Evidence of across-channel processing for spectral-ripple discrimination in cochlear implant listeners[a)]

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Spectral-ripple discrimination has been used widely for psychoacoustical studies in normal-hearing, hearing-impaired, and cochlear implant listeners. The present study investigated the perceptual mechanism for spectral-ripple discrimination in cochlear implant listeners. The main goal of this study was to determine whether cochlear implant listeners use a local intensity cue or global spectral shape for spectral-ripple discrimination. The effect of electrode separation on spectral-ripple discrimination was also evaluated. Results showed that it is highly unlikely that cochlear implant listeners depend on a local intensity cue for spectral-ripple discrimination. A phenomenological model of spectral-ripple discrimination, as an "ideal observer," showed that a perceptual mechanism based on discrimination of a single intensity difference cannot account for performance of cochlear implant listeners. Spectral modulation depth and electrode separation were found to significantly affect spectral-ripple discrimination. The evidence supports the hypothesis that spectral-ripple discrimination involves integrating information from multiple channels.
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I. INTRODUCTION

Spectral-ripple discrimination, originally developed to investigate the spectral resolution of the normal auditory system (e.g., Supin *et al.*, 1994, 1998, 1999), has recently gained a wide range of attention in the cochlear implant (CI) research field (e.g., Henry and Turner, 2003; Henry *et al.*, 2005; Won *et al.*, 2007; Litvak *et al.*, 2007; Saoji *et al.*, 2009; Drennan *et al.*, 2010; Won *et al.*, 2010, 2011; Anderson *et al.*, 2011). These previous studies demonstrated that spectral-ripple discrimination correlates with vowel and consonant recognition in quiet (Henry *et al.*, 2003, 2005; Saoji *et al.*, 2009), speech perception in noise (Won *et al.*, 2007), and music perception (Won *et al.*, 2010). Henry *et al.* (2005) demonstrated that normal-hearing listeners showed best spectral-ripple discrimination performance followed by hearing-impaired listeners and CI users. Spectral-ripple discrimination is also useful to compare CI sound encoding strategies (Berenstein *et al.*, 2008; Drennan *et al.*, 2010), and for evaluating the brain-behavior relationship for spectral sensitivity using an electrophysiological acoustic change complex in response to spectral-ripple phase inversion (Won *et al.*, 2011). All of those previous reports suggest that spectral-ripple discrimination is an efficient measure of spectral resolution, which is useful for multiple clinically relevant research purposes.

Figure 1 shows the acoustic spectrum, excitation pattern, and sound processor output for spectral-ripple stimuli. Stimuli with ripple densities of 1, 2, and 4 ripples/octave are shown. Two different ripple stimuli are used for the discrimination task: standard and inverted ripple with the location of the spectral peaks and valleys reversed relative to each other. The spectral-ripple depth is 30 dB in this case. As shown in the acoustic spectrum, as the ripple density increases, ripples are spaced more closely, making it more difficult to discriminate between standard and inverted ripple spectrum. The middle column of Fig. 1 shows excitation patterns (Glasberg and Moore, 1990; Moore *et al.*, 1997) for spectral-ripple stimuli. The excitation patterns represent the distribution of neural activity as a function of frequency in a normal auditory system. The largest excitation-pattern differences were observed at 1 ripple/octave, whereas the difference became smaller as the ripple density increased. The right column of Fig. 1 shows the CI sound processor output corresponding to 16 electrodes. The Advanced Bionics HiResolution® sound processing strategy was used for this analysis. Average outputs over the duration of ripple stimuli (0.5 s) for each electrode are plotted. For the ripple densities of 1 and 2 ripples/octave, multiple peaks and valleys are faithfully present across the electrode outputs; however, there is a gradual decrease in the distance between the peaks and valley as the ripple density increases, resulting in reduced spectral contrast between the standard and inverted ripple stimuli, especially at high ripple density (4 ripples/octave). This is consistent with the excitation pattern shown in the middle panel of Fig. 1. Behavioral discrimination also shows a similar trend that CI subjects' discrimination performance is worse at high ripple density. The spectral contrast between the standard and inverted ripple stimuli is reflected in the

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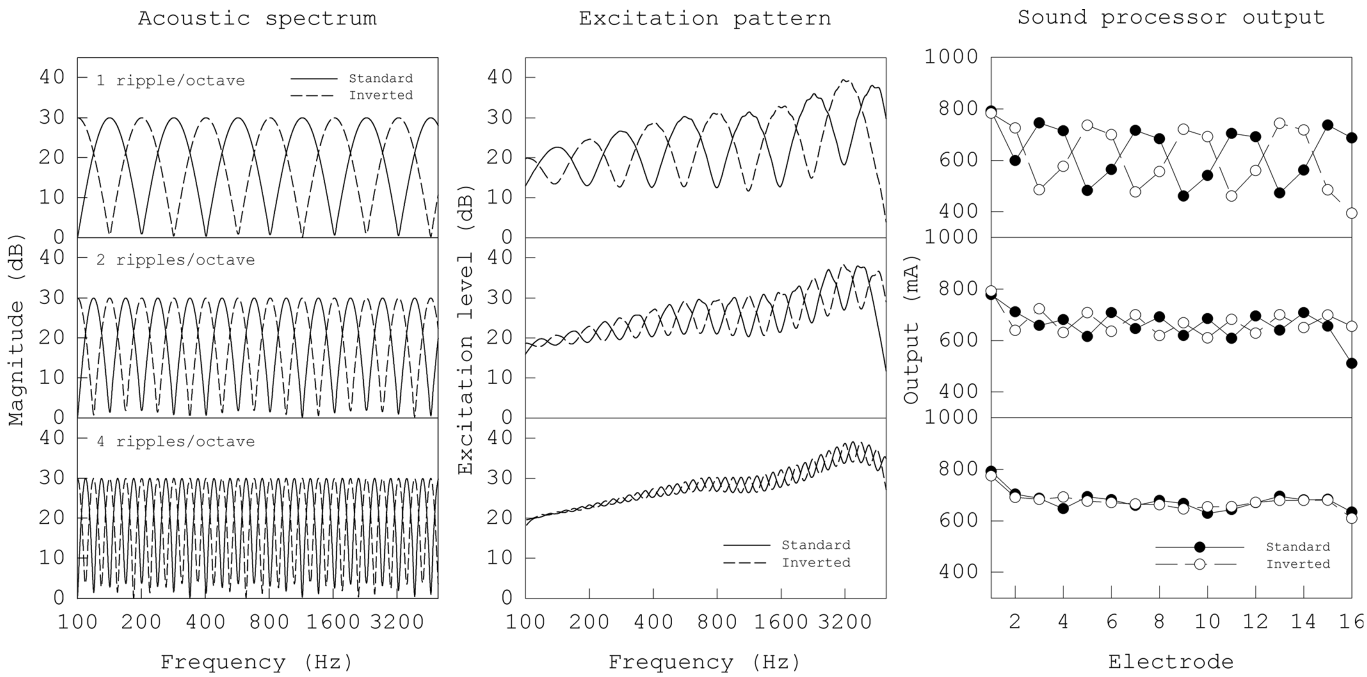

FIG. 1. Acoustic spectrum (left column), cochlear filter excitation pattern (middle column), and sound processor output (right column) for standard (solid lines) and inverted (dotted lines) spectral-ripple stimuli. Stimuli with ripple densities of 1, 2, and 4 ripples/octave are shown in the upper, middle, and lower plot in each panel.

sound processor outputs, and these electrical stimulation patterns would evoke a different excitation pattern for the standard and inverted ripple stimuli in the auditory nerve, suggesting that one of the possible mechanisms of spectral-ripple discrimination is the CI listeners' ability to detect and discriminate any possible spectral maxima and minima over a broad frequency region.

