

Correlation between Auditory Spectral Resolution and Speech Perception in Children with Cochlear Implants

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What's Known

- Auditory spectral resolution is an important acoustic component in speech perception.
- Spectral resolution is associated with considerable variability and limitations among users of cochlear implants.

What's New

- Auditory spectral resolution correlated with speech perception in quiet among our children with cochlear implants.
- Spectral resolution ability accounted for about 40% of the variance in speech perception among our children with cochlear implants.

Abstract

Background: Variability in speech performance is a major concern for children with cochlear implants (CIs). Spectral resolution is an important acoustic component in speech perception. Considerable variability and limitations of spectral resolution in children with CIs may lead to individual differences in speech performance. The aim of this study was to assess the correlation between auditory spectral resolution and speech perception in pediatric CI users.

Methods: This cross-sectional study was conducted in Shiraz, Iran, in 2017. The frequency discrimination threshold (FDT) and the spectral-temporal modulated ripple discrimination threshold (SMRT) were measured for 75 pre-lingual hearing-impaired children with CIs (age=8–12 y). Word recognition and sentence perception tests were completed to assess speech perception. The Pearson correlation analysis and multiple linear regression analysis were used to determine the correlation between the variables and to determine the predictive variables of speech perception, respectively.

Results: There was a significant correlation between the SMRT and word recognition ($r=0.573$ and $P<0.001$). The FDT was significantly correlated with word recognition ($r=0.487$ and $P<0.001$). Sentence perception had a significant correlation with the SMRT and the FDT. There was a significant correlation between chronological age and age at implantation with SMRT but not the FDT.

Conclusion: Auditory spectral resolution correlated well with speech perception among our children with CIs. Spectral resolution ability accounted for approximately 40% of the variance in speech perception among the children with CIs.

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Introduction

One of the most important purposes of cochlear implants (CIs) in hearing-impaired children is to provide sufficient acoustic information for good speech perception.¹ Spectral resolution is an important acoustic component in speech perception. This property of the auditory system reflects the listener's ability both to analyze and use the frequency information in complex signals like speech and to discriminate sounds based on their frequency

differences.^{2,3} The available spectral resolution for CI users is degraded by the number of implanted electrodes, electric current dispersion, and the integrity of auditory neurons.⁴ Given the importance of spectral resolution in speech perception and considerable variability and limitations of spectral resolution in CI users, the differences in speech performance among pediatric CI users may be explained by the differences in their spectral resolution abilities.

The spectral ripple discrimination (SRD) task, where spectrally rippled broadband noise is discriminated from another rippled stimulus with the reversal of the position of spectral peaks and valleys, is a valuable and valid tool for spectral resolution assessment.^{5,6} While this test is a broadband assessment of spectral resolution, the frequency discrimination threshold (FDT) is a narrowband evaluation examining spectral resolution in a different way from the first one.^{3,7} Spectral resolution ability tends to improve with age.⁸ Moreover, early degraded auditory input provided by the device restricts the available spectral resolution for pediatric CI users and influences their ability to use spectral cues for speech perception.⁹

The perception of the frequency positions of the peaks in a complex acoustic spectrum is very important for vowel recognition and speech perception.¹⁰ Many studies on CI users by SRD have mentioned a relationship between the discrimination of spectral peaks and speech perception in quiet.^{6,10,11} A study showed a correlation between spectral resolution and consonant-nucleus-consonant word recognition.⁶ In the other study, the SRD threshold was correlated only with sentence perception in quiet. The correlations between SRD and vowel recognition in quiet and sentence perception in noise did not reach a significant level in another investigation.¹²

Speech signals contain the resonant frequencies of the vocal tract, known as “formant frequencies”. The discrimination between these frequencies is an important aspect of vowel and word identification.¹³ The studies on the correlation between speech perception and narrowband spectral resolution via the FDT in CI users have obtained mixed results. While Wei and colleagues¹⁴ revealed a significant relationship between the FDT at 1000 Hz and tone discrimination, Goldsworthy and others¹⁵ mentioned the lack of a correlation between the FDT and phoneme identification.

