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Original Research

Feasibility of an Objective Approach Using Acoustic Change Complex for Evaluating Spectral Resolution in Individuals with Normal Hearing and Hearing Loss

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Abstract

Background: Identifying the temporal and spectral information in sound is important for understanding speech; indeed, a person who has good spectral resolution usually shows good speech recognition performance. The spectral ripple discrimination (SRD) test is often used to behaviorally determine spectral resolution capacity. However, although the SRD test is useful, it is difficult to apply to populations who cannot execute the behavioral task, such as younger children and people with disabilities. In this study, an objective approach using spectral ripple (SR) stimuli to evoke the acoustic change complex (ACC) response was investigated to determine whether it could objectively evaluate the spectral resolution ability of subjects with normal hearing (NH) and those with hearing loss (HL). **Method**: Ten subjects with NH and eight with HL were enrolled in this study. All subjects completed the behavioral SRD test and the objective SR-ACC test. Additionally, the HL subjects completed speech perception performance tests while wearing hearing aids. **Results**: In the SRD test, the average thresholds were 6.48 and 1.52 ripples per octave (RPO) for the NH and HL groups, respectively, while in the SR-ACC test, they were 4.90 and 1.35 RPO, respectively. There was a significant difference in the average thresholds between the two groups for the SRD ($p < 0.001$) and the SR-ACC ($p < 0.001$) tests. A significant positive correlation was observed between the SRD and SR-ACC tests ($\rho = 0.829$, $p < 0.001$). In the HL group, there was a statistically significant relationship between speech recognition performance in noisy conditions and the SR-ACC threshold ($\rho = 0.911$, $p < 0.001$ in Sentence score of Korean Speech Audiometry (KSA)). **Conclusions**: The results supported the feasibility of the SR-ACC test to objectively evaluate auditory spectral resolution in individuals with HL. This test has potential for use in individuals with HL who are unable to complete the behavioral task associated with the SRD test; therefore, it is proposed as a more inclusive alternative to the SRD test.

Keywords: acoustic change complex; electrophysiology; auditory evoked potential; spectral resolution; hearing loss; hearing aids

1. Introduction

Sound contains temporal and spectral information, which are important factors for understanding speech and listening to music. Hearing loss (HL) can lead to reduced speech perception performance [1–3]. A greater auditory processing capacity to distinguish the important information in sound generally confers a greater speech perception performance. Several previous studies have evaluated auditory spectral resolution in a quiet situation using the concept of spectral ripple discrimination (SRD) [4–7]. The results of these studies indicate a significant relationship between the spectral resolution and the speech recognition ability of listeners with normal hearing (NH), impaired hearing, and those with cochlear implants (CI) [4–7]. Auditory spectral resolution has also been found to be significantly correlated with speech recognition proficiency for CI listeners in noisier situations [7] and with amplified speech recognition for hearing-impaired listeners [4].

Generally, professional musicians have better spectral processing capacity than non-musicians. Several studies have indicated that musicians show greater spectral discrimination ability, as observed by frequency discrimination or pitch discrimination tasks, compared to non-musicians [8–10]. One previous study, which investigated musicians' and non-musicians' speech perception performance in a noisy environment, reported that musicians showed better speech-in-noise performance and frequency discrimination thresholds compared to non-musicians [11]. This evidence suggests that musical training could enhance an individual's spectral processing capacity. These studies also suggest that the ability to discriminate spectral information in sound enables accurate speech recognition [8–11]. Thus, the spectral resolution test was suggested to evaluate spectral resolution and predict speech recognition performance [5,7]. The spectral resolution test used in these studies has the advantage that it can be administered to subjects across the world as the test uses non-linguistic stimuli. Therefore, the auditory spectral resolution could be a promising index to evaluate auditory prosthesis outcomes in hearing-impaired populations.

The SRD test is a behavioral tool that is used to evaluate an individual's spectral resolution capacity [7]. The SRD shows good test-retest reliability and no learning effects. In addition, it overcomes the problem of the limited number of materials used in traditional speech audiometry. However, this behavioral approach is difficult to apply in populations who cannot execute behavioral tasks, such as uncooperative individuals, infants, and people with disabilities. It is often difficult to obtain reliable spectral resolution capacity information from these populations because the behavioral response test depends on their feedback. Therefore, an alternative, more inclusive, approach that can objectively evaluate specific auditory properties is required.

The auditory evoked potentials (AEP), known as the P1-N1-P2 complex, is a cortical-level index of acoustic signal that occurs in response to certain auditory stimuli, such as the onset or offset of sound [12–14]. The acoustic change complex (ACC) is an auditory evoked potential that is elicited by changes (such as spectral, temporal, or loudness changes) within an ongoing acoustic stimulus [13,15,16]. The ACC can also be provoked in response to speech stimuli [13,17]. The ACC response is triggered when a change in ongoing sound is perceived, and the response depends on the magnitude of the change. Indeed, previous research has demonstrated that a change in stimulus magnitude is reflected in the ACC response [18], where the ACC amplitude decreases as the temporal gap duration, frequency change magnitude, or intensity change magnitude in stimulus decreases. Another study demonstrated that the magnitude of the frequency change affected the latency and amplitude of the ACC response [19]. The ACC response can be measured in various clinical populations, including adults, children, and infants, in a passive listening paradigm [20–25]. ACC responses have been observed in subjects with NH [18,26,27], HL [13,28], and CI [29–32].

Previous research has also demonstrated that ACC responses can be elicited by spectral ripple (SR) stimuli in individuals with NH, hearing aids users, and musicians [33,34]. A decrease in the amplitude of the ACC was observed in response to an increase in the frequency compression ratio in individuals with NH and hearing aids users [34]; this indicates that the ACC response is sensitive to changes in frequency compression ratio. In a study that compared musicians and non-musicians, it was found that the ACC response thresholds of musicians, who are known to be more sensitive to frequency discrimination, were greater than those of non-musicians [33]. Therefore, it is thought that the ACC could be utilized as a promising index to objectively evaluate spectral resolution capacity via SR density changes.

