Pitch ranking, electrode discrimination, and physiological spread of excitation using current steering in cochlear implants

Jenny L. Goehring, Donna L. Neff, Jacquelyn L. Baudhuin, and Michelle L. Hughes^{a)}

Boys Town National Research Hospital, Lied Learning and Technology Center, 425 North 30th Street, Omaha, Nebraska 68131

(Received 7 July 2014; revised 7 October 2014; accepted 8 October 2014)

The first objective of this study was to determine whether adaptive pitch-ranking and electrode-discrimination tasks with cochlear-implant (CI) recipients produce similar results for perceiving intermediate “virtual-channel” pitch percepts using current steering. Previous studies have not examined both behavioral tasks in the same subjects with current steering. A second objective was to determine whether a physiological metric of spatial separation using the electrically evoked compound action potential spread-of-excitation (ECAP SOE) function could predict performance in the behavioral tasks. The metric was the *separation index* (Σ), defined as the difference in normalized amplitudes between two adjacent ECAP SOE functions, summed across all masker electrodes. Eleven CII or 90 K Advanced Bionics (Valencia, CA) recipients were tested using pairs of electrodes from the basal, middle, and apical portions of the electrode array. The behavioral results, expressed as d' , showed no significant differences across tasks. There was also no significant effect of electrode region for either task. ECAP Σ was not significantly correlated with pitch ranking or electrode discrimination for any of the electrode regions. Therefore, the ECAP separation index is not sensitive enough to predict perceptual resolution of virtual channels.

© 2014 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4900634>]

PACS number(s): 43.64.Me, 43.64.Pg, 43.66.Hg, 43.66.Ts [BLM]

Pages: 3159–3171

I. INTRODUCTION

Virtual channels were developed to increase the number of stimulating sites along the cochlear implant (CI) electrode array. The mechanisms used to achieve virtual channels differ across devices [e.g., “current steering” for Advanced Bionics (Valencia, CA) and “dual-electrode” mode for Cochlear Corporation (Macquarie, New South Wales, Australia)]. With current steering, virtual channels are produced by adjusting the relative weighting of current with simultaneous stimulation of two physical electrodes. The result is that the current fields from the two physical electrodes summate sufficiently to stimulate the neurons intermediate to the two physical electrodes (Frijns *et al.*, 2009). With adequate nerve survival, more than one intermediate pitch percept can be generated between the adjacent physical electrodes (e.g., Donaldson *et al.*, 2005; Firszt *et al.*, 2007; Koch *et al.*, 2007; Donaldson *et al.*, 2011; Snel-Bongers *et al.*, 2012). Dual-electrode mode, on the other hand, uses electrical coupling (i.e., shorting together) of adjacent electrodes, creating one intermediate channel between the two electrodes. Presently, current steering is Food and Drug Administration approved for clinical applications; however, dual-electrode mode is investigational.

Previous studies have shown significant variability in CI users’ ability to distinguish virtual channels on formal psychophysical tasks; however, methodological differences across studies make it difficult to evaluate the range of performance (Busby and Plant, 2005; Donaldson *et al.*, 2005; Firszt *et al.*, 2007; Koch *et al.*, 2007; Brendel *et al.*, 2008;

Busby *et al.*, 2008; Firszt *et al.*, 2009; Donaldson *et al.*, 2011; Snel-Bongers *et al.*, 2012). Therefore, the first aim of the present study was to examine measures of pitch ranking and electrode discrimination in the same subjects using devices capable of current steering. Previous work has also shown that it can be difficult to predict which CI recipients will benefit from the spectral detail potentially offered by virtual channels (Donaldson *et al.*, 2011). Pitch tasks are often quite difficult, even for trained adults. For recipients who cannot provide reliable perceptual judgments, it would be useful to have an objective measure to help determine virtual-channel perception. Therefore, the second aim of this study was to determine how well perception of virtual channels produced by current steering in Advanced Bionics devices can be predicted by objective measures of spatial separation using the electrically evoked compound action potential spread-of-excitation (ECAP SOE) function. This study was performed concurrently with another study from our laboratory, investigating similar comparisons with dual-electrode mode in recipients of the Cochlear Corporation device (Goehring *et al.*, 2014).

