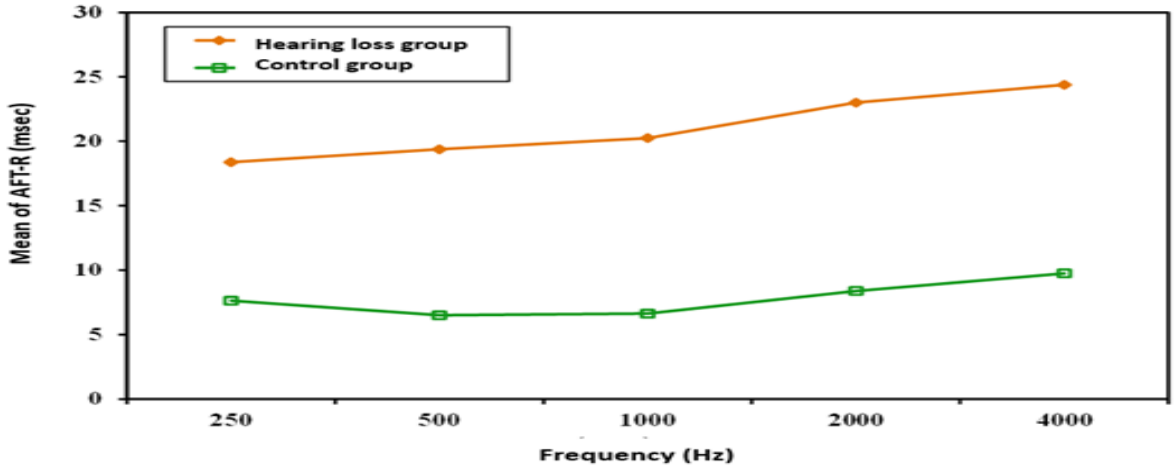

Fig 2. Comparison of auditory fusion test-revised (AFT-R) between the hearing-impaired group and control group

Table 2. Correlation speech-in-noise (SIN) test with temporal processing tests in hearing-impaired group (n = 20)

SIN	White noise (%)		Cafeteria noise (%)	
	Correlation Coefficient	p	Correlation Coefficient	p
PDT (%)	r_s= 0.791	<0.001*	r_s= 0.796	<0.001*
PPS test (%)	r= 0.805	<0.001*	r= 0.814	<0.001*
AFT-R (msec)				
250 Hz	r= -0.728	<0.001*	r= -0.732	<0.001*
500 Hz	r= -0.759	<0.001*	r= -0.767	<0.001*
1000 Hz	r= -0.809	<0.001*	r= -0.811	<0.001*
2000 Hz	r= -0.736	<0.001*	r= -0.740	<0.001*
4000 Hz	r= -0.724	<0.001*	r= -0.726	<0.001*

r_s: Spearman's rank correlation coefficient; r: Pearson coefficient; *: Statistically significant after Bonferroni correction (adjusted significance threshold $p \leq 0.0036$); SIN: Speech-in-noise; PDT: Pitch discrimination test; PPS test: Pitch pattern sequence test; AFT-R: Auditory fusion test- revised

To examine the independent contribution of temporal processing to SIN performance in the hearing-impaired group, partial correlations were conducted, controlling separately for IQ and language test scores. The reduction in correlation coefficients was greater when controlling for IQ than for language; however, most correlations remained statistically significant (Tables 3 and 4). Furthermore, to isolate the effects of CAP from peripheral hearing loss severity, partial correlations were executed between SIN scores and temporal processing measures, controlling for the baseline unaided PTA of the participants. After controlling for hearing loss severity, the correlations remained significant, confirming that auditory temporal processing deficits independently impact speech perception in noise regardless of the baseline degree of SNHL.

Table 3. Partial Correlation between SIN test with temporal processing tests after controlling for IQ scores in hearing impaired group (n = 20)

SIN	White noise (%)		Cafeteria noise (%)	
	Coefficient	p	Coefficient	p
PDT (%)	0.563*	0.012*	0.538*	0.017*
PPS test (%)	0.588*	0.008*	0.600*	0.006*
AFT-R (msec)				
250 Hz	-0.429	0.067	-0.429	0.067
500 Hz	-0.454	0.051	-0.463*	0.046*
1000 Hz	-0.512*	0.025*	-0.504*	0.028*
2000 Hz	-0.352	0.139	-0.346	0.146
4000 Hz	-0.338	0.157	-0.329	0.170

Partial Correlation coefficient *: Statistically significant at $p \leq 0.05$; SIN test: Speech-in-noise test; PDT: Pitch discrimination test; PPS test: Pitch pattern sequence test; AFT-R: Auditory fusion test- revised

Table 4. Partial Correlation between SIN test with temporal processing tests after controlling for language test scores in hearing impaired group (n = 20)