Other possible factors that could influence spectral-ripple discrimination performance in CI listeners include the number of electrodes available to the subjects, integrity or health of the auditory nerve, channel interaction, or sound processing strategies. Previous studies showed that spectral-ripple discrimination improved as the number of electrodes increased (Henry and Turner, 2003), suggesting that spectral-ripple discrimination ability benefits from having multichannel information. Another possible factor is that the levels at the edge frequencies (i.e., lowest and highest frequency) could change depending on the spectral modulation starting phase and it could potentially provide a cue for discrimination. Anderson *et al.* (2011) evaluated the spectral edge effect on discrimination performance. They created smooth spectral edge rippled noise by applying a Hanning window to the spectral edges. When CI listeners were tested with steep (i.e., non-windowed) and smooth spectral edges, they did not show a difference in performance, which suggests that the spectral edge effect is unlikely to affect discrimination performance. Anderson *et al.* (2011) also investigated spectral-ripple discrimination using four different octave-wide band conditions and showed substantial variations in threshold across frequency for most subjects. This observation might indicate if a certain frequency region has a better peripheral condition with, for example, more neural survival or more optimal positioning of the electrodes, then better spectral-ripple discrimination may be observed in that region. From the perspective of CI devices, spectral-ripple discrimination performance depends in part on the sound encoding strategy. Drennan *et al.* (2010) measured spectral-ripple discrimination with the HiResolution and Fidelity120 strategies and showed a significantly better threshold with Fidelity120 than with HiResolution. Here and throughout this paper, "spectral-ripple threshold" means "threshold for discriminating ripple density"; thus lower thresholds imply worse ripple discrimination performance.

However, some questions have been raised recently about spectral-ripple discrimination (e.g., McKay *et al.*, 2009), speculating that CI listeners can potentially discriminate spectral-ripple stimuli using cues that are not related to spectral resolution such as spectral center of gravity or local loudness changes. Spectral center of gravity refers to the gross maxima of the spectrum shape of the acoustic sound (Chistovich and Lublinskaya, 1979). Normal-hearing listeners can distinguish vowels if differences between formants exceed the critical distance of 3 bark for the spectral center of gravity (Chistovich and Lublinskaya, 1979). One can determine if spectral center of gravity serves as a powerful acoustic cue for spectral-ripple discrimination by estimating the spectral center of gravity for spectral-ripple stimuli. Figure 2 shows examples of spectral center of gravity for ripple stimuli with 1 and 2 ripples/octave (bandwidth: 100–5000 Hz) estimated every 0.02 s, computed using a custom MATLAB program (Clark and Atlas, 2009; Atlas *et al.*, 2010). Standard and inverted ripple phases are shown by the solid and dashed lines, respectively. For rippled noise with 1 ripple/octave spacing, an average difference for spectral center of gravity between standard and inverted ripple was 20 Hz. For 2 ripples/octave, it was 12 Hz. The maximum difference

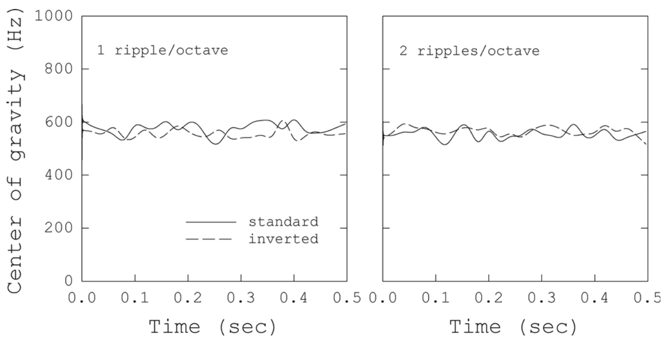

FIG. 2. Spectral center of gravity over the 500-ms duration of standard- and inverted-phase ripple stimuli with 1 and 2 ripples/octave. The time window for the center of gravity estimation (i.e., the size of each bin) was 0.02 s.

at one specific time location was 75 and 48 Hz for 1 and 2 ripples/octave, respectively. All of these differences are less than 0.5 bark, demonstrating that it is highly unlikely that the spectral center of gravity is a cue and especially unlikely it is the only cue for spectral-ripple discrimination by CI listeners and even by normal-hearing listeners.

Given the wide range of practical applications of the spectral-ripple discrimination test for CI users, it is important to determine the dependence, if any, of spectral-ripple discrimination on non-spectral cues. The present study is a further examination of whether CI listeners discriminate spectral-ripple stimuli by integrating information from multiple channels (i.e., across-channel processing). Goupell *et al.* (2008) found no evidence of across-channel processing in CI users in a "profile analysis" task, and they specifically questioned whether CI users respond to intensity information in just one channel in the spectral-ripple discrimination test. In contrast with spectral-ripple discrimination, Goupell *et al.* used a testing paradigm in which only a single spectral peak or trough was presented and the electrical pulse amplitude in each channel was fixed over the stimulus duration. In addition to these stimulus differences, it should be noted that there are subtle but important differences between the two tasks in the role and purposes of the level rove. In psychoacoustical experiments, a level rove is widely used to prevent listeners from using intensity cues for discrimination when the stimuli are different in level. The traditional profile analysis task and spectral-ripple discrimination differ in that the "peak" stimulus has a higher overall level than the "no peak" stimulus in the profile analysis task; whereas, standard- and inverted-phase rippled noise tokens are equal in level (if unroved). In light of multiple differences in the stimuli and the task, it is unclear whether the absence of any evidence of across-channel processing in the study of Goupell *et al.* is relevant to spectral-ripple discrimination by CI users.

The current study presents a series of experiments to evaluate the perceptual mechanisms for spectral-ripple discrimination in CI users. Experiment 1 was designed to test the hypothesis that spectral-ripple discrimination involves integrating information from multiple channels. Standard and inverted ripple stimuli are equal in level, but as a result of cochlear implant sound processing, each individual subject receives different patterns of the growth of loudness across electrodes. The magnitude of level rove was generally smaller than the spectral-ripple depth in the previous studies (e.g., Henry and Turner, 2003; Henry *et al.*, 2005; Won *et al.*, 2007; Anderson *et al.*, 2011), thus there is still a concern that listeners may perform the test on the basis of intensity cues without resolving the spectral peaks and valleys. To address the concern about whether spectral-ripple discrimination is driven by the use of a loudness cue, behavioral performance and model prediction were evaluated for different degrees of intensity cues.

In Experiment 2, the effect of electrode separation on spectral-ripple discrimination in CI listeners was evaluated by testing the hypothesis that spectral-ripple discrimination abilities improve with decreasing channel interaction. Sensitivity to a single electrode stimulus decreases when one or more electrodes stimulate overlapping subsets of nerve fibers due to the decrease of across-fiber independence in excitation. This "channel interaction" effect was examined as a potential contributing factor in spectral-ripple discrimination. Larger electrode separation would be expected to decrease possible channel interaction between two active electrodes.