In this study, we developed an objective approach to evaluate an individual's spectral resolution capacity and investigated its potential in subjects with HL and those with NH. The new approach, the spectral ripple-acoustic change complex (SR-ACC) test, utilizes the ACC response evoked by spectral ripple stimulus. Specifically, we confirmed the feasibility of the objective approach through group comparison and examined the correlations between the behavioral and objective approaches. This study also explored the impact of HL on the amplitude and latency of the ACC response. In addition, the relationship between aided speech recognition performance and spectral resolution was examined in subjects with HL.

2. Materials and Methods

2.1 Subjects

The study included a total of 18 subjects, 10 of them had NH (NH group; mean age, 25.1 years; range, 22–30 years; SD = 2.02 years; 5 females), and eight had sensorineural HL (HL group; mean age, 60.6 years; range 47–70 years; SD = 8.28 years; 4 females). Pure-tone audiometry was used to evaluate the subjects' hearing and to divide them into the appropriate group based on the presence of HL. The NH subjects had an audiometric threshold below 25 dB HL at all octave frequencies (from 0.25 to 8 kHz). Individuals with symmetrical bilateral sensorineural HL with a four-frequency average higher than 40 dB were included in the HL group. In the NH group, the pure-tone average (PTA) thresholds in the range of 0.125–8 kHz were 9.55 ($\pm$4.03) dB HL in the right ear and 7.40 ($\pm$3.50) dB HL in the left ear. In the HL group, the PTA thresholds were 55.88 ($\pm$20.09) in the right ear and 57.44 ($\pm$20.06) dB HL in the left ear (Fig. 1). All HL subjects had experience with bilateral receiver-in-canal hearing aids for over 7 months.

All subjects completed both the behavioral SRD test and the objective SR-ACC test for spectral resolution evaluation. Subjects in the HL group also completed Korean Speech Audiometry (KSA) speech perception performance tests in both quiet and noisy conditions while wearing hearing aids. All test procedures were executed in a double-walled, soundproof booth.

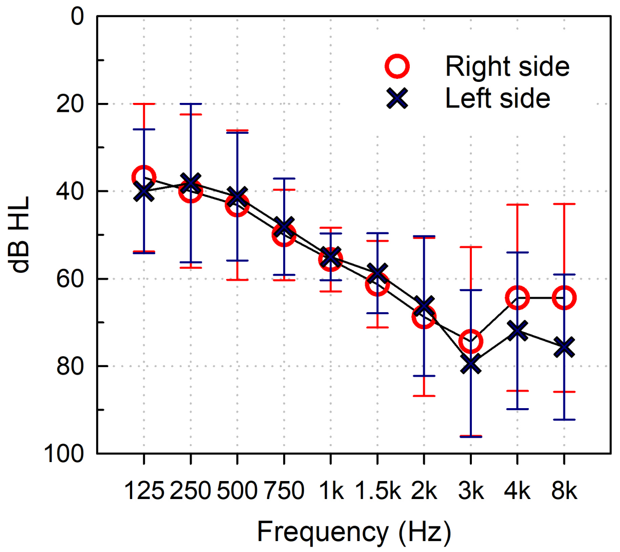

Fig. 1. Mean pure-tone thresholds in the hearing loss (HL) group. The mean pure-tone thresholds are illustrated as a function of frequency (0.125–8 kHz). Red circles indicate mean pure-tone thresholds for the right ear; blue crosses indicate mean pure-tone thresholds for the left ear. Error bars indicate standard deviations of pure-tone thresholds at each frequency. dB, decibel.

2.2 Aided Speech Perception Performance

In the HL group, the aided hearing performance was assessed via KSA [35] in both quiet and noisy conditions. Electroacoustic testing was conducted to ensure that the hearing aids were appropriately fitted to the subjects during their clinic visit. The HL subjects performed the KSA test wearing their own hearing aids with no adjustments made to the devices. The subjects sat on a chair centered in a semi-anechoic chamber and were instructed to perform a listen-and-repeat task. The presentation level for KSA was 60 dBA in the quiet condition and 0 dB signal to noise ratio (SNR) (speech and noise presented at 60 dBA) in the noise condition. The speech was presented through a loudspeaker (HS-50M, Yamaha Corporation, Hamamatsu, Japan) located approximately 1 meter in front of the subjects, and the babble noise was presented via four loudspeakers placed between 45 to 315 degrees in 90-degree increments. The KSA test has eight sentence lists; each list has 40 target words within 10 sentences. During the test, two lists were used for each condition. The mean scores for words and sentences, calculated as percentages, were used in the analysis.

2.3 Behavioral Spectral Ripple Discrimination (SRD) Test

The SRD test was used to behaviorally assess the spectral resolution capacity by measuring the maximum distinguishable ripples per octave (RPO). Stimulation parameters described in the study by Won *et al*. [7] were modified and used in this study. The SR stimuli were a standard ripple and a 90-degree phase-inverted SR. The SR was created using summated 2555 pure-tone frequency components at a 100 to 5000 Hz bandwidth. The ripple amplitudes demonstrated the full-wave rectified sinusoidal spectral shape, with peaks spaced equally on a logarithmic frequency scale. The ripple depth was 13 dB from peak to valley. The ripple stimuli were presented with 16 different densities, ranging from 0.125 to 22.628 RPO by ratios of 1.414.

The test procedure followed the description in Won *et al*. [7]. The spectral resolution threshold was determined using a three-interval forced-choice, two-up one-down adaptive procedure, converging on 70.7% correct. Therefore, the density level was increased by two steps with a correct response and decreased by one step with an incorrect response. Each test run started at 0.125 RPO and was adjusted with the same two-up one-down adaptive procedure with a ratio of 1.414. The ripple duration was 500 ms, and the interstimulus duration was 700 ms. Subjects were instructed to pick the interval that sounded different among the three intervals (consisting of the two standard ripples and one inverted ripple) by pressing a button on the test monitor. The threshold was determined as the mean of ripple density for the final eight reversals in a run of 13 reversals. The final threshold was decided as the mean of thresholds obtained from three runs.

The average SR stimulus level was 65 dBA, which was applied through a loudspeaker located 1 meter away from the subject at 0-degree azimuth for the NH group. For the HL group, the stimulus was presented at the most comfortable level (MCL) via ER-3A inserted earphones (Etymotic Research, Elk Grove Village, IL, USA) bilaterally with hearing aids removed.