SIN	White noise (%)		Cafeteria noise (%)	
	Coefficient	p	Coefficient	p
PDT (%)	0.704*	<0.001*	0.695*	<0.001*
PPS test (%)	0.613*	0.005*	0.632*	0.004*
AFT-R (msec)				
250 Hz	-0.537*	0.018*	-0.545*	0.016*
500 Hz	-0.757*	<0.001*	-0.760*	<0.001*
1000 Hz	-0.722*	<0.001*	-0.726*	<0.001*
2000 Hz	-0.569*	0.011*	-0.577*	0.010*
4000 Hz	-0.551	0.014*	-0.556*	0.014*

Partial Correlation coefficient *: Statistically significant at $p \leq 0.05$; SIN test: Speech-in-noise test; PDT: Pitch discrimination test; PPS test: Pitch pattern sequence test; AFT-R: Auditory fusion test- revised

To confirm whether auditory temporal processing independently predicted speech perception in noise, two multivariable linear regression models were constructed using speech perception in cafeteria noise as the dependent variable. The PPS test was included as the predictor of primary interest, while IQ and Arabic language test scores were entered separately as additional predictors in two separate models. The PPS test was selected because it demonstrated the strongest bivariate correlation with speech perception in noise and served as the representative measure of temporal processing. Separate two-predictor models were fitted to minimize model complexity and reduce the risk of overfitting given the relatively small sample size (n = 20). Across both models, the PPS test remained a significant independent predictor of speech perception in cafeteria noise (Model 1 with IQ: $\beta = 0.554$ and $p = 0.006$; Model 2 with Arabic language test: $\beta = 0.608$ and $p = 0.004$). IQ score approached statistical significance ($p = 0.055$), whereas the Arabic language test was not independently associated with speech perception in noise ($p > 0.05$). Collinearity diagnostics indicated no evidence of multicollinearity in any model. Total IQ scores showed significant correlations with the SIN and temporal processing measures in both groups ($p < 0.001$). In the hearing-impaired group, IQ demonstrated moderate to strong positive correlations with SIN test (Figure 3), PDT, and PPS test scores as well as inverse correlations with AFT-R thresholds across frequencies, whereas the control group showed weaker but significant associations.

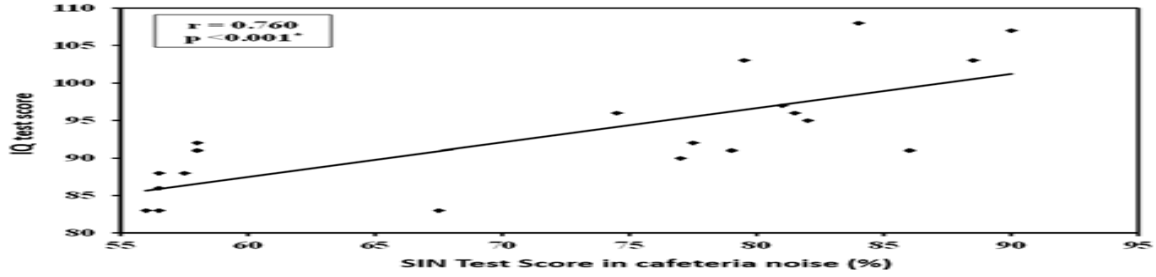

Fig 3. Correlation between speech-in-noise (SIN) test in cafeteria noise and IQ test in the hearing- impaired group

A statistically significant correlation was found between the age at amplification and performance on the SIN test and temporal processing measures.

The duration of HA use showed significant, strong positive correlations with the SIN test, PDT, and PPS test and significant, strong inverse correlations with the AFT-R across several tested frequencies (Table 5). To confirm that the observed correlations were not merely a byproduct of chronological maturation, a partial correlation was performed while controlling for age. The relationship between the HA use duration and SIN scores remained statistically significant ($p < 0.05$).

Table 5. Correlation between duration of hearing aid (HA) use with speech-in-noise (SIN) and temporal processing tests in hearing impaired group (n = 20)

	Duration of HA use (years)	
	Correlation Coefficient	**p**
SIN test		
White noise (%)	r= 0.838	<0.001*
Cafeteria noise (%)	r= 0.848	<0.001*
PDT (%)	r_s = 0.689	<0.001*
PPS test (%)	r= 0.732	<0.001*
AFT-R (msec)		
250 Hz	r= -0.584	0.007
500 Hz	r= -0.648	0.002*
1000 Hz	r= -0.697	<0.001*
2000 Hz	r= -0.673	0.001*
4000 Hz	r= -0.634	0.003*

r_s: Spearman's rank correlation coefficient; r: Pearson coefficient; *: Statistically significant after Bonferroni correction (adjusted significance threshold $p \leq 0.0056$); HA: Hearing aid; SIN test: Speech-in-noise test; PDT: Pitch discrimination test; PPS test: Pitch pattern sequence test; AFT-R: Auditory fusion test- revised

The aided PTA showed no statistically significant correlation with the SIN test, PDT, or PPS test. In contrast, it demonstrated significant positive correlations with the AFT-R at certain frequencies. The right-aided PTA was significantly associated with AFT-R at 2000 Hz ($p = 0.021$) and 4000 Hz ($p = 0.023$). The left-aided PTA showed broader significant correlations with AFT-R, including frequencies at 250 Hz ($p = 0.031$), 1000 Hz ($p = 0.013$), 2000 Hz ($p = 0.030$), and 4000 Hz ($p = 0.003$).