Pitch-ranking and/or electrode-discrimination tasks have been used to evaluate whether CI recipients can distinguish electrodes on the basis of pitch (Collins *et al.*, 1997; Zwolan *et al.*, 1997; Busby and Plant, 2005; Donaldson *et al.*, 2005; Hughes and Abbas, 2006a; Firszt *et al.*, 2007; Busby *et al.*, 2008; Snel-Bongers *et al.*, 2012). Clinically, these tasks may help decisions regarding channel deactivation in speech-processor programs. With pitch ranking, subjects judge a stimulus along a tonotopic scale as either “higher” or “lower” in pitch compared to another stimulus. This is often assessed with a two-interval forced-choice (2IFC) task. Correct-answer feedback is generally *not*

^{a)}Author to whom correspondence should be addressed. Electronic mail: michelle.hughes@boystown.org

provided, as this is a subjective judgment of the recipient's perception of pitch with electrical stimulation (i.e., there is no "right" answer). In contrast, with electrode discrimination, subjects are instructed that one stimulus is different from the others and are asked to judge which stimulus is different in pitch. When more than two intervals are used (e.g., three-interval forced-choice, 3IFC), it becomes a task of selecting which one is "different" from the comparison stimuli. Feedback is often provided to help participants learn the percepts associated with place of stimulation along the array.

Early studies comparing pitch percepts for physical-electrode stimulation showed that pitch-ranking and electrode-discrimination tasks using the same subjects did not yield equivalent perceptual outcomes (Collins *et al.*, 1997; Zwolan *et al.*, 1997; Collins and Throckmorton, 2000). For all but one subject, these studies revealed more discriminable electrodes for electrode discrimination than for pitch ranking. However, these subjects had older Cochlear Corporation devices, which utilized bipolar stimulation modes (rather than the more common monopolar mode of newer devices). Recent data from our laboratory, which investigated pitch ranking and electrode discrimination for adjacent physical electrodes and corresponding dual electrodes using newer Cochlear devices [CI24RE(CA)/CI422 and CI512; Goehring *et al.*, 2014], showed similar performance for the two tasks. However, the mechanism used to achieve virtual channels (dual-electrode mode) in that study is different from current steering. Consequently, this study investigated whether pitch ranking and electrode discrimination with current steering would yield similar estimates of pitch perception for Advanced Bionics recipients.

With current steering, virtual-channel perception is defined by α , which is the smallest proportion of current split between two electrodes that can be perceptually detected (e.g., Firszt *et al.*, 2007). Values of α range from 0 to 1 ($0 < \alpha < 1$), where α is the proportion of current directed to the basal physical electrode, and $1 - \alpha$ is the proportion of current directed to the apical electrode. Smaller α values indicate that lesser proportions of current distribution can be detected, which translates to a greater number of discriminable intermediate virtual-channel percepts. For example, $\alpha = 0.1$ indicates that the virtual channel can be distinguished from the apical physical electrode in the pair when only 10% of the total current is directed to the basal physical electrode. Early work investigating virtual-channel percepts using current steering was reported by Donaldson *et al.* (2005), Firszt *et al.* (2007), and Koch *et al.* (2007). These studies used a 2IFC pitch-ranking task in which α was adapted. These studies established that additional pitch percepts beyond the number of physical-electrode contacts could be created using current steering for at least a subset of subjects (a total of 2–9 pitch percepts per physical-electrode pair). Further, they found that perception of virtual channels differed across regions of the electrode array, being poorest for basal electrodes.

One challenge for studies of pitch perception with CI recipients is that loudness cues often occur with changes in stimulation parameters and can confound measures of pitch perception. Earlier studies only used loudness balancing for

the physical electrodes associated with each virtual channel to equate loudness across stimuli (Donaldson *et al.*, 2005; Firszt *et al.*, 2007; Koch *et al.*, 2007). Although this should reduce loudness cues, only a subset of the stimuli (i.e., physical electrodes) were balanced. Therefore, residual loudness cues might still have affected performance, which could have contributed to *better* apparent perception of virtual channels. To further reduce potential loudness cues, a small variation ("rove") in level can be applied to each stimulus presentation. Subjects are informed of this rove and instructed to base their judgments on changes in pitch, not level. In Donaldson *et al.* (2011), which used level rove, virtual-channel percepts were evaluated in ten Advanced Bionics subjects using a 2IFC task. Thresholds ranged from $\alpha = 0.09$ to $\alpha > 1.0$ (values > 1.0 indicated inability to pitch rank adjacent physical electrodes). Further, the study examined whether performance on speech-perception tasks with the Fidelity 120¹ speech-processing strategy could be predicted by individual outcomes on the psychophysical pitch-ranking tasks. Performance with Fidelity 120 was only correlated with second formant features from a vowel-discrimination task. Subjects with α thresholds < 0.3 tended to have better performance with Fidelity 120, while those with $\alpha > 0.3$ tended to do better with standard HiRes. In sum, the pitch-ranking study of Donaldson *et al.* (2011) showed the difficulty of determining which recipients would benefit from virtual-channel technology. Further, long trial periods were needed to gauge improvements over time. Thus, it would be useful if an objective measure were available to help assess the use of virtual channels in the clinical management of CI recipients.