2.4 Objective SR-ACC Test

2.4.1 Stimuli

The stimuli for the SR-ACC test was generated using a standard ripple and the 90-degree phase-shifted inverted ripple utilized in the behavioral SRD test. The total duration of the stimulus was 1.5 s (consisting of 1 s of the standard ripple and 0.5 s of the inverted ripple). The interstimulus interval period (i.e., the silence period) was 1.5 s, and the presentation rate was 0.33 Hz. A spectral change was made at the 1-s point to elicit the ACC response. The root mean square (RMS) of each section was matched to eliminate loudness change. After normalization, 5-ms rise and fall ramp periods were applied to the entire stimulus to avoid abrupt onset and offset artifacts. A 5-kHz lowpass filter was applied to the whole stimulus in order to reduce frequency components higher than 5 kHz at the 1-s combining point, which occurred due to stimulus concatenation.

The stimulus was presented bilaterally to the subject via ER-3A inserted earphones (Etymotic Research, Elk Grove Village, IL, United States) connected to a stimulus presentation (STIM2) system (Compumedics Neuroscan, Charlotte, NC, USA). The stimulus ripple density ranged from 0.5 to 6 RPO. Ripple densities of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, and 6.0 RPO were presented to subjects in the NH group, while ripple densities of 0.5, 0.707, 1.0, 1.414, 2.0, 3.0, 4.0, 5.0, and 6.0 RPO were presented to subjects in the HL group. The stimulus level was equal to the stimulus level in the behavioral SRD test.

2.4.2 Recording

The subjects were instructed to stay awake and remain relaxed while sitting in a reclining chair and watching a captioned movie without sound during the recording sessions. The electroencephalogram (EEG) signals were acquired using a Scan 4.5/SynAmps2 system (Compumedics Neuroscan, Charlotte, NC, USA) with Ag–AgCl electrodes. The electrode placement followed the international 10–20 system [36]. The active electrode (Cz) was placed on the midline of the scalp, and the reference and ground electrodes were placed on the bilateral mastoids and the forehead. To remove artifacts, eye movements were monitored using electrodes attached above and below the left eye and the outer canthi. Impedances and inter-electrode impedances were maintained below 5 and 2 kΩ, respectively. Stimuli presented 150 sweeps per block at each RPO level. The individual EEG for each condition was composed of the average of a minimum of 200 accepted sweeps from two blocks, which each consisted of more than 100 accepted sweeps.

During acquisition, the EEG activity was amplified 10 times, band-pass filtered between 0.1 and 100 Hz, and digitized at an analog-to-digital sampling rate of 1000 Hz. Post-processing was conducted after recording. Portions containing electro-ocular artifacts were excluded. EEG data were epoched using a window ranging from –100 to 2900 ms and corrected using a 100 ms pre-stimulus baseline. Epochs in which the absolute amplitude exceeded 100 µV were rejected. Band-pass filtering (ranging from 1 to 30 Hz with 12 dB/octave) was applied. The filtered epochs were averaged for each stimulus condition and each subject. The moving average was conducted using a 40ms boxcar filter to smooth waveforms. Finally, the grand-mean average waveforms were created by averaging the waveforms across subjects.

2.5 Objective Threshold Detection

The amplitude and latency of the ACC response are sensitive to the magnitude change in the stimuli, according to the frequency and intensity [18,19]; the ACC amplitude gradually decreases and eventually disappears as the magnitude of frequency changes decreases. In this study, the presence and amplitude of ACC responses regarding RPO were utilized to determine the threshold for spectral resolution. The effect of HL on ACC amplitude and latency based on RPO was also explored.

The determination of the ACC threshold was based on two criteria: the visual detection results and the RMS amplitude ratio of the ACC to the noise floor. The presence of ACC responses was decided when two experienced researchers reached identical judgments. The largest RPO at which ACC responses were confirmed was considered a candidate threshold. Subsequently, the threshold was decided when the RMS amplitude of the ACC was higher than that of the noise floor by at least 50%. The windows used to measure the RMS amplitude of the ACC and the noise floor were 1050–1260 ms (210-ms window) and 2690–2900 ms (210-ms window) after onset, respectively.

2.6 Statistical Analysis

The thresholds obtained from the SRD and SR-ACC tests were utilized for the statistical analyses. A two-way analysis of variance (ANOVA) was used to analyze thresholds, considering the factors of the subject group and the measurement approach. For the amplitude and latency data, a two-way repeated measures analysis of variance (RM ANOVA) was conducted, with the main factors being the subject group and the RPO. Normality was confirmed using the Shapiro-Wilk test, and all datasets passed the test. The data for RM ANOVA met the assumption of sphericity according to Mauchly's test. Statistical significance was set at an alpha level of 0.05. Multiple pairwise comparisons were performed using the Bonferroni *t*-test when significance was observed. Correlation analysis was conducted using Spearman's correlation when the normality test failed.

3. Results

Fig. 2 shows the correlation between the four-frequency average PTAs and the behavioral and objective spectral resolutions. The PTA thresholds for the individuals' "better" ears were 7.5 (±3.44) dB HL and 56.1 (±7.95) dB HL in the NH and HL groups, respectively. There were no significant correlations in either the NH or HL group. The general PTA results obtained in clinics cannot predict a patient's ability to discriminate spectral information.

The relationship between the spectral resolution and the speech perception performance in the HL group is described in Fig. 3. In the KSA results, the spectral resolution tended to have positive correlations with speech perception performance in the noisy condition. Both the SRD and SR-ACC thresholds indicated statistically significant correlations with both the sentence (Spearman correlation, ρ = 0.771, p = 0.021; ρ = 0.911, $p < 0.001$) and word (Spearman correlation, ρ = 0.707, p = 0.037; ρ = 0.763, p = 0.0212) scores from the KSA in the noise condition. However, significant correlations were not obtained in the quiet condition because all HL subjects reached the ceiling level.