It is less known whether the correlation between spectral resolution and speech perception in adult CI users, as was mentioned above, exists in pediatric CI users as well. There

are inconsistent data on the developmental trajectory of spectral resolution in children; in addition, higher variabilities of spectral resolution ability are seen in children with CIs than in their adult counterparts.¹⁶ The differences in the mechanisms of the two types of spectral resolution tasks (SRD and FDT) warrant an assessment of both. Accordingly, in the present study, we measured the spectral-temporal modulated ripple discrimination threshold (SMRT) to avoid confounding factors (local loudness cues, shifts in the spectral centroid of the stimulus, and the spectral edge cues) in the traditional SRD task¹⁷ with a view to investigating the correlation between spectral resolution and speech perception in pediatric CI users and determining the predictive power of the two spectral resolution variables in speech perception among these children.

Patients and Methods

Participants

This cross-sectional study was performed in 2017 in Shiraz, Iran. Seventy-five pre-lingual hearing-impaired children with CIs (45 male and 30 female subjects) at an age range of 8 to 12 years (mean=10.26±1.32 y) participated in the study. The sample size was calculated by estimating the effect size from previous data to provide a power of 80% ($\alpha=0.05$ by two-sided test). A sample size of 75 was estimated using the following formula:

$$n = \frac{\left(z_{1-\frac{\alpha}{2}} + z_{1-\beta} \right)^2}{\left(\frac{1}{2} h \frac{1+\rho}{1-\rho} \right)^2} + 3$$

The inclusion criteria consisted of age between 8 and 12 years, pre-lingual hearing impairment, unilateral CIs, and intelligence quotients above 85. The exclusion criteria were the presence of auditory neuropathy and a history of learning disability, developmental disorders, and behavioral or cognitive deficits. The children were implanted in Shiraz CI Center, and they had at least three years of experience with their implants. The mean age at implantation was 3.35±1.06 years. According to the children’s medical history and previous audiologic test results, they had no additional disabilities except hearing loss. The children used the Nucleus device, with a variety of speech processors including Sprint, Freedom, Esprit 3G, and CP810. In addition, the whole study

population had the advanced combinational encoder processing strategy. The parents of all the children gave written informed consent for their children's participation. The study was approved by the Ethics Committee of the University of Social Welfare and Rehabilitation Sciences (Ethics Committee's code: IR.USWR.REC.1395.191), Iran, as a part of a dissertation for a Ph.D. in audiology.

Test Administration

All the children were tested using the regular setting of their own sound processor in a double-walled sound-treated booth. The Angel Sound and SMRT software on an HP Pavilion dv3 laptop were used for spectral resolution tests (<http://angelsound.tigerspeech.com/>; <http://smrt.tigerspeech.com>). Stimuli from the laptop and live-voice speech stimuli from an OB822 Madsen audiometer were delivered to a single loudspeaker (Sony SS-TS53), positioned one meter from the children at 0° azimuth with a BNK BK-222 amplifier in the sound field. The stimuli were presented at an average level of a 65-dB sound pressure level. The level of sound pressure was measured at the position of the head. The order of test presentation was selected randomly. For each subject, all the tests were completed in one day. All the children included in the study completed the tests.

Spectral Resolution Measures

None of the children had any previous experience with psychoacoustic tests. The children were asked to judge different sounds by clicking on one of three icons displayed on a laptop monitor. Prior to assessment, multiple practice trials were completed with the participants to familiarize them with the procedure and software. Feedback was not provided during the test run.

SMRT

The test was performed using the SMRT software. Spectral-temporal modulated rippled broadband noise was used. Acoustic stimuli were 500 ms in duration with 100-ms onset and offset linear ramps. A three-alternative forced-choice (3AFC) paradigm using a one-down/one-up adaptive procedure was used to measure the SMRT, converging on a 50% threshold. In each trial, three ripple noises were presented. Two stimuli were reference signals with 20 ripple/octave (rpo) density, and another stimulus was as a target signal with a lower rpo density. The initial density of the target signal was 0.5 rpo and varied with a step size of 0.2 rpo. The adaptive run was terminated after ten reversals.