In Experiment 3, the effect of spectral modulation depth was examined. In principle, the available cues are larger at greater modulation depths. Our previous reports used a spectral ripple modulation depth of 30 dB (Won *et al.*, 2007, 2010, 2011), whereas Experiment 1 in the present study used a spectral modulation depth of 13 dB. This experiment compared spectral-ripple discrimination thresholds obtained with spectral modulation depths of 13 and 30 dB. We predicted that spectral-ripple discrimination thresholds with 30-dB depth would be greater than thresholds with 13-dB depth; however, the thresholds with each depth would be highly correlated.

II. EXPERIMENT 1: THE EFFECT OF SPECTRAL MODULATION PHASE AND LEVEL ROVE ON SPECTRAL-RIPPLE DISCRIMINATION

A. Subjects

Eight postlingually deafened CI listeners participated. Table I shows relevant information for the listeners. This study was approved by the University of Washington Institutional Review Board.

B. Procedure

To create spectral-ripple stimuli, the following equation was used:

$$s(t) = \sum_{i=1}^{200} 10^{D\times\{\text{abs}[\sin(\pi\times R\times F_i+\phi)]\}/20} \times \sin(2\times\pi\times 100\times 50^{(i-1)/200}\times t+\varphi_i), \quad (1)$$

in which D is ripple depth in dB, R is ripples/octave, F_i is the number of octaves from the low cutoff frequency of the passband to the ith component frequency (i.e., $[(i-1)\log_{10}(50)]/[200\log_{10}(2)]$), ϕ is the spectral modulation starting phase in radians, t is time in seconds, the φ_i are the randomized phases in radians (ranged between 0 to 2 π) for 200 pure tone components, and "×" indicates multiplication. The ripple depth (D)

TABLE I. Subject characteristics.

Subject	Age (yr)	Duration of hearing loss (yr)[a]	Duration of implant use (yr)	Implant device	Sound processor strategy	Experiment participated
S03	64	5	14	Nucleus 22	SPEAK	1
S04	66	1	7	Nucleus 24	ACE	1,2
S12	53	0	6	MedEl Combi40+	CIS	1
S34	59		5	HiRes90K	HiRes	2
S40	72	5	6	HiRes90K	HiRes	3
S41	52	7	5	HiRes90K	HiRes	3
S42	68	5	3	HiRes90K	Fidelity 120	3
S48	70	10	3	HiRes90K	HiRes	1,2
S49	64	4	1	HiRes90K	Fidelity 120	3
S50	40	15	6	Clarion CII	Fidelity 120	3
S51	56	7	6	Clarion CII	HiRes	3
S52	79	0	3	HiRes90K	Fidelity 120	1,2
S53	63	3	7	Clarion CII	Fidelity 120	3
S54	25	3	2.5	HiRes90K	HiRes	3
S55	65	40	1	HiRes90K	HiRes	3
S69	60	30	1.5	HiRes90K	Fidelity 120	1,2
S71	71	15	1.5	HiRes90K	Fidelity 120	1,2
S79	64	10	0.5	N5	ACE	1,2

[a]The duration of their hearing loss before implantation.

of 13 dB was used in this experiment. The 200 tones were spaced equally on a logarithmic frequency scale with a bandwidth of 100 – 4903 Hz. The ripple peaks were spaced equally on a logarithmic frequency scale. The stimuli had 500 ms total duration and were ramped with 150 ms rise/fall times. Stimuli were filtered with a long-term, speech-shaped filter that was created in CoolEdit 2000 with parameters specified in accordance with the findings of Byrne *et al.* (1994).

To determine whether spectral-ripple discrimination is dependent on within-channel intensity difference cues or global intensity changes (i.e., information integrated from multiple electrodes), the present study examined spectral-ripple discrimination with three different level roves and two different spectral modulation starting phase conditions. The three different level roves include 0-, 7-, or 15-dB level roves with 1-dB step size. When a level rove of 15-dB was used, it was a condition where the ripple depth (13-dB) was less than the level rove. The two different spectral modulation starting phase conditions include (1) fixed-phase stimuli, in which the spectral modulation starting phase was set to zero radian (sine phase) for standard ripples, and for inverted ripples, it was set to $\pi/2$, and (2) random-phase stimuli, in which the starting phase was randomly selected from a uniform distribution (0 to 2π rad), and for each corresponding inverted ripple stimulus, the phase was determined by adding $\pi/2$ to the phase of the standard ripple stimulus. These two spectral phase conditions were tested to determine if the starting phase of the sinusoid ripple shape in the spectral domain gives any cue for discrimination. In theory, the randomization of the starting phase limits the ability of listeners to rely exclusively on a certain frequency channel to perform spectral-ripple discrimination at a certain ripple density. A similar approach was used by Eddins and Bero (2007), who examined spectral modulation detection in normal-hearing listeners.

The procedure for determining spectral-ripple discrimination thresholds in this experiment is the same as that described by Won *et al.* (2007). A three-interval paradigm, two-up and one-down adaptive procedure was used to determine the spectral-ripple discrimination threshold. More specifically, for the fixed-phase condition, in which the "odd" stimulus always had $\pi/2$ starting phase, the test is a three-interval, three-alternative forced-choice task. For the random-phase condition, in which the starting phase of the "odd" stimulus varies across trials, the test is a three-interval oddity task (Versfeld *et al.*, 1996). Subjects were asked to click on an onscreen button that was labeled 1, 2, and 3 after they were presented the stimuli. The "odd" stimulus was different from two other reference stimuli. The interstimulus interval (offset to onset) was 500 ms. The threshold for a single adaptive track was estimated by averaging the ripple spacing (the number of ripples/octave) for the final eight of 13 reversals. The ripple densities differed by ratios of 1.414. A single adaptive track took about 5 min to complete. Six different testing conditions were carried out in random order (3 level roves $\times$ 2 phase conditions). For each testing condition, three adaptive tracks were completed to determine the average thresholds for that condition, and then subjects were tested with another testing condition. All tests were conducted in a double-walled, sound-treated booth (IAC). Custom MATLAB (The Mathworks, Inc.) programs were used to present stimuli on a Macintosh G5 computer with a Crown D45 amplifier. A single loudspeaker (B&W DM303), positioned 1 m in front of the subjects, presented stimuli in a sound field. When the level rove was 15 dB, the presentation level for each interval was randomly chosen between 49 and 64 dBA with 1-dB step. For the level rove of 7 dB, the presentation level was varied randomly between 57 and 64 dBA. Without the level rove, the presentation level was set to 65 dBA. The speaker exceeded ANSI standards for speech