Fig. 4 illustrates the schematic for the stimulation used to evoke the ACC response (Fig. 4A) and the grand average waveforms for each condition and subject group (Fig. 4B). The time window was modified from –100 to 2000 ms to

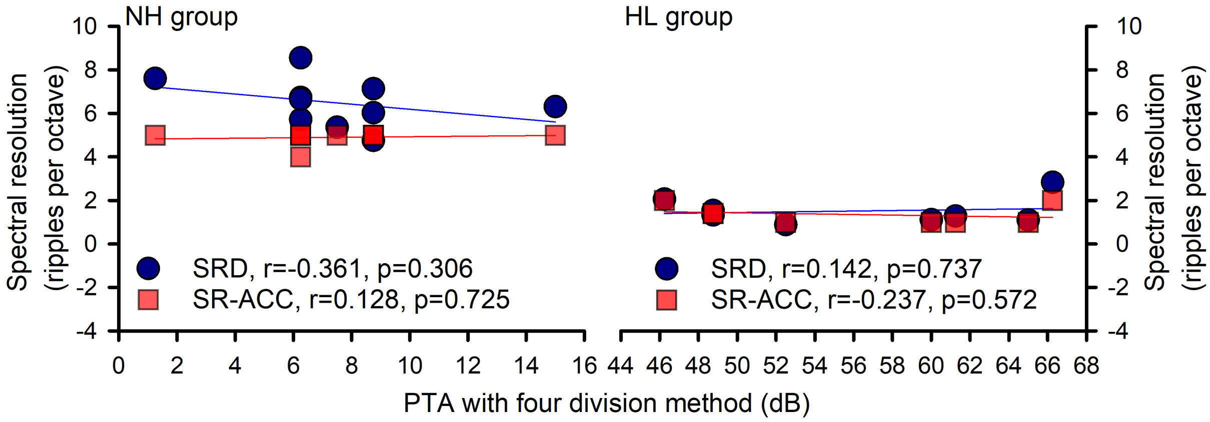

Fig. 2. Relationship between the pure-tone average and the spectral resolution. Circles represent the spectral resolution obtained by the SRD test, and squares indicate the objective spectral resolution by the SR-ACC method. Statistical significance was not observed. NH, normal hearing; SRD, spectral ripple discrimination; SR-ACC, spectral ripple-acoustic change complex; PTA, pure-tone average.

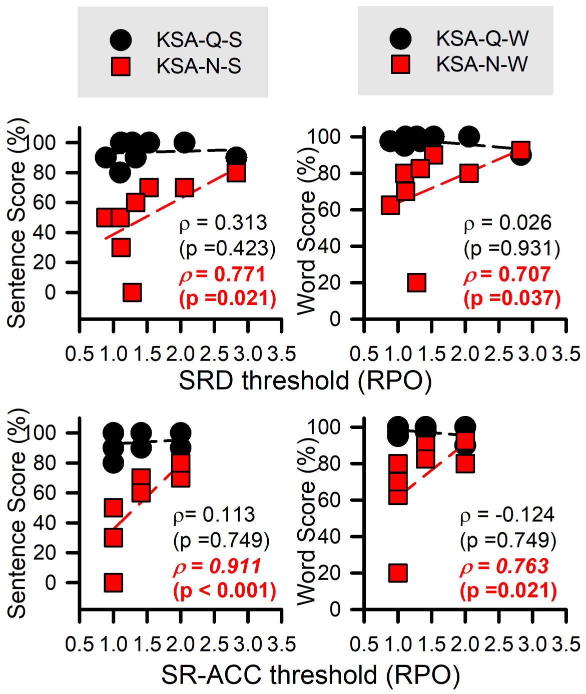

Fig. 3. Association between speech perception performance and spectral resolution in hearing loss (HL) group. Relationship between the spectral resolution and speech perception performance obtained by Korean Speech Audiometry (KSA). Q and N denote quiet and noisy testing conditions. S and W indicate sentence and word scores from KSA. Thus, KSA-Q-S means the sentence score of the KSA test in quiet conditions. The Spearman correlation coefficient rho (ρ) value and p-value for each condition are shown in each quadrant. Rho (ρ) values with statistically significant correlations are written in bold-italics. Better spectral resolution tended to lead to better speech perception performance results, especially in the noise condition. RPO, ripples per octave.

Table 1. Behavioral and objective thresholds of spectral resolution in the NH and HL groups.

Threshold (θ)	SRD test	SR-ACC test
NH group (n = 10)	6.48 (SD = 1.11)	4.90 (SD = 0.32)
HL group (n = 8)	1.52 (SD = 0.64)	1.35 (SD = 0.44)
p-value	<0.001	<0.001

NH, normal hearing; HL, hearing loss; SRD, spectral ripple discrimination; SR-ACC, spectral ripple-acoustic change complex; SD, standard deviation.

show the onset and the ACC response in more detail. The spectral threshold in grand average waveforms was 5 and 1.414 for the NH and HL groups, respectively. The ACC responses were clearly identified after the 1-s point and decreased as the RPO increased. For the 0.5 RPO, the ACC responses were identified in all subjects.

The spectral resolution threshold was compared using a two-way ANOVA for the two main factors: the subject group (i.e., NH vs. HL) and the threshold measure approach (i.e., SRD vs. SR-ACC). The results of the average thresholds for individual thresholds had significant main effects for both group and approach as well as a significant interaction effect [F (1,32) = 318.62, $p < 0.001$; F (1,32) = 13.397, $p < 0.001$; F (1,32) = 8.877, $p = 0.005$; respectively]. *Post hoc* analysis using the Bonferroni method was performed. The average thresholds for the NH and HL groups were 6.48 and 1.52 RPO, respectively, in the SRD test and 4.90 and 1.35 in the SR-ACC test (Table 1). Concerning the subject group, the HL group threshold was statistically significantly lower than that of the NH group for both the behavioral and the objective tests.