The SMRT was calculated across the last six reversals. Three runs were completed for each child, and the final threshold was determined by averaging the three runs.

Frequency Discrimination Test

The test was performed using the Angel Sound software. A 3AFC paradigm using a two-down/one-up adaptive procedure was used to measure the FDT, converging on 71% correct. Each trial consisted of three 300-ms pure tones with a rise/fall time of 10 ms separated by a 500-ms interstimulus interval. Two of the three tones had the same frequency of a 1000-Hz standard, and one was different. The initial frequency difference was 25.6 Hz, and the step size was adjusted for individual subjects. The adaptive run was terminated after 30 trials, with a minimum of four reversals. The FDT was calculated as the average frequency difference across the reversals.

Speech Perception Measures

Natural speech in the auditory-only condition by way of the open-set response method was presented in quiet. No training and feedback were provided.

Word Recognition Test

Two lists of 25 Persian-language phonetically-balanced monosyllabic words were used. The content validity indices for the lists number one and number two were 0.86 and 0.9, respectively.¹⁸ One list was randomly used for each child. The words were presented orally to the children, who were asked to repeat each word immediately after the presentation. The score was calculated as the percentage of the words correctly repeated.

Sentence Perception Test

Eight list pairs containing every-day Persian-language sentences were used. The pairs of each list had two lists, with each list containing 10 sentences. The first sentence had four keywords, and the remaining sentences each had three. The content validity index for the total test was 0.93.¹⁹ One list was randomly used for each child. The sentences were presented orally to the children, who were asked to repeat the sentence immediately after the presentation. The total score was calculated as the percentage of the keywords correctly repeated.

Data Analysis

The percent-correct scores for the speech perception assessments were converted to rational arcsine units (RAUs).

The RAU-transformed scores were used for data analysis. The correlations between each speech score and each spectral resolution score were evaluated using the Pearson correlation analyses. The relationship between chronological age and age at implantation and each spectral resolution score was also obtained through correlation analysis. In addition, a multiple linear regression analysis was performed to determine how much of the variance in the speech scores was explained by the FDT, the SMRT, and the age variables in the children with CIs. The data analyses were completed using SPSS Statistics, version 19.0, and a P value less than 0.05 was considered significant.

Results

Table 1 shows the mean and standard deviation

of the speech and spectral resolution scores in the children with CIs. The correlations between the SMRT, the FDT, chronological age, age at implantation, and two RAU-transformed speech scores are presented in table 2.

As is shown in table 2, there was a significant strong positive correlation between the SMRT and the speech scores. Moreover, the FDT had a significant moderate negative correlation with the speech scores. The correlations were higher for the SMRT than for the FDT. The RAU-transformed word recognition and sentence perception scores are plotted as a function of the SMRT and the FDT in figures 1 and 2. For the correlation between spectral resolution and sentence perception, as to the visual inspection of the data, quadratic terms were included to fit the curves to the data using linear regression, which resulted in a fairly stronger correlation (Figure 2).

Table 1: Distribution of the speech and spectral resolution scores in the children with cochlear implants (n=75)

Score	Mean±SD
Frequency discrimination threshold (Hz)	168.19±78.87
Spectral-temporally modulated ripple threshold (ripple per octave)	2.18±0.97
Word recognition score (percentage of the words correctly repeated)	66.69±18.40
Word recognition score (rationalized arcsine units)	66.18±18.28
Sentence perception score (percentage of the keywords correctly repeated)	76.69±22.87
Sentence perception score (rationalized arcsine units)	78.87±24.59

Table 2: Pearson correlations between spectral resolution, speech, and age variables