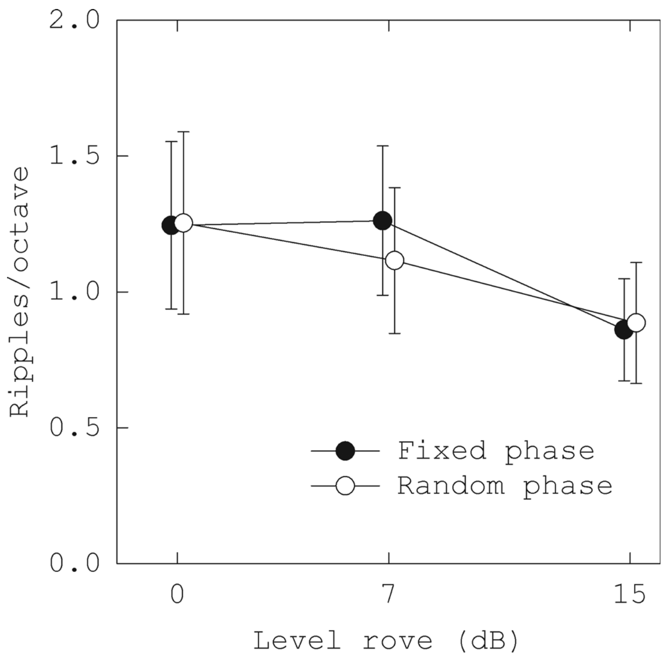

FIG. 3. Spectral-ripple discrimination thresholds for six testing conditions. Error bars represent one standard error across subjects. Data points are slightly horizontally displaced for clarity.

audiometry, varying ± 2 dB from 100 to 20 000 Hz. All subjects listened to the stimuli using their own sound processor set to a comfortable listening level. This experiment took about 2 h for each subject.

C. Results

Figure 3 shows mean spectral-ripple thresholds for each of the six testing conditions. Error bars indicate ± one standard error across eight subjects. Comparison between the phase conditions reveals that the spectral-ripple threshold is robust regardless of spectral modulation starting phase. Thresholds for the 15-dB level rove condition were not significantly different from the 0-dB level rove condition (paired *t*-test, $p > 0.05$) although thresholds trended worse. A $2 \times 3 \times 3$ repeated measures analysis of variance (ANOVA) (two phases, three level roves, and three repetitions) indicated that ripple starting phase ($F_{1,7} = 0.27$, $p = 0.62$), level rove ($F_{2,14} = 3.01$, $p = 0.079$), and repetition ($F_{2,14} = 2.13$, $p = 0.16$) had no effect on thresholds. No interaction was found between the parameters. A *post hoc* Tukey test also showed that thresholds with three different level roves were not significantly different from each other. Significant correlations were found among thresholds for the six testing conditions. In particular, a strong correlation ($r = 0.88$, $p < 0.01$) was found between thresholds obtained with the fixed phase, 0-dB level rove and the random phase, 15-dB level rove conditions, suggesting that a similar hearing mechanism was used for the two markedly different testing conditions.

D. Use of a single intensity cue: Model results

The results of the experiment described above are consistent with the use of cues in multiple channels, but they do not specifically rule out a single-channel mechanism of spectral-ripple discrimination. Thus, a phenomenological model was developed to determine whether it is possible to account for the performance of CI users with a single-channel mechanism. As illustrated in Fig. 4, for each acoustic stimulus the model calculated the pulse trains delivered by a speech processor using an Advanced Bionics HiResolution processing strategy and then multiplied a matrix of channel interactions by the mean pulse amplitudes at the CI electrodes. Tests with the model were conducted using a three-interval oddball paradigm and two-up/one-down adaptive procedure as with human subjects. In each trial, the testing program randomly selected three rippled noise tokens and three stimulus presentation levels within the tested level roving range, and the model output (the "activity vector" in Fig. 4) was calculated for each of the three noise tokens.[1]

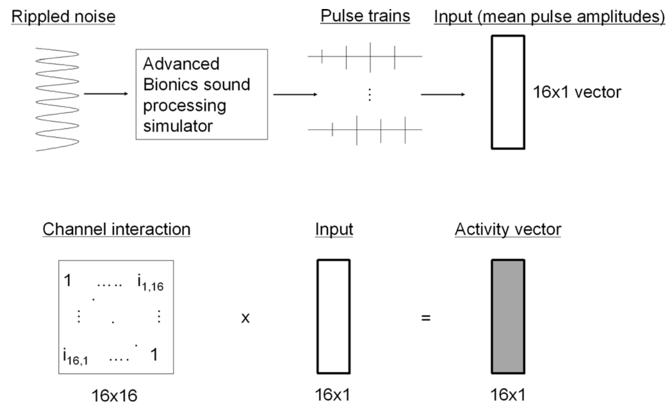

FIG. 4. This schematic diagram illustrates the workings of a two-step phenomenological model that was used to determine whether a single-channel mechanism can account for the spectral-ripple discrimination thresholds of CI users. In the first step the model takes the acoustic stimulus and calculates the electrical stimulus delivered by the device. In the second step the electrical stimulus is multiplied by a matrix of interactions between cochlear implant channels.

For this "single-channel mechanism," the modeled ideal observer had a two-step decision process. First, the model selected the channel in which the difference between the maximum and the minimum of activity was largest. That is, the model was allowed to attend to all channels during the three stimulus intervals and then pick the channel that gave it the largest cue. Second, the model compared activity at the selected channel for the three rippled noise tokens, discarded the two stimuli for which the difference in activity at this channel was smallest, and selected the remaining rippled noise token as the "oddball." The model's response was marked as correct if it chose the inverted-phase noise token as the "oddball" and as incorrect if it chose one of the two standard-phase tokens. For each condition, the mean (± standard error) of thresholds from 10 model runs is plotted. A single asterisk indicates comparisons for which $p < 0.05$; two asterisks indicate comparisons for which $p < 0.01$. It is clear from the model results [open symbols in Fig. 5(a)] that single-channel model thresholds declined markedly as the level rove was increased. This is in marked contrast with the relatively stable thresholds of CI users as the level rove was increased [filled circles in Fig. 5(a)]. A striking example of the effect of level roving on these single-