Scatterplot in Fig. 5 illustrates the correlation between the SRD and SR-ACC test results. The relationship of the overall data indicated a positive correlation with statistical significance (Spearman correlation, $\rho = 0.829$, $p < 0.001$). The strong correlation suggests the similarity between the

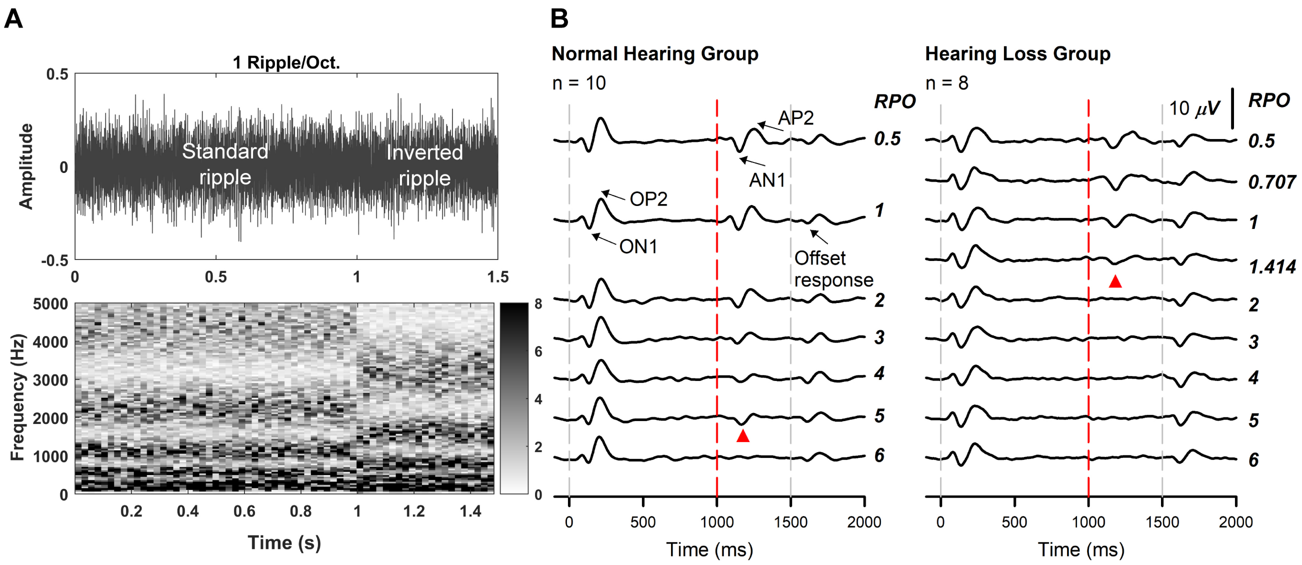

Fig. 4. Stimulation example and grand average waveforms according to the ripple per octave (RPO) level in the NH and HL groups. (A) An example of spectral ripple stimulation (1 RPO) used in the auditory evoked potential recording. The upper panel is a stimulation in the time domain, and the lower panel is a spectrogram of stimulation with 1 RPO. (B) After the onset and offset of the stimuli (indicated by gray dashed lines), P1-N1-P2 complexes were evoked at all RPO levels. These responses represent onset and offset responses sequentially. After the stimulus change (indicated by red dashed lines), P1-N1-P2 complexes could observed in both groups. Triangles indicate the thresholds for each group, which were 5 and 1.414 RPO for the NH and HL groups, respectively. OP2, Onset P2; ON1, onset N1; AP2, ACC P2; AN1, ACC N1.

behavioral and objective tests in terms of their ability to accurately evaluate spectral resolution. In the HL group results, a particularly strong correlation was observed between the two tests (Spearman correlation, $\rho = 0.926$, $p < 0.001$). However, no significant correlation was observed for the results from the NH group.

The N1 latencies and P2-N1 amplitudes of threshold and 0.5 RPO conditions were analyzed in all subjects to identify how HL influences EEG. Waveforms with 0.5 RPO were used as a suprathreshold level, because the ACC response was induced in all subjects at the 0.5 RPO level, and the minimum threshold level in the threshold results was determined at 1 RPO. The latency and amplitude of the onset response between the threshold and suprathreshold levels were not anticipated to differ within each subject group. To verify this expectation, onset responses at both levels were examined. ACC latency in the HL group was anticipated to be longer than in the NH group due to the influence of hearing loss. Moreover, ACC amplitude at the suprathreshold level was expected to be larger than at the threshold level, owing to the increased difficulty in discriminating between standard and inverted SRs at higher RPO levels.

For the latency results, the mean onset N1 latencies for the threshold after onset were 131.3 (SD: 12.13) ms and 139.9 (SD: 9.37) ms for the NH and HL groups, respectively. The suprathreshold mean onset N1 latencies were 132.5 (SD: 8.17) ms and 136.5 (SD: 11.41) ms for NH and HL groups, respectively. For the ACC responses after the

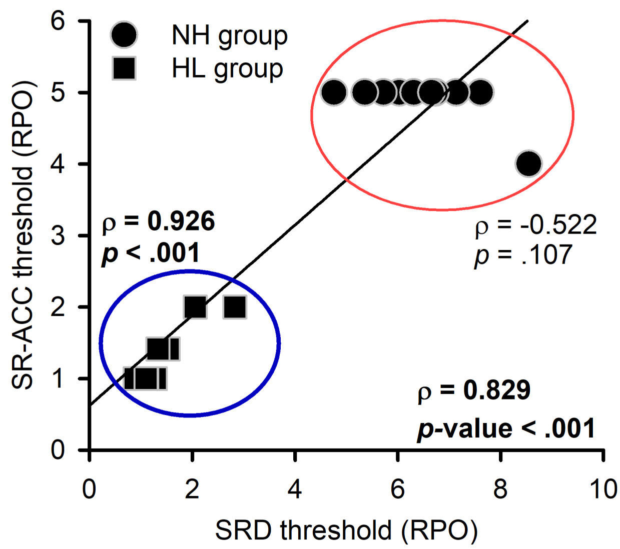

Fig. 5. Correlation between the behavioral and objective spectral resolution tests. The scatterplot shows the correlation between the behavioral SRD and objective SR-ACC thresholds. A significant relationship between the SRD and SR-ACC thresholds was observed ($\rho = 0.829$, $p < 0.001$). Circles indicate the thresholds for the NH group; squares indicate the thresholds for the HL group.