	FDT		SMRT		Chronological Age	Age at Implantation
	r	P value	r	P value	r	P value
Word recognition score (RAU)	-0.487*	<0.001	0.573*	<0.001	0.199	0.054
Sentence perception score (RAU)	-0.427*	<0.001	0.556*	<0.001	0.191	0.051
Chronological age	-0.065	0.577	0.243*	0.036		
Age at implantation	0.138	0.237	-0.234*	0.043		

RAU: Rationalized arcsine units; FDT: Frequency discrimination threshold; SMRT: Spectral-temporal modulated ripple discrimination threshold; r: Pearson correlation coefficient; *significant at 0.0

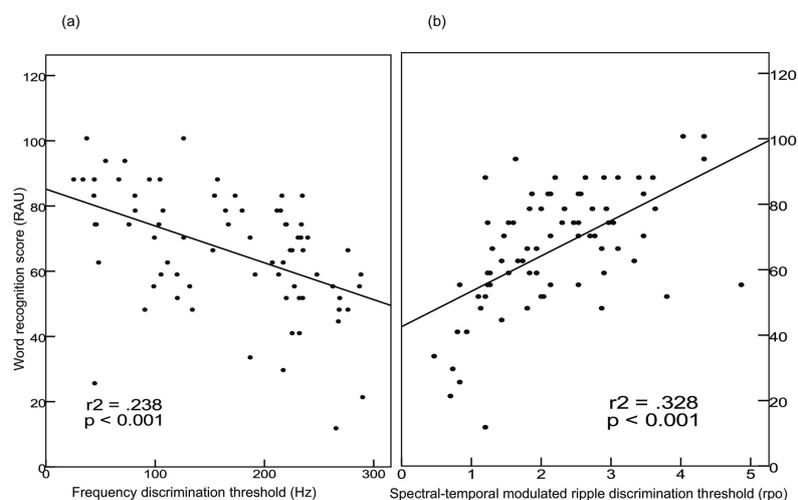


Figure 1: The figure illustrates the word recognition score transformed into rationalized arcsine units as a function of the frequency discrimination threshold (a) and the spectral-temporal modulated ripple discrimination threshold (b)

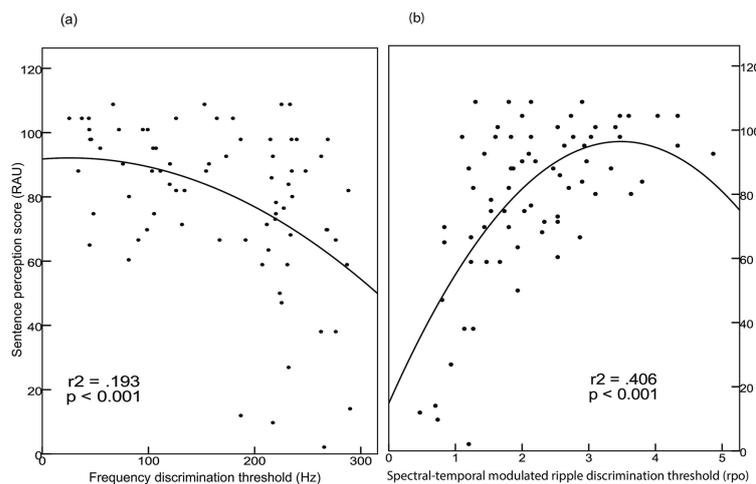


Figure 2: The figure depicts the sentence perception score transformed into rationalized arcsine units as a function of the frequency discrimination threshold (a) and the spectral-temporal modulated ripple discrimination threshold (b). The regression lines are quadratic fits.

The correlations between the age variables and the FDT did not reach the significance level ($P=0.577$ and $P=0.237$ for chronological age and age at implantation, respectively). Statistically significant correlations were found between chronological age and age at implantation and the SMRT. There was a significant negative correlation between age at implantation and the speech scores. The children who had been implanted earlier had a better speech performance.