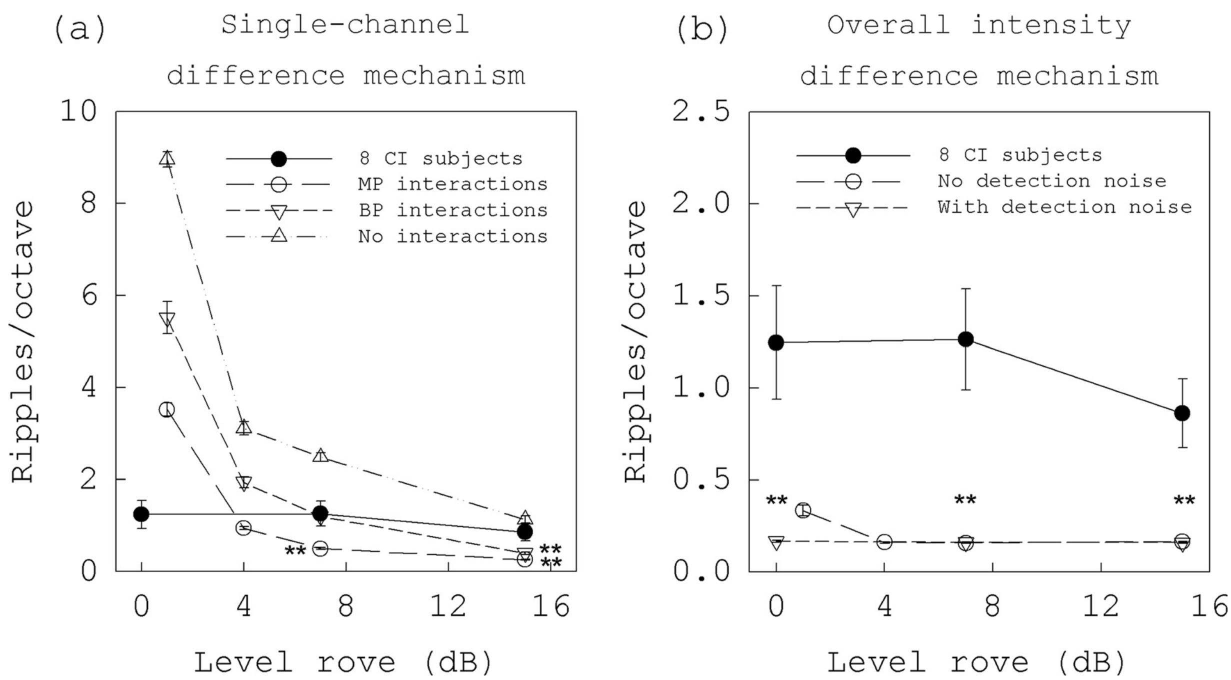

FIG. 5. Thresholds of a phenomenological model that uses discrimination of a single intensity difference to perform the spectral-ripple discrimination task are shown for a mechanism based on the largest single-channel intensity difference (left panel) or on overall intensity difference across all channels (right panel). Model thresholds are shown by open symbols connected by dashed lines, and measured thresholds in 8 CI subjects (shown by filled circles and solid lines) are included for ease of comparison. "MP" and "BP" refer to monopolar and bipolar stimulation modes. Note that the vertical scale differs between the two plots. *: $p < 0.05$, **: $p < 0.01$. Error bars represent one standard error.

channel thresholds is shown by the upward pointing triangles in Fig. 5(a): Even when modeled channel interaction was zero, the single-channel mechanism achieved spectral-ripple discrimination thresholds that were not much greater than the mean thresholds of CI users (filled circles) at a 15-dB level rove. Relative to the no-interaction condition (infinite current decay), performance decreased when current decay was reduced to 8 or 4 dB/mm, which are typical of bipolar and monopolar stimulation modes, respectively (Bingabr *et al.*, 2008). For interactions typical of bipolar stimulation mode (downward pointing triangles), the model's thresholds at a 15-dB level rove were found by *t*-tests to be lower than thresholds of CI users ($p < 0.01$). When interactions were stepped up further to a level typical of monopolar stimulation mode (open circles), which is the stimulation mode of all CI users in this study, the model's thresholds were lower than those of CI users at level roves of 7 and 15 dB ($p < 0.01$ for both). Model calculations in Fig. 5(a) are for tests with fixed ripple starting phase; similar results were obtained with random starting phase (data not shown). These simulations suggest that CI users cannot perform spectral-ripple discrimination by discriminating intensity differences in a single CI channel.

Figure 5(b) shows results when the oddball was selected by an "overall intensity difference" mechanism. Specifically, the model calculated the mean of each activity vector (i.e., averaged across all channels), discarded the two stimuli for which the difference in the means was smallest, and selected the remaining stimulus as the "oddball." The data are plotted as a function of level rove, and performance of CI users at these level roves is shown for comparison [filled circles and solid lines in Fig. 5(b)]. When a small amount of detection noise was simulated [open triangles in Fig. 5(b)] thresholds with the overall intensity discrimination mechanism were lower than thresholds of CI users at roves of 0, 7, and 15 dB ($p < 0.001$ for all three comparisons). The conservative (small) estimate of detection noise used here was the mean of the intensity difference limens for words of the top two performers in the data reported by Rogers *et al.* (2006). Even when no detection noise was modeled [open circles in Fig. 5(b)] thresholds were lower with the overall intensity discrimination mechanism than thresholds of CI users at roves of 7 and 15 dB ($p < 0.001$ for both). These results suggest that CI users cannot rely on overall level differences among rippled noise tokens to perform spectral-ripple discrimination. Taken together, the modeling results strongly suggest that CI users do not perform spectral-ripple discrimination by simply discriminating a single intensity difference between standard- and inverted-phase rippled noise tokens.

TABLE II. Active electrodes for each electrode separation condition for Advanced Bionics and Cochlear devices. The frequency range of the implant map was 250 to 8700 Hz for Advanced Bionics devices and was 188 to 7938 Hz for cochlear devices for all three electrode separation conditions.

	Electrode separation conditions		
Device	1	2	3
Advanced Bionics	6, 7, 8, 9, 10	4, 6, 8, 10, 12	2, 5, 8, 11, 14
Cochlear	9, 10, 11, 12, 13	7, 9, 11, 13, 15	5, 8, 11, 14, 17

III. EXPERIMENT 2: THE EFFECT OF ELECTRODE SEPARATION ON SPECTRAL-RIPPLE DISCRIMINATION

A. Subjects

Seven CI listeners participated. Advanced Bionics device users were tested with the HiResolution strategy using a laboratory sound processor. Cochlear device users were tested with the ACE strategy using a laboratory sound processor.

B. Procedure

To determine the effect of electrode separation on spectral-ripple discrimination, separations between active electrodes were varied parametrically. Three different electrode separations were tested ($\Delta = 1$, 2, and 3) in a random order. For each condition, five electrodes were used, which are shown in Table II. The five electrodes covered the normal input bandwidth of the sound processor. For the three separation conditions, the same filter cutoffs and bandwidths were used; thus, the exact same information was sent to channels for the three conditions. The same procedure described in Experiment 1 was used to determine spectral-ripple discrimination thresholds. In this experiment, spectral-ripple stimuli with fixed phase, 30-dB of spectral-ripple depth, and 7-dB level rove were presented. It was hypothesized that spectral-ripple discrimination thresholds would improve as the electrode separation increased.

C. Results

Figure 6 shows spectral-ripple thresholds as a function of electrode separation. Performance improved as the electrode separation increased. A 3×3 repeated-measures ANOVA (three separation conditions, and three repetitions) showed that the electrode separation had a significant effect ($F_{2,12} = 8.49$, $p = 0.005$), whereas the repetition did not ($F_{2,12} = 2.64$, $p = 0.11$). A *post hoc* Tukey test also showed that thresholds with $\Delta = 3$ are significantly different from thresholds with $\Delta = 1$.

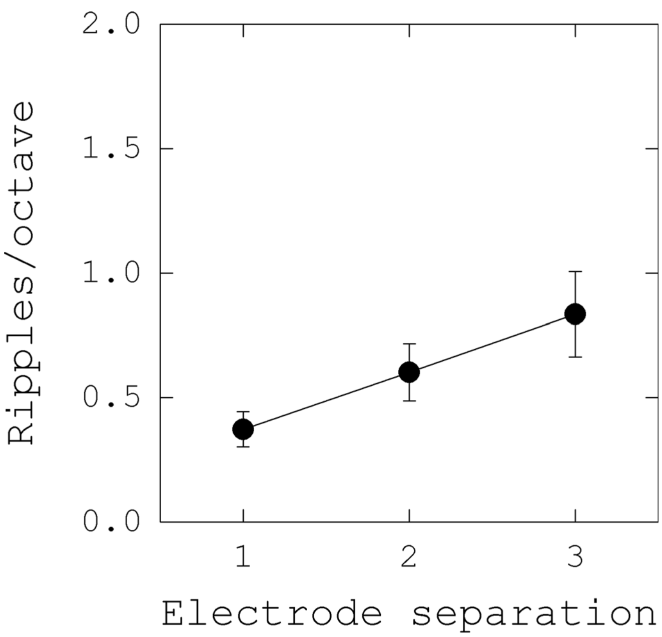

FIG. 6. Spectral-ripple discrimination thresholds as a function of electrode separation. Error bars represent one standard error across subjects.