Correlation analysis between aided SRS in quiet and the SIN/temporal processing measures revealed no significant associations with SIN performance, PDT, PPS test, or AFT-R at 500 Hz. In contrast, it showed significant negative correlations with AFT-R thresholds at the remaining frequencies.

A statistically significant correlation was found between Arabic language test scores and performance on the SIN test, PPS test, PDT, and AFT-R at 250 and 1000 Hz in the hearing-impaired group (adjusted $p < 0.0055$).

Correlation analysis demonstrated that phonological ability in the hearing-impaired group was significantly correlated with temporal resolution but not with other temporal processing or SIN measures ($p > 0.05$).

Discussion

The primary purpose of this cross-sectional study was to evaluate speech recognition in noise in children with SNHL using HAs and to examine the relationship between their speech perception in noise performance and various temporal processing measures, while also considering other factors that may influence performance, including language and cognitive abilities. The key findings confirm that, despite achieving excellent SRS in quiet, the hearing-impaired cohort exhibited significant deficits in both speech perception in noise and temporal processing compared with their normal-hearing peers.

The hearing-impaired group demonstrated highly significant differences across all audiological measures when compared to the control group. Importantly, even after achieving effective aided PTA (mean = 28 dB), the hearing-impaired group showed poor performance on the SIN test, PDT, PPS test, and AFT-R. The poor performance of the hearing-impaired group on the SIN test in the present study was consistent with other studies. Goldsworthy and Markle (20) found that HL in children had a substantial negative impact on speech recognition in different types of noise,

especially 2-talker babble. Kocabay et al. (21) found poor performance of adults with SNHL in speech in noise, but the study was done without using HAs.

We used three different tests to evaluate different aspects of temporal processing, including frequency discrimination, temporal ordering, pattern recognition, interhemispheric transfer, and temporal resolution. The poor performance of the hearing-impaired group on auditory temporal assessment in this study was in line with previous research investigating temporal ordering in patients with SNHL (22, 23). This confirms that while HAs restore audibility, they do not fully remediate the underlying central processing deficits, particularly temporal resolution, which is essential for decoding rapid acoustic cues in speech.

We found a robust, significant correlation between SIN test scores and all measures of temporal processing (PDT, PPS test, and AFT-R) in the hearing-impaired group. This is consistent with the hypothesis that degraded temporal processing is a major mechanism contributing to poor speech understanding in noise in listeners with SNHL (24). The strong negative correlation between SIN test scores and AFT-R (temporal resolution) suggests that the ability to rapidly detect and resolve gaps in the acoustic signal directly influences a child's capacity to segregate speech from fluctuating noise. Significant correlations were also found in the control group; however, the higher correlation coefficients in the hearing-impaired group suggest a greater dependence of the auditory system on temporal cues with compromised peripheral input.

Preliminary analyses showed high zero-order correlations between the SIN scores and measures of temporal processing, which could, to some extent, be attributable to shared variance with cognitive and linguistic abilities, as both IQ and language scores correlated positively with SIN performance. These associations may have been further inflated by the relatively small, homogeneous sample and the use of sentence-level stimuli, which engaged both auditory perception and higher-level cognitive and linguistic processing. Partial correlations controlling for IQ and language scores separately yielded larger reductions when controlling for IQ than for language, although most correlations remained significant.

The multivariable regression analyses demonstrated that auditory temporal processing, as represented by PPS test performance, remained independently associated with speech perception in cafeteria noise. The persistence of this association across both models indicates that the relationship between temporal processing and speech perception in noise is robust and is not explained by differences in language or cognitive performance. Although IQ and Arabic language test scores were significantly associated with speech perception in bivariate analyses, neither remained a significant independent predictor in the multivariable models; however, IQ approached statistical significance. These findings suggest that auditory temporal processing explains unique variance in speech perception beyond that accounted for by cognitive and linguistic factors. Nevertheless, given the relatively small sample size, the independent contributions of IQ and language ability should be interpreted with caution and warrant further investigation in larger cohorts.

These findings indicate that cognitive, linguistic, and auditory mechanisms interact synergistically in children with hearing impairment, yet temporal processing exerts a unique, independent role in speech perception. Further research using larger and more heterogeneous samples is needed to confirm the strength and generalizability of these relationships as well as to clarify the relative contributions of auditory, cognitive, and linguistic factors.