The multiple linear regression analysis via the stepwise method identified the variables relating to speech perception skills in the children with CIs. The results of the assessments of spectral resolution and the age variables as predictive variables and the word recognition and sentence perception scores as a dependent variable were entered into the model. The model summary of the regression analysis is shown in tables 3 and 4. The SMRT and the FDT were the significant predictors of the word recognition score, accounting for 41.2% of the variance ($r=0.642$) in word recognition skills in the children with CIs. Additionally, 41.3% of the variance ($r=0.643$)

in sentence perception skills in the study population was accounted for by the SMRT, age at implantation, and the FDT.

Discussion

The results of the present study revealed a notable correlation between spectral resolution and speech perception in pediatric CI users. We found that the SMRT was a better predictor of speech perception in quiet than was the FDT among our children with CIs. Age at test and age at implantation were correlated with the SMRT, whereas there were no correlations between the age variables and the FDT.

In the present study, the mean SMRT was 2.18 rpo, which is close to the mean SRD threshold (2.08 rpo) reported by Jung and colleagues²⁰ in their study on children aged between 8 and 16 years. However, Landsberger and others,²¹ using the SMRT, reported a mean 3.06-rpo spectral resolution. Bilateral CIs in their study may be a possible reason for the desirable thresholds compared with those in the current study. The authors reported that 75% of the children in their

Table 3: Model summary of the regression analysis for word recognition

Predictor Variable	B	Std. error	β	T value	P value
SMRT	8.538	1.845	0.452	4.627	<0.001
FDT	-0.073	0.023	-0.314	-3.214	0.002

SMRT: Spectral-temporal modulated ripple discrimination threshold; FDT: Frequency discrimination threshold

Table 4: Model summary of the regression analysis for sentence perception

Predictor variable	B	Std. error	β	T value	P value
SMRT	10.420	2.548	0.410	4.089	<0.001
Age at implantation	-5.360	2.161	-0.232	-2.480	0.016
FDT	-0.074	0.031	-0.238	-2.412	0.018

SMRT: Spectral-temporal modulated ripple discrimination threshold; FDT: Frequency discrimination threshold

study performed better on the SMRT in bilateral than unilateral conditions.

We observed a clear correlation between the age variables and the SMRT. Among our study population, the children who had received their CIs earlier tended to perform better in the ripple discrimination task. Landsberger and colleagues²¹ mentioned the absence of such a relationship in pediatric CI users. The discrepancies between our studies may have been caused by the relatively small sample size (20 children) in the investigation by Landsberger and coworkers.

We found a considerable correlation between the SMRT and speech skills in our study population, which is consistent with the studies on adults with CIs. The significance of this finding lies in the fact that speech recognition with degraded spectral cues in children is less precise than that in adults.²² The discrimination between spectral peaks and valleys is associated with the identification of the important spectral cues in speech signals like vowel formant frequencies, voicing, manner, and place of consonant production.¹² Henry and Turner¹⁰ demonstrated that listeners with more desirable spectral peak discrimination abilities were better capable of extracting vowel information from speech signals. Since pediatric CI users are less skillful than are their adult counterparts in using the sentence context for word recognition in the sentence, the relationship between spectral resolution and sentence perception highlights the importance of efficient spectral resolution for sentence perception in these children.²³

According to our findings, the average of the FDT at the 1000-Hz standard frequency was 168.19 Hz, which is similar to that reported by Kopelovich and others,²⁴ who demonstrated an average of 156 Hz for implanted children below 10 years old. In contrast, an FDT survey on CI users aged between 6 and 13 by Santarelli and colleagues²⁵ showed thresholds that are better than those we obtained in the present study. The authors reported that just five of the studied children performed the FDT. This may not reflect the frequency discrimination ability of the implanted children population, particularly children with diminished abilities.

Age at test and age at implantation did not show a significant correlation with the FDT. This has also been demonstrated in adult CI users. Turgeon and others³ reported that the FDT was not correlated with either the deafness duration or the years of CI experience. Elsewhere, Goldsworthy and colleagues⁷ also noted the absence of a correlation between the FDT and the age variables.