IV. EXPERIMENT 3: THE EFFECT OF SPECTRAL MODULATION DEPTH ON SPECTRAL-RIPPLE DISCRIMINATION

A. Subjects

A different group of nine CI listeners participated in Experiment 3. The subjects' own clinical processors were used for this experiment.

B. Procedure

Two different spectral modulation depths [D in Eq. (1)] were tested including 13 and 30-dB. Fixed spectral modulation starting phase [ϕ in Eq. (1)] was used for both conditions. Six adaptive tracks were performed using an incomplete Latin square design to determine the average thresholds for 13- and 30-dB depth conditions. A level rove of 7 dB was used.

C. Results

Figure 7 shows the thresholds with 30-dB depth plotted against the thresholds with 13-dB depth for each subject. A highly significant correlation was found between the two thresholds ($r = 0.89$, $p = 0.001$). The slope of the regression line was 0.68 and a paired t-test showed that thresholds obtained with 30-dB depth (average: 2.56 ripples/octave) were significantly higher ($p = 0.001$) than thresholds obtained with 13-dB depth (average: 1.57 ripples/octave), indicating that large modulation depth leads to better discrimination performance.

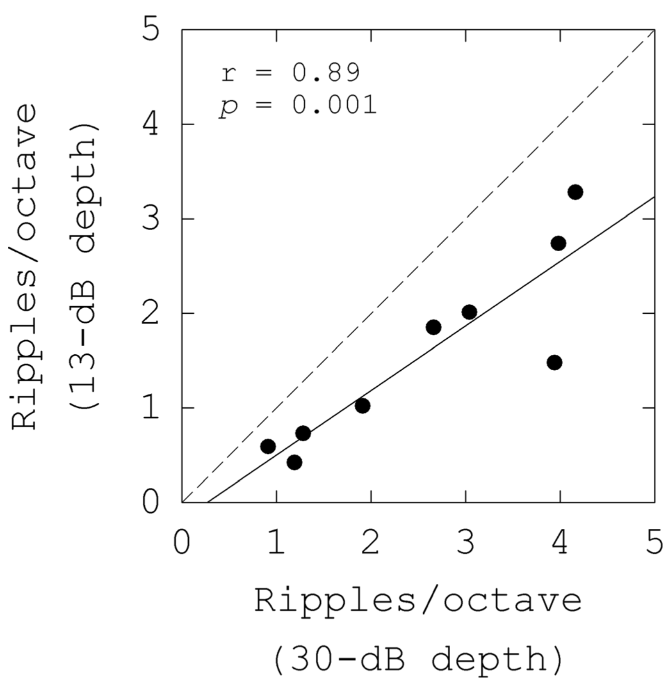

FIG. 7. Comparison between spectral-ripple thresholds obtained with 13- and 30-dB ripple depth in 9 CI users. Thresholds determined with 30-dB depth are plotted (on x axis) against thresholds determined with 13-dB depth (on y axis) for each subject. Linear regression is represented as a solid line. The dotted diagonal line represents $y = x$.

V. DISCUSSION

A. Evidence of across-channel processing: Behavioral data

The spectral-ripple stimulus produces modulation in level as a function of frequency; therefore, standard and inverted ripple stimuli are equal in overall acoustic level, except for variations due to level rove. If the CI listeners use a single within-channel intensity cue, such that the listeners focus on using a certain electrode comparing the level corresponding to a standard and inverted stimulus, then the randomization of the starting phase would negate any benefit from focusing on that electrode over and over again. It should be noted that even for the fixed-phase condition, the electrode showing the largest level difference varies with ripple density. Therefore, it may be unrealistic to expect that CI listeners can focus on a certain electrode exclusively and use the level difference on that electrode for spectral-ripple discrimination. The fact that the results were the same with randomized ripple phase suggests that CI listeners cannot achieve their performance by using between-interval intensity differences on a single electrode, but they utilize across-channel comparisons of level to conduct spectral-ripple discrimination.

Another possibility is that subjects had the ability to select the channel with the biggest difference in level and make a decision on each trial. While it is somewhat implausible that they could switch their attention to the best channel from trial to trial, this approach would fail when 15-dB level rove was used with a 13-dB ripple depth, because the roving variations would mask such a cue. The thresholds measured with the minimum (fixed phase and 0-dB level rove) and maximum (random phase and 15-dB level rove) limitation in the utility of within-channel intensity cues were significantly correlated ($r = 0.88$, $p < 0.01$). The strong correlation suggests the results are driven by the spectral sensitivity. The modeling results also support this position.

B. Evidence of across-channel processing: Model simulations

The phenomenological model presented in Experiment 1 also suggests that across-channel rather than within-channel level cues are used by demonstrating that level cues fail to account for the behavioral results. Two mechanisms were tested in the model: (1) a "single-channel" mechanism, and (2) an "overall intensity difference" mechanism. The "single-channel" mechanism produced generally higher thresholds than the "overall intensity difference mechanism," but CI subjects still outperformed the single-channel model at the largest level rove. Particularly when the single-channel model was implemented with the monopolar stimulation mode, CI subjects showed significantly better thresholds than the model outputs. When the "overall intensity difference" mechanism was used, the model thresholds were significantly lower than thresholds obtained from CI subjects for all level roves, suggesting that CI listeners did not use the overall level cue for spectral-ripple discrimination. Taken together, the significantly lower performance obtained with the two models suggest that CI listeners use neither a single-channel intensity cue nor an overall intensity cue for spectral-ripple discrimination.

C. Influence of level rove and its implication for level cue

Profile analysis (e.g., Green *et al.*, 1983; Green, 1988) is another psychoacoustic measure for spectral sensitivity. An electrical variant of the typical profile analysis paradigm was used with CI users in a study by Goupell *et al.* (2008). In that study performance of CI users declined with increasing level rove, and thresholds were such that the use of level cues could not be ruled out. Thus, no evidence was found that across-channel processes were used. Based on this result, Goupell *et al.* questioned whether spectral-ripple discrimination by CI users depends on across-channel processing. The traditional profile analysis testing paradigm, however, differs from spectral-ripple discrimination in many aspects. In the traditional profile analysis paradigm, the reference stimulus presents a fixed number of equal-amplitude pure tone components simultaneously. The test stimulus presents the same number of pure tone components with the same amplitudes as the reference stimulus except that one of the tones has an intensity increment. Therefore, the overall level (overall root-mean-square, RMS) for the test stimuli for a typical profile analysis test is greater than the reference stimulus. In the present spectral ripple discrimination task, the overall rms level for standard and inverted ripple *is the same* trial to trial. Thus, in this spectral ripple paradigm, *there is no overall level cue*. Green (1988, p. 20) defined the level rove required to make overall level cues unusable; however, these calculations do not apply to spectral-ripple discrimination because the overall RMS level in spectral ripple discrimination is the same from trial to trial.