1-s stimulus change point, the threshold mean ACC N1 latencies were 164.4 (SD: 9.48) ms and 187.3 (SD: 35.43) ms for NH and HL groups, respectively. The suprathreshold mean ACC N1 latencies were 154.3 (SD: 8.15) ms and 175.6 (SD: 22.56) ms for NH and HL groups, respectively. Meanwhile, the mean onset P2 latencies for the threshold were 215.5 (SD: 22.30) ms and 243.9 (SD: 19.40) ms for NH and HL groups, respectively. The mean onset P2 latencies for the suprathreshold were 214.1 (SD: 11.01) ms and 248.25 (SD: 27.01) ms for both groups. The mean ACC P2 latencies at the threshold were 245.9 (SD: 13.10) ms and 284.13 (SD: 48.28) ms for NH and HL groups, respectively. The mean ACC P2 latencies at the suprathreshold were 243.8 (SD: 19.10) ms and 261.38 (SD: 31.41) ms for NH and HL groups, respectively.

Fig. 6 indicates the onset (ON1) and ACC latency (AN1) for threshold and suprathreshold levels of the two subject groups. Two-way RM ANOVA was conducted with two group levels (NH vs. HL) and two RPO levels (threshold vs. 0.5 RPO) on onset latency. No main effects or interaction effects were observed for either factor on onset latency (ON1) [F (1,16) = 1.853, p = 0.192; F (1,16) = 0.404, p = 0.534; F (1,16) = 1.786, p = 0.200]. The ACC latency results were analyzed via two-way RM ANOVA with two group levels (NH vs. HL) and two RPO levels (threshold vs. 0.5 RPO). The main effect of RPO level and interaction effect on N1 latency in ACC responses (AN1) were not statistically significant [F (1,16) = 4.004, p = 0.063; F (1,16) = 0.020, p = 0.890]. However, a main effect of group factor on AN1 latency was observed [F (1,16) = 7.254, p = 0.016]. The *post hoc* analysis using the Bonferroni method revealed that the AN1 latencies between the NH and HL groups had statistically significant differences in both threshold (t = 2.323, p = 0.028) and suprathreshold (t = 2.168, p = 0.039) conditions. The mean AN1 latencies of HL subjects were significantly more prolonged than those of NH subjects in both threshold and suprathreshold level conditions.

The P2-N1 amplitude values are depicted in Fig. 7. The threshold mean onset amplitudes were 6.94 (SD: 3.19) µv and 6.10 (SD: 3.23) µv for the NH and HL groups, respectively. The suprathreshold mean onset amplitudes were 8.82 (SD: 3.52) µv and 6.70 (SD: 3.52) µv for the NH and HL groups, respectively. The ACC responses' mean threshold amplitudes were 2.86 (SD: 0.61) µv and 2.57 (SD: 1.15) µv for the NH and HL groups, respectively. The suprathreshold mean ACC amplitudes were 6.00 (SD: 1.58) µv and 4.65 (SD: 2.59) µv for NH and HL groups, respectively.

Two-way RM ANOVAs were performed with two group levels (NH vs. HL) and two RPO levels (threshold vs. 0.5 RPO) for the onset P2-N1 amplitude and the ACC P2-N1 amplitude. The analysis of amplitude indicated a significant main effect of RPO level on onset response [F (1,16) = 17.203, $p < 0.001$]. The main effect of group level and interaction effect on onset response showed no significance [F (1,16) = 0.912, p = 0.354; F (1,16) = 4.133, p = 0.059]. The *post hoc* analysis using the Bonferroni method revealed that significant onset amplitude differences existed

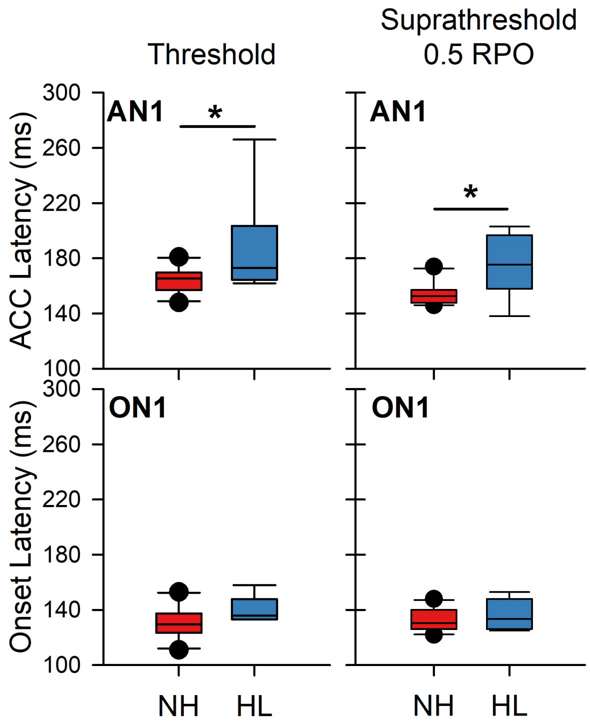

Fig. 6. Onset and ACC latencies results. The latency values of onset (bottom) and ACC (top) responses at the threshold and suprathreshold levels. In each graph, the left box plot shows the results from the NH group, and the right box plot shows the results from the HL group. Statistically significant differences between groups were observed in the ACC latency results (* indicates $p <$ 0.05).

between the threshold and the suprathreshold levels in the NH group (t = 4.635, $p < 0.001$). In contrast, no significant onset amplitude differences were observed between the NH and HL groups for both thresholds (t = 0.551, p = 0.589) and 0.5 RPO (t = 1.324, p = 0.203).

For the ACC response, a significant main effect was observed for the RPO level [F (1,16) = 50.489, $p < 0.001$]. The other main effect and interaction effect showed no statistical significance [F (1,16) = 1.530, p = 0.234; F (1,16) = 2.068, p = 0.170]. The ACC amplitudes were significantly larger for the suprathreshold level than for the threshold level in both the NH (t = 6.408, $p <$ 0001) and HL (t = 3.802, p = 0.002) groups. Meanwhile, no significant differences were observed between the NH and HL groups for both threshold (t = 0.387, p = 0.702) and 0.5 RPO (t = 1.778, p = 0.088) levels.