A major consideration in the interpretation of these functional outcomes is the potential influence of key confounding variables, most notably the severity of hearing loss at baseline and the technology of the HAs. Peripheral threshold shifts inevitably lead to reduced signal audibility and degraded spectral/temporal fine structure cues. Nevertheless, our partial correlation analysis controlling for baseline unaided PTA demonstrated the independent contribution of central temporal processing deficits to speech perception in noise. Another potential confounder is the variation in technology of the HAs. Complex signal processing features of

modern HAs such as digital noise reduction, dynamic range compression, or directional microphones fundamentally modify the acoustic temporal envelope and spectral cues presented to the auditory cortex. Nevertheless, this heterogeneity reflects routine clinical practice, where HA selection and fitting are individualized according to each child's audiological profile rather than standardized to a single device. Restricting recruitment to users of a single HA model would have reduced the feasibility of enrolling an adequate number of participants and limited the generalizability of the findings. Furthermore, replacing participants' routinely used HAs with a standardized device solely for study testing would likely have introduced adaptation bias, as optimal performance with a new HA typically requires an adaptation period. Consequently, the findings may have greater ecological validity, rendering them more representatives of typical clinical pediatric populations than highly controlled laboratory conditions.

The significant positive correlations found between IQ scores and all temporal processing and SIN test measures support the notion that cognitive resources can play supportive and compensatory roles. It is likely that a greater cognitive capacity is required in a system that is processing degraded auditory input to successfully process complex temporal information and fill in missing acoustic details, particularly in noise (25). Conversely, it has also been reported that hearing loss can affect cognition, and hearing loss causes delay in cognitive abilities (26).

Interestingly, the aided PTA was not significantly correlated with the overall performance on the SIN test, PDT, and PPS test but was significantly correlated with AFT-R at high frequencies (e.g., right aided PTA with AFT-R at 2000 Hz and 4000 Hz). This dissociation suggests that, with the restoration of audibility to functional levels, the SIN deficit may be more dependent on limitations in temporal processing than aided PTA.

Perhaps early and continuous HA usage that greatly enhances SIN scores and temporal processing may be the clinically meaningful finding. The data indicate that early and continuous consistent auditory input is necessary for the central auditory system to develop these abilities because this relation persists even after controlling for age. In the end, this validates the idea of neuroplasticity: early intervention promotes the development of auditory circuits, resulting in better functional outcomes (10, 27).

The correlation between SIN performance and Arabic language test scores underscores the importance of linguistic proficiency in recognizing speech in noisy environments. This is in line with previous studies showing that language ability accounts for a large amount of variance in speech perception in noise performance (28, 29).

Phonology was significantly correlated only with AFT-R, which suggests that phonological development depends on the ability to resolve rapid acoustic changes, a function that is directly assessed by the AFT-R. Alternatively, the lack of correlation between aided SRS in quiet and the other measures (the SIN test, PDT, and PPS test) may be explained by a ceiling effect, with the well-aided hearing-impaired group performing very well on SRS, providing little variation for correlations to be observed with the more difficult speech and temporal tasks.

There are some limitations in this study. First, the cross-sectional design does not allow establishing causality. The observed associations reflect strong structural co-variance rather than definitive direct causation. The unmeasured variables (e.g., working memory, auditory attention, and environmental listening exposure) might account for a portion of the shared variance, particularly within our sample size. Longitudinal studies are required to follow how the duration of HA use improves speech in noise perception and temporal processing. Second, the relatively small sample size limits the generalizability of the results. Future multi-center studies with larger cohorts are recommended to validate these correlations and perform comprehensive multivariable regression modeling to clarify independent predictors of speech-in-noise perception. Third, however, all participants were well-aided; the study did not control for specific HA signal processing variations, which could affect performance in the SIN test. Finally, the highly homogeneous cohort is due to the selection criteria, which included only children with IQ $\geq$ 80 and age-appropriate language development.

While this avoided confounding factors of variable cognitive abilities, these findings may not be generalizable to children with SNHL who present with additional developmental disorders. Addressing these factors in future research will enhance our understanding of the relationship between peripheral hearing and CAP. Prospective interventional studies are needed to determine whether incorporating CAP training into rehabilitation programs can enhance long-term functional outcomes in children with SNHL using HAs.

Conclusion

This study suggests that temporal processing deficits may be related to poor speech perception in noise performance among children with SNHL, even with adequate aided audibility. In addition, language and cognitive abilities may be related to auditory performance in noise. Earlier and longer HA use, potentially reflecting greater cumulative auditory experience, was associated with better speech perception in noise and temporal processing outcomes. The study indicates the potential importance of inclusion of CAP rehabilitation in pediatric HA users.

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