An important and practical question is how large the level rove range needs to be to ensure that listeners are not using level cues, and at the same time, the listeners' performance is not degraded by excessive level rove. The following analysis shows that in this paradigm, 15-dB is a sufficient level rove for spectral ripple stimuli with a 13-dB ripple depth by demonstrating that the maximum possible percent correct than could be achieved with the unwanted level cue is much less than the percent correct actually achieved using the Levitt tracking (70.7%). Dai and Micheyl (2010) provided the relationship among the roving range (R), the largest proportion of correct responses that could conceivably be achieved on the basis of the unwanted cue ($PC_{unwanted}$), and the size of the unwanted cue ($\Delta_{unwanted}$) for oddity tasks. Using the pulse train outputs of HiResolution sound processing, these metrics were evaluated. Two different unwanted cues were evaluated: (1) within-band maximum electric level difference; and (2) overall electric level difference. For this analysis, ripple stimuli with 13-dB depth and random starting phase were used, which were presented with a three-interval oddity task. For the within-band maximum electric level difference, an absolute value of the electric level difference between standard and inverted ripple stimuli was computed for each of 16 channels, then the maximum difference was taken as a final value. For the overall

TABLE III. $\Delta_{unwanted}$/R and $PC_{unwanted}$ values as a function of ripple densities (ripples/octave). $PC_{unwanted}$ values were estimated using Table 4 in Dai and Micheyl (2010). "R_a" and "R_e" refer to level rove in acoustic level (dB) and electric level (μA).

(A) $\Delta_{unwanted}$ estimated using maximum within-channel electric level difference

Density	1		1.414		2		4	
$\Delta_{unwanted}$ (μA)	142.03		119.60		72.36		25.54	
R_a	7	15	7	15	7	15	7	15
R_e (one channel)	126	270	126	270	126	270	126	270
$\Delta_{unwanted}/R_e$	1.13	0.53	0.95	0.44	0.57	0.27	0.20	0.095
$PC_{unwanted}$	1	0.56	0.95	0.5	0.6	0.4	0.37	0.34

(B) $\Delta_{unwanted}$ estimated using overall electric level difference

Density	1		1.414		2		4	
$\Delta_{unwanted}$ (μA)	15.76		2.21		4.5		4.85	
R_a	7	15	7	15	7	15	7	15
R_e (across 16 channels)	2016	4320	2016	4320	2016	4320	2016	4320
$\Delta_{unwanted}/R_e$	0.0078	0.0036	0.0011	0.00051	0.0022	0.001	0.0024	0.0011
$PC_{unwanted}$	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33

electric level difference, the current levels (in μA) for 16 channels over the duration of the stimulus (500 ms) were summed, then the absolute value of the difference between standard and inverted ripple stimuli was calculated.

Table III shows the size of unwanted cue determined by the two methods described above. The first row shows four different ripple densities, the second row shows $\Delta_{unwanted}$, the third row shows two different level roves in acoustic dB units, the fourth row shows level roves computed in electric level (R_e in μA), the fifth row shows values of $\Delta_{unwanted}/R_e$, and the sixth row shows values of $PC_{unwanted}$ corresponding to $\Delta_{unwanted}/R_e$. Table 4 and Fig. 3 of Dai and Micheyl (2010) provide $PC_{unwanted}$ values corresponding to $\Delta_{unwanted}/R_e$. When the within-band maximum electric level difference was used as the (unwanted) cue, $PC_{unwanted}$ values varied across ripple densities (Table IIIA). When a 15-dB level rove was used, $PC_{unwanted}$ values ranged from 0.34 to 0.56. When the overall electric level difference was used as the unwanted cue, $PC_{unwanted}$ values with a 15-dB level rove were 0.33 for all ripple densities (Table IIIB). This suggests that 15-dB level rove was sufficient to ensure that CI subjects could not obtain 70.7% correct responses in spectral-ripple discrimination with a three-interval, oddity task on the basis of either an overall or a within-band level difference cue. Experiment 1 demonstrated that the average thresholds for the 13-dB fixed phase and 13-dB random phase conditions were not different; therefore 15-dB level rove is also sufficient for the fixed-phase condition. The spectral-ripple test used a two-up, one-down adaptive procedure, so the targeted proportion correct level is 0.707 (Levitt, 1971). The $PC_{unwanted}$ value of 0.33 is not only significantly below the targeted level of 0.707 but is also at chance level. This suggests that the CI subjects did not use overall electric level difference for spectral-ripple discrimination.

D. Influence of electrode separation

Experiment 2 showed that better spectral-ripple discrimination was achieved with large electrode separation (Fig. 6), suggesting that channel interaction is one of the factors influencing spectral-ripple discrimination in CI users. Such an effect would not occur if listeners were basing decisions on an overall level change, because electrode separation has no effect on the overall level. The stimuli were processed with the same filter cutoffs and bandwidths for the three conditions. Litvak *et al.* (2007) simulated various amounts of current spread and showed that variability in spread of neural activation largely accounts for the variability in spectral modulation detection thresholds in CI listeners, which is consistent with the present results. The extent to which peripheral channel interactions occur in individual subjects would be expected to partly account for the subject's ability to analyze and integrate information from multiple channels.

E. Effect of modulation depth

Larger modulation depth provides a greater contrast between the peaks and valleys for standard and inverted stimuli and enhances perceptual discrimination. Experiment 3 showed that although spectral-ripple discrimination is strongly dependent on the modulation depth, the strong correlation ($r = 0.89$ in Fig. 7) between the thresholds with 13- and 30-dB depth suggests that the same underlying mechanism is used regardless of the modulation depth. Previous spectral-ripple discrimination studies (e.g., Henry *et al.*, 2005; Won *et al.*, 2007) used 30-dB modulation depth with 8-dB level rove. Although the level rove was smaller than the ripple depth in these previous studies, the high correlation between 13- and 30-dB depth ripples suggests a common across-channel mechanism.

VI. SUMMARY

(1) Reducing intensity cues by varying level rove did not lead to big changes in spectral-ripple thresholds. This suggests that spectral-ripple thresholds in CI users are not driven by the use of an intensity cue.
(2) Reducing intensity cues by varying level rove *did* lead to big changes in spectral-ripple thresholds when a modeled "ideal observer" used a single channel or overall intensity cue. The model also did not obtain the level of

the behavioral performance observed in CI users, indicating that such intensity cues are not the basis of spectral-ripple discrimination in CI users.

(3) Larger electrode separation improved spectral-ripple thresholds, suggesting that channel interaction significantly affects spectral-ripple discrimination.

(4) A greater spectral modulation depth produced better thresholds, but the thresholds obtained with 13- and 30-dB depth were highly correlated, suggesting that a simple change in the spectral modulation depth does not affect which mechanisms are used to perform the task.

(5) Taken together, the results provide evidence of the use of across-channel mechanisms in discrimination of spectral ripple stimuli in CI users.