4. Discussion

In this study, the feasibility of assessing spectral resolution objectively was explored using the SR-ACC test. Prior research has demonstrated that an objective approach using spectral ripples with vocoded stimulation was a valid approach for measuring spectral resolution in CI and NH listeners [37]. Another previous study tested individuals

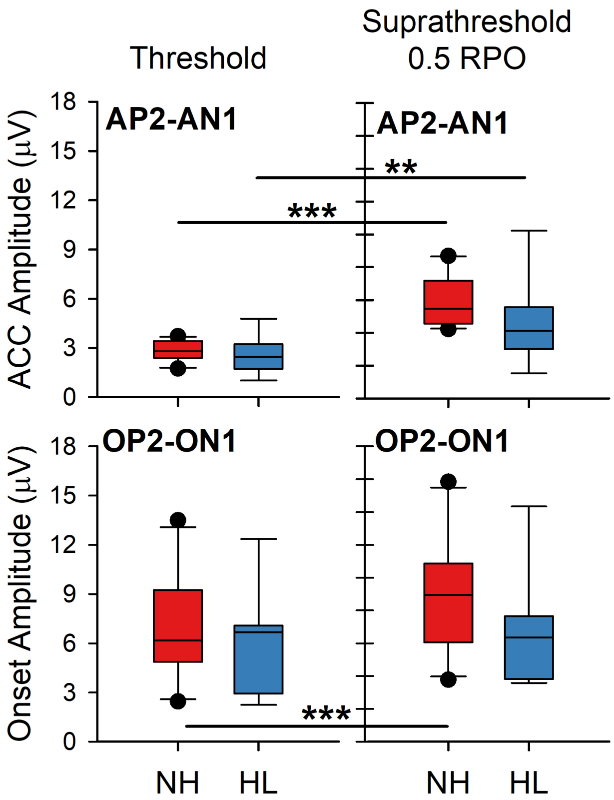

Fig. 7. Onset and ACC amplitude results. The amplitude values of onset (bottom) and ACC (top) responses at the threshold and suprathreshold levels. In each graph, the left box plot shows the results for the NH group, and the right box plot shows the results for the HL group. Although the NH group's amplitude was slightly larger than that of the HL group, there were no statistically significant differences. ** and *** indicate $p < 0.01$, $p < 0.001$, respectively.

with HL, and the results indicated that the ACC response to SRs had the potential to verify a frequency compression technique for hearing aids [34]. In the current study, we confirmed the potential of the objective approach using the ACC response to spectral ripple stimuli and extended the prior work by attempting to assess spectral resolution electrophysiologically.

A broadened auditory filter bandwidth has been observed in listeners with sensorineural HL [38]. Deprived spectral information processing capacity can lead to reduced speech recognition performance, especially in unfavorable conditions [39]. However, like the behavioral spectral resolution, the objective auditory spectral resolution did not reflect the PTA, as seen in Fig. 2. Meanwhile, a statistical correlation was observed between both behavioral and objective spectral resolution and aided speech perception performance in the noise condition, as shown in Fig. 3. These results are in line with the results reported in previous literature [5,7,37]. It has been reported previously that the relationship between the absolute threshold, with the average thresholds of 0.5, 1, and 2 kHz, and the spectral peak resolution threshold did not show a significant correlation in listeners with HL [5]. However, the relationship between the absolute threshold and speech recognition (vowel and consonant recognition) showed statistical significance. Other studies have reported that behavioral spectral resolution is significantly related to the speech reception threshold in noisy conditions [7,37]. The relatively low number of subjects in our study, 8 HL subjects, was insufficient to confirm the association between spectral resolution and speech perception performance. Further study with a larger sample size is necessary to enhance the statistical strength of our results and confirm the correlation between objective spectral resolution and speech perception performance. Nevertheless, based on the previous findings, it can be inferred that both PTA and spectral resolution influence speech perception performance, but in different ways. Therefore, the objective spectral resolution information could help to intervene in various auditory assessments for optimal hearing rehabilitation of individuals.

All subjects who participated in this study showed a clear ACC response at a suprathreshold RPO. As shown in Fig. 4B, in both groups, the ACC response magnitude diminished and eventually disappeared as spectral ripple discrimination became more difficult. There was a significant threshold difference between the NH and HL groups in not only the behavioral SRD test but also in the objective SR-ACC test. The results could be interpreted such that spectral resolution influenced by HL was reflected in brain activity; accordingly, the spectral resolution threshold could be assessed objectively.

Our data showed a statistically significant relationship between the SRD and SR-ACC thresholds. Specifically, a strong correlation was observed between the two tests for the HL subjects. The SR-ACC thresholds for NH subjects appeared to have a ceiling effect. A ripple depth of 13 dB was applied in the current study to increase the difficulty of discrimination between standard and inverted spectral ripples for the NH group. However, this parameter value might be insufficient to determine the spectral resolution of the NH group. Horn *et al*. [40] showed that spectral ripple discrimination became difficult with a lower ripple depth in the SR stimulation. The stimulus parameter difference could explain the variance in the threshold values for spectral resolution. The SR-ACC thresholds had the following discrete values: 1, 1.414, and 2 RPO for the HL group, and 4 and 5 RPO for the NH group. These discrete values limit the precision of correlations with other measurements. The correlation results therefore need to be interpreted cautiously. A more accurate threshold could be determined by obtaining an average value of the results of repeated measurements at RPO levels near the threshold and by presenting finer RPO step sizes. If the SR-ACC data for several ripple density levels between 4 and 6 RPO or data for lower ripple depth is obtained, some positive correlation tendency might have been observed in the NH subjects. Determining the stimulation parameters for each subject population is necessary to obtain valid and reliable outcomes. Further studies that employ more specific spectral density levels and optimal stimulation parameters might confirm the SR-ACC test's feasibility in NH subjects. However, the objective approach to assessing spectral processing ability is more necessary for individuals with HL who have difficulty performing behavioral tests compared to those with NH. Therefore, the SR-ACC test used in this study seems to be more suited for subjects with HL than those with NH.

The threshold and suprathreshold levels' onset amplitudes (OP2-ON1) in the two groups showed no significant differences, although the amplitude in the NH group was somewhat higher than that in the HL group. The spectral stimuli were loud enough for participants to hear in the HL group because the stimuli were presented at the MCL. The stimulus intensity for the NH group was 65 dBA. Prior studies have suggested that onset responses for auditory stimuli are influenced by sound level [41–43]. Therefore, it could be inferred that sufficient input would elicit similar onset latencies and onset amplitudes in both groups.