In line with the studies in adult CI users, we obtained a significant correlation between the

FDT and speech perception in our children with CIs. Dorman and others²⁶ demonstrated a clear correlation between the FDT and phoneme, word, and sentence perception in adults aged between 21 and 37 years. Turgeon and colleagues³ indicated a significant correlation between the FDT at 500-Hz standard frequency and monosyllable word recognition. The discrimination of small acoustic differences in signals has an important role in speech perception.²⁷ Different speech sounds contain different values of formant frequencies, and the discrimination of formant frequencies provides important information for phoneme identification.¹³ pediatric CI users who have reduced ability to extract the cues relating to frequency discrimination from the input signal, as seen by a lower FDT, may show a poor speech performance.

Comparisons of the correlation coefficient between spectral resolution assessments and speech perception scores suggest that the SMRT is a better predictor of speech perception in quiet than is the FDT in pediatric CI users. Litvak and others²⁸ compared three spectral resolution assessments of backward masking, simultaneous threshold interaction, and spectral shape perception and concluded that spectral shape perception had the best correlation with speech perception. Spectral ripple stimuli contain a wide range of frequencies similar to speech. Whereas the SMRT is the task of integrating information across several channels, the FDT is at the single-channel level.²⁹ Given that speech perception relies on the information from rather wide spectral regions and CI listeners take advantage of multi-channel information in real-world listening situations,²⁹ it is reasonable to expect that the SMRT has a higher correlation with speech skills than does the FDT in the pediatric population with CIs.

It is worth noting that pediatric CI users show diverse spectral resolution abilities ranging from 25.4 to 289.9 Hz for the FDT and from 0.47 to 4.87 rpo for the SMRT, despite using the same processor strategy. This makes the high variability of spectral resolution in CI-using children evident, which in turn leads, at least in part, to the great variability of their speech and language results. However, spectral resolution only accounted for about 40% of the variance in speech perception in the current study, which underscores the need to consider other variables such as demographic and psychoacoustic factors for this variability.

The present study is limited in several ways, first and foremost among which are the facts that we surveyed only a limited number of factors as predictors of speech perception and did not

include a control group. We cannot, therefore, properly compare spectral resolution ability between implanted children and normal hearing children and also adults with CIs.

Conclusion

The data obtained from the current study suggest a clear relationship between spectral resolution and speech perception in children with CIs. The broadband spectral resolution assessment had a higher correlation with speech perception than did the narrowband assessment. About 40% of the variance in the speech perception of the implanted children was accounted for by their spectral resolution ability. Further research is required to develop a model to predict speech perception in pediatric CI users more reliably through the inclusion of a set of psychoacoustic factors along with individual variables as predictor factors for speech perception.