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[1]In a few special cases where the test conditions were quite simple, e.g., no level roving along with no detection noise and/or no channel interactions, the modeled ideal observer achieved 100% correct performance at all tested ripple densities. In such cases, tests at level roves of 1 and 4 dB were also conducted and thresholds at these level roves are plotted in place of the 0-dB rove. In the small subset of tests for which the entire range of the rove was just 1 dB, the rove was in 0.25-dB steps; otherwise the rove was in 1-dB steps.

Anderson, E. S., Oxenham, A. J., Kreft, H., Nelson, P. B., and Nelson, D. A. (**2011**). "Comparing spectral tuning curves, spectral ripple resolution, and speech perception in cochlear implant users," J. Acoust. Soc. Am. **130**, 364–375.

Atlas, L., Clark, P., and Schimmel, S. (**2010**). Modulation Toolbox Version 2.1 for MATLAB, http://isdl.ee.washington.edu/projects/modulationtoolbox/, University of Washington. (Last viewed 7/14/11).

Berenstein, C. K., Mens, L. H., Mulder, J. J., and Vanpoucke, F. J. (**2008**). "Current steering and current focusing in cochlear implants: comparison of monopolar, tripolar, and virtual channel electrode configurations," Ear. Hear. **29**(2), 250–60.

Bingabr, M., Espinoza-Varas, B., and Loizou, P. C. (**2008**). "Simulating the effect of spread of excitation in cochlear implants," Hear. Res. **241**, 73–9.

Byrne, D., Dillon, H., Tran, K., Arlinger, S., Wilbraham, K., Cox, R., Hagerman, B., Hetu, R., Kei, J., Lui, C., Kiessling, J., Kotby, M., Nasser, A., Kholy, W., Nakanishi, Y., Oyer, H., Powell, R., Stephens, D., Meredith, R., Sirimanna, T., Tavartkiladze, G., Frolenkov, G., Westerman, S., and Ludvigsen, C. (**1994**). "An international comparison of long-term average speech spectra," J. Acoust. Soc. Am. **96**, 2108–2120.

Chistovich, L. A., and Lublinskaya, V. V. (**1979**). "The 'center of gravity' effect in vowel spectral and critical distance between the formants: Psychoacoustical study of the perception of vowel-like stimuli," Hear. Res. **1**, 185–195.

Clark, P., and Atlas, L. (**2009**). "Time-frequency coherent modulation filtering of nonstationary signals," IEEE Trans. Signal Process. **57**(11), 4323–4332.

Dai, H., and Micheyl, C. (**2010**). "On the choice of adequate randomization ranges for limiting the use of unwanted cues in same-different, dual-pair, and oddity tasks," Atten., Percept., Psychophys. **72**, 538–547.

Drennan, W. R., Won, J. H., Nie, K., Jameyson, M. E., and Rubinstein, J. T. (**2010**). "Sensitivity of psychophysical measures to signal processor modifications in cochlear implant users," Hear. Res. **262**, 1–8.

Eddins, D. A., and Bero, E. M. (**2007**). "Spectral modulation detection as a function of modulation frequency, carrier bandwidth, and carrier frequency region," J. Acoust. Soc. Am. **121**, 363–372.

Glasberg, B. R., and Moore, B. C. J. (**1990**). "Derivation of auditory filter shapes from notched-noise data," Hear. Res. **47**, 103–138.

Goupell, M. J., Laback, B., Majdak, P., and Baumgartner, W. D. (**2008**). "Current-level discrimination and spectral profile analysis in multi-channel electrical stimulation," J. Acoust. Soc. Am. **124**, 3142–3157.

Green, D. M., Kidd, G., Jr., and Picardi, M. C. (**1983**). "Successive versus simultaneous comparison in auditory intensity discrimination," J. Acoust. Soc. Am. **73**, 639–643.

Green, D. M. (**1988**). *Profile Analysis: Auditory Intensity Discrimination* (Oxford University Press, New York), p. 20.

Henry, B. A., and Turner, C. W. (**2003**). "The resolution of complex spectral patterns by cochlear implant and normal-hearing listeners," J. Acoust. Soc. Am. **113**, 2861–2873.

Henry, B. A., Turner, C. W., and Behrens, A. (**2005**). "Spectral peak resolution and speech recognition in quiet: normal hearing, hearing impaired, and cochlear implant listeners," J. Acoust. Soc Am. **118**, 1111–1121.

Levitt, H. (**1971**). "Transformed up-down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467–477.

Litvak, L. M., Spahr, A. J., Saoji, A. A., and Fridman, G. Y. (**2007**). "Relationship between perception of spectral ripple and speech recognition in cochlear implant and vocoder listeners," J. Acoust. Soc. Am. **122**, 982–991.

McKay, C. M., Azadpour, M., and Akhoun, I. (**2009**). "In search of frequency resolution," Presented at the 2009 Conference on Implantable Auditory Prostheses, Tahoe City, CA, Abstract book page 54.

Moore, B. C. J., Glasberg, B. R., and Baer, T. (**1997**). "A model for the prediction of thresholds, loudness and partial loudness," J. Audio Eng. Soc. **45**, 224–240.

Rogers, C. F., Healy, E. W., and Montgomery, A. A. (**2006**). "Sensitivity to isolated and concurrent intensity and fundamental frequency increments by cochlear implant users under natural listening conditions," J. Acoust. Soc. Am. **119**, 2276–2287.

Saoji, A. A., Litvak, L. M., Spahr, A. J., and Eddins, D. A. (**2009**). "Spectral modulation detection and vowel and consonant identifications in cochlear implant listeners," J. Acoust. Soc. Am. **126**, 955–958.

Supin, A. Y., Popov, V. V., Milekhina, O. N., and Tarakanov, M. B. (**1994**). "Frequency resolving power measured by rippled noise," Hear. Res. **78**, 31–40.

Supin, A. Y., Popov, V. V., Milekhina, O. N., and Tarakanov, M. B. (**1998**). "Ripple density resolution for various rippled-noise patterns," J. Acoust. Soc. Am. **103**, 2042–2050.

Supin, A. Y., Popov, V. V., Milekhina, O. N., and Tarakanov, M. B. (**1999**). "Ripple depth and density resolution of rippled noise," J. Acoust. Soc. Am. **106**, 2800–2804.

Versfeld, N. J., Dai, H., and Green, D. M. (**1996**). "The optimum decision rules for the oddity task," Percept. Psychophys. **58**, 10–21.

Won, J. H., Drennan, W. R., and Rubinstein, J. T. (**2007**). "Spectral-ripple resolution correlates with speech reception in noise in cochlear implant users," J. Assoc. Res. Otolaryngol. **8**, 384–392.

Won, J. H., Drennan, W. R., Kang, R. S., and Rubinstein, J. T. (**2010**). "Psychoacoustic abilities associated with music perception in cochlear implant users," Ear. Hear. **31**, 796–805.

Won, J. H., Clinard, C. G., Kwon, S. Y., Dasika, V. K., Nie, K., Drennan, W. R., Tremblay, K. L., and Rubinstein, J. T. (**2011**). "Relationship between behavioral and physiologic spectral-ripple discrimination," J. Assoc. Res. Otolaryngol. **12**, 375–393.