The N1 latency comparison between the two groups at the threshold and suprathreshold levels was analyzed to identify how degraded spectral resolution due to HL is reflected in the ACC response. The ACC N1 latency (AN1) was longer for the HL group than the NH group. Two previous studies reported similar results to those presented here [44,45]. Oates *et al*. [44] reported that prolonged latencies of event-related potential peaks were observed as the magnitude of sensorineural HL increased. Campbell and Sharma [45] indicated that adults with HL had longer latencies of the P2 cortical auditory evoked potential relative compared to individuals with NH. Delayed latencies have been indicated to be related to inefficient neural synchrony. It was observed that the Onset P2 (OP2) latency in the HL group was more prolonged than that in the NH group at both the suprathreshold RPO ($t = –3.36$, $p = 0.009$) and the threshold RPO ($t = –2.838$, $p = 0.0119$) in our study. However, there was no group difference in the P2 latency on ACC response. Meanwhile, the AN1 latency was longer in the HL group compared to the NH group for both the threshold and suprathreshold levels. These results should be interpreted considering age, as the HL group was significantly older than the NH group. A previous study that investigated the ACC response evoked by frequency change showed that N1 latency was more prolonged in older adults compared to younger adults with similar HL [46]. In contrast, another study with a similar test design (frequency change) reported no significant relationship between ACC latency and age [43]. Furthermore, the previous study also reported that the ACC latency increased with the progression of HL [43]. Further study with age-matched subjects with and without HL is required to investigate the confounding effect of age.

In summary, HL was reflected in the OP2 latency, but not in the AP2 latency, elicited using spectral change. An AN1 latency delay was observed in the HL group compared with the NH group, but no delay in ON1 latency was observed. The results of this study suggest that HL degrades the subject's spectral resolution capacity in auditory processing, which can be detected at the cortical level, especially the N1 latency of the ACC response. Therefore, spectral resolution deterioration could project onto the N1 latency of the ACC response.

For the amplitude results illustrated in Fig. 7, contrary to our expectations, differences in onset amplitude were observed between threshold and suprathreshold levels in the NH group. The amplitude increment of N1 component could be observed by auditory attention [47]. To determine whether ACC responses were elicited in each individual, EEG data for 0.5 RPO were initially obtained during the recording session. Although subjects were instructed to ignore the stimulus during the recording session, the abrupt initial stimulus may have captured the subjects' attention. This may have contributed to the observation of greater onset amplitude at the suprathreshold level. However, this difference was not observed in the HL group, suggesting that it may be attributed to individual variability. ACC amplitudes at the threshold and suprathreshold levels did not significantly differ between the NH and HL groups. However, regarding the suprathreshold level, 0.5 RPO, the ACC amplitude differed between the NH and HL groups, although not significantly, which may have been due to the small number of subjects in our study. To avoid such confounding and to determine the relationship between AEP amplitude and HL, randomized stimulus presentation, investigation with a larger sample size, and the examination of speech perception scores in NH subjects are necessary.

As shown in Fig. 7 and Fig. 4B, the ACC amplitude of the threshold was significantly lower than that of the suprathreshold level, and the spectral threshold could have been determined as the ACC amplitudes decreased as a function of ripple density. Therefore, the ACC amplitude could be utilized when determining the spectral threshold at an individual level, and the N1 latency of ACC response could indicate how HL is reflected at the cortical level when processing spectral information. Similar electrophysiological works for detecting spectral discrimination suggest the ACC response's feasibility as a predictive index of auditory processing capacity [43,48]. Vonck *et al*. [43] reported that cortical responses elicited by tonal frequency changes could predict speech perception in noise. Although the stimuli used to assess spectral resolution in this previous study differed to that used in the current study, the reported results were similar to our own. The previous results showed that subjects with longer ACC latencies had deteriorated speech perception performance. However, in contrast to our results, the ACC response was significantly correlated with hearing threshold. This may have resulted from the specific tonal frequencies (0.5, 1, 2, and 4 kHz) used to assess frequency discrimination in the previous study. In contrast, we utilized SR stimuli derived from frequency components within the 100–5000 Hz range. Sohier *et al*. [48] used standard and inverted spectral ripples at 1 RPO to evoke the ACC response. Their results indicated that a larger ACC amplitude was related to better speech perception performance. They also reported a correlation between the behavioral spectral threshold and the ACC response. Taken together, the results of the previous studies and those of our own study suggest the potential of the ACC as a tool to assess auditory processing capacity by determining the RPO threshold.

5. Conclusions

This study confirmed the feasibility of an objective approach using the SR-ACC threshold in order to determine auditory spectral resolution. Although statistical outcomes were obtained, additional data from more subjects could strengthen the statistical verification. Further research is necessary to investigate the effectiveness of the SR-ACC method in aural rehabilitation for individuals of various populations who experience difficulty with behavioral tests, such as infants, children, and the elderly.

Abbreviations

ACC, Acoustic change complex; AEP, auditory evoked potential; CI, Cochlear implant; HL, Hearing loss; KSA, Korean Speech Audiometry; MCL, Most comfortable level; NH, Normal hearing; RPO, Ripples per octave; RIC, Receiver in the canal; RMS, Root mean square; SRD, Spectral ripple discrimination; SNR, Signal to noise ratio.

Availability of Data and Materials

The dataset analyzed in the present study is available from the first author upon reasonable request.

Author Contributions

SK, JW, and SHH suggested the idea of this study. SK, JW, and IJM conceived the experiments. SHH and IJM reviewed the concept. SK conducted the experiments and analyzed the results. SK, KML, and HYS interpreted data and results. SK, KML, HYS and IJM wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study protocols were approved by the Samsung Medical Center Institutional Review Board (SMC2017-02-027) and were carried out in accordance with approved relevant guidelines and regulations. The study was carried out in accordance with the guidelines of the Declaration of Helsinki. Written informed consent was obtained from all subjects prior to the test, and all subjects were rewarded for their participation in the study.

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Conflict of Interest

The authors declare no conflict of interest.

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