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References

- Scheperle RA, Abbas PJ. Relationships Among Peripheral and Central Electrophysiological Measures of Spatial and Spectral Selectivity and Speech Perception in Cochlear Implant Users. *Ear Hear.* 2015;36:441-53. doi: 10.1097/AUD.000000000000144. PubMed PMID: 25658746; PubMed Central PMCID: PMC4478147.
- Davies-Venn E, Nelson P, Souza P. Comparing auditory filter bandwidths, spectral ripple modulation detection, spectral ripple discrimination, and speech recognition: Normal and impaired hearing. *J Acoust Soc Am.* 2015;138:492-503. doi: 10.1121/1.4922700. PubMed PMID: 26233047; PubMed Central PMCID: PMC4514721.
- Turgeon C, Champoux F, Lepore F, Ellemberg D. Deficits in auditory frequency discrimination and speech recognition in cochlear implant users. *Cochlear Implants Int.* 2015;16:88-94. doi: 10.1179/1754762814Y.0000000091. PubMed PMID: 25117940.
- Fu QJ, Nogaki G. Noise susceptibility of cochlear implant users: the role of spectral resolution and smearing. *J Assoc Res Otolaryngol.* 2005;6:19-27. doi: 10.1007/s10162-004-5024-3. PubMed PMID: 15735937; PubMed Central PMCID: PMC2504636.
- Supin A, Popov VV, Milekhina ON, Tarakanov MB. Frequency resolving power measured by rippled noise. *Hear Res.* 1994;78:31-40. PubMed PMID: 7961175.
- Won JH, Drennan WR, Rubinstein JT. Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users. *J Assoc Res Otolaryngol.* 2007;8:384-92. doi: 10.1007/s10162-007-0085-8. PubMed PMID: 17587137; PubMed Central PMCID: PMC2538435.
- Goldsworthy RL. Correlations Between Pitch and Phoneme Perception in Cochlear Implant Users and Their Normal Hearing Peers. *J Assoc Res Otolaryngol.* 2015;16:797-809. doi: 10.1007/s10162-015-0541-9. PubMed PMID: 26373936; PubMed Central PMCID: PMC4636591.
- Peter V, Wong K, Narne VK, Sharma M, Purdy SC, McMahon C. Assessing spectral and temporal processing in children and adults using temporal modulation transfer function (TMTF), Iterated Ripple Noise (IRN) perception, and spectral ripple discrimination (SRD). *J Am Acad Audiol.* 2014;25:210-8. doi: 10.3766/jaaa.25.2.9. PubMed PMID: 24828221.
- Halliday LF, Bishop DV. Frequency discrimination and literacy skills in children with mild to moderate sensorineural hearing loss. *J Speech Lang Hear Res.* 2005;48:1187-203. doi: 10.1044/1092-4388(2005/083). PubMed PMID: 16411805.
- Henry BA, Turner CW. The resolution of complex spectral patterns by cochlear implant and normal-hearing listeners. *J Acoust Soc Am.* 2003;113:2861-73. doi: 10.1121/1.1561900. PubMed PMID: 12765402.
- Anderson ES, Oxenham AJ, Nelson PB, Nelson DA. Assessing the role of spectral and intensity cues in spectral ripple detection and discrimination in cochlear-implant users. *J Acoust Soc Am.* 2012;132:3925-34. doi: 10.1121/1.4763999. PubMed PMID: 23231122; PubMed Central PMCID: PMC3529540.
- Anderson ES, Nelson DA, Kreft H, Nelson PB, Oxenham AJ. Comparing spatial tuning curves, spectral ripple resolution,

- and speech perception in cochlear implant users. *J Acoust Soc Am.* 2011;130:364-75. doi: 10.1121/1.3589255. PubMed PMID: 21786905; PubMed Central PMCID: PMCPMC3155592.
- 13 Sagi E, Kaiser AR, Meyer TA, Svirsky MA. The effect of temporal gap identification on speech perception by users of cochlear implants. *J Speech Lang Hear Res.* 2009;52:385-95. doi: 10.1044/1092-4388(2008/07-0219). PubMed PMID: 18806216; PubMed Central PMCID: PMCPMC2664850.
 - 14 Wei C, Cao K, Jin X, Chen X, Zeng FG. Psychophysical performance and Mandarin tone recognition in noise by cochlear implant users. *Ear Hear.* 2007;28:62S-5S. doi: 10.1097/AUD.0b013e318031512c. PubMed PMID: 17496650; PubMed Central PMCID: PMCPMC2674760.
 - 15 Goldsworthy RL, Delhorne LA, Braidia LD, Reed CM. Psychoacoustic and phoneme identification measures in cochlear-implant and normal-hearing listeners. *Trends Amplif.* 2013;17:27-44. doi: 10.1177/1084713813477244. PubMed PMID: 23429419; PubMed Central PMCID: PMCPMC4040862.
 - 16 Moore DR, Ferguson MA, Halliday LF, Riley A. Frequency discrimination in children: perception, learning and attention. *Hear Res.* 2008;238:147-54. doi: 10.1016/j.heares.2007.11.013. PubMed PMID: 18222053.
 - 17 Aronoff JM, Landsberger DM. The development of a modified spectral ripple test. *J Acoust Soc Am.* 2013;134:EL217-22. doi: 10.1121/1.4813802. PubMed PMID: 23927228; PubMed Central PMCID: PMCPMC3732300.
 - 18 Lotfi Y, Salim S, Mehrkian S, Ahmadi T, Biglarian A. The Persian version of words-in-noise test for young population: development and validation. *Auditory and Vestibular Research.* 2016;25:194-200.
 - 19 Moossavi A, Mehrkian S, Karami F, Biglarian A, Bakhtiari BM. Developing of Persian version of the BKB sentences and content validity assessment. *Auditory and Vestibular Research.* 2017;26:27-33.
 - 20 Jung KH, Won JH, Drennan WR, Jameyson E, Miyasaki G, Norton SJ, et al. Psychoacoustic performance and music and speech perception in prelingually deafened children with cochlear implants. *Audiol Neurootol.* 2012;17:189-97. doi: 10.1159/000336407. PubMed PMID: 22398954; PubMed Central PMCID: PMCPMC3375765.
 - 21 Landsberger DM, Padilla M, Martinez AS, Eisenberg LS. Spectral-Temporal Modulated Ripple Discrimination by Children With Cochlear Implants. *Ear Hear.* 2018;39:60-8. doi: 10.1097/AUD.0000000000000463. PubMed PMID: 28682810.
 - 22 Eisenberg LS, Shannon RV, Martinez AS, Wygonski J, Boothroyd A. Speech recognition with reduced spectral cues as a function of age. *J Acoust Soc Am.* 2000;107:2704-10. doi:10.1121/1.428656, PubMed PMID: 10830392.
 - 23 Conway CM, Deocampo JA, Walk AM, Anaya EM, Pisoni DB. Deaf children with cochlear implants do not appear to use sentence context to help recognize spoken words. *J Speech Lang Hear Res.* 2014;57:2174-90. doi: 10.1044/2014_JSLHR-L-13-0236. PubMed PMID: 25029170; PubMed Central PMCID: PMCPMC4396617.
 - 24 Kopelovich JC, Eisen MD, Franck KH. Frequency and electrode discrimination in children with cochlear implants. *Hear Res.* 2010;268:105-13. doi: 10.1016/j.heares.2010.05.006. PubMed PMID: 20553829; PubMed Central PMCID: PMCPMC3670150.
 - 25 Santarelli R, Magnavita V, De Filippi R, Ventura L, Genovese E, Arslan E. Comparison of speech perception performance between Sprint/Esprit 3G and Freedom processors in children implanted with nucleus cochlear implants. *Otol Neurotol.* 2009;30:304-12. doi: 10.1097/MAO.0b013e3181967a19. PubMed PMID: 19225440.
 - 26 Dorman MF, Smith LM, Smith M, Parkin JL. Frequency discrimination and speech recognition by patients who use the Ineraid and continuous interleaved sampling cochlear-implant signal processors. *J Acoust Soc Am.* 1996;99:1174-84. doi: 10.1121/1.414600. PubMed PMID: 8609301.
 - 27 Kraus N, McGee T, Carrell TD, Sharma A. Neurophysiologic bases of speech discrimination. *Ear Hear.* 1995;16:19-37. doi: 10.1097/00003446-199502000-00003. PubMed PMID: 7774767.
 - 28 Litvak LM, Spahr AJ, Saoji AA, Fridman GY. Relationship between perception of spectral ripple and speech recognition in cochlear implant and vocoder listeners. *J Acoust Soc Am.* 2007;122:982-91. doi: 10.1121/1.2749413. PubMed PMID: 17672646.
 - 29 Faulkner KF. Understanding Frequency Encoding and Perception in Adult Users of Cochlear Implants: Spectral ripple thresholds can be improved with training in CI users: but what are we training?. Washington: University of Washington; 2012.