For current steering, electrode-discrimination tasks have been less frequently examined. Snel-Bongers *et al.* (2012) examined electrode discrimination for virtual channels using a 3IFC task in 12 Advanced Bionics 90 K recipients with a level rove. They found poorer performance for the electrode discrimination task compared with that from the 2IFC pitch-ranking studies described above (Firszt *et al.*, 2007; Koch *et al.*, 2007). In the Snel-Bongers *et al.* (2012) study, subjects had an average of 20 additional pitch percepts summed across the array, compared with 64 channels in Firszt *et al.* (2007), and 93 in Koch *et al.* (2007). Although it might be concluded that pitch ranking and electrode discrimination do not yield the same number of virtual-channel percepts, it is difficult to directly compare the results across the studies. First, as stated above, no stimulus-level rove was applied to the Firszt *et al.* and Koch *et al.* pitch-ranking studies, so virtual-channel perception based on pitch may have been overestimated. Second, there are large individual differences in ability to perceive virtual channels, so subject samples across studies may account for the differences in outcomes. Therefore, the present study compares pitch ranking and electrode discrimination in the same subject sample using current steering.

Given that clinical CI populations include recipients who cannot be tested using psychophysical or speech-perception measures, it is important to investigate whether an objective measure can be developed to predict perception of virtual channels. The ECAP SOE function has been

examined for virtual-channel stimulation (Busby *et al.*, 2008; Saoji *et al.*, 2009; Hughes and Goulson, 2011; Snel-Bongers *et al.*, 2012; Hughes *et al.*, 2013). These studies have shown that virtual channels produce ECAP SOE patterns similar to those of physical electrodes. More recently, Hughes and Goulson (2011) determined that virtual-channel SOE amplitudes fall approximately half-way between the amplitudes of adjacent physical electrodes for both dual-electrode mode and current steering. Hughes *et al.* (2013) showed that spatial separation of SOE patterns was greater between adjacent physical electrodes than between the intermediate virtual channels and the flanking physical electrodes, indicating measurable separation between neural populations. Therefore, it seems conceivable that the ECAP SOE could be used as an objective tool to assist in predicting behavioral perception of virtual channels.

Few studies have directly compared the ECAP SOE with pitch-based measures for virtual channels (Busby *et al.*, 2008; Snel-Bongers *et al.*, 2012; Goehring *et al.*, 2014). Busby *et al.* (2008) evaluated the relation between the ECAP SOE width (calculated at 75% of the normalized peak amplitude) and pitch ranking (2IFC) for dual electrodes versus physical electrodes in eight Cochlear subjects. The ordering of electrodes at the peaks and sides of the ECAP SOE for adjacent physical electrodes and the corresponding dual electrode were compared. Results showed no significant relation between the ECAP SOE width and pitch ranking for dual electrodes. In a study with the Advanced Bionics device and a 3IFC electrode-discrimination task, Snel-Bongers *et al.* (2012) compared the ECAP SOE width (same 75% normalized-amplitude criterion) with α thresholds for 12 recipients. They, too, found no significant correlation between α and the ECAP SOE width. These results are consistent with earlier findings reported by Hughes and Abbas (2006a) for physical-electrode comparisons, in which they suggested that the 75% normalized-width measure of the SOE function was not suitable for predicting pitch-based cues, likely because it does not take into account the entire SOE function. Hughes (2008) subsequently developed the

ECAP separation index (Σ) as an alternative to the width measure, and used it to compare with pitch-ranking findings in the same group of ten Cochlear subjects from Hughes and Abbas (2006a). The separation index sums the absolute value of the difference in normalized ECAP amplitudes across all masker electrodes. The Hughes (2008) study found that ECAP Σ was significantly correlated with pitch-ranking accuracy for physical electrodes. Specifically, as the spatial distance between physical electrodes increased along the cochlea (from one to six electrode separations), ECAP Σ became larger and pitch-ranking accuracy improved. The methodology from Hughes (2008) was extended from the measurement of physical electrodes to virtual channels in the present study, as well as in a companion study by Goehring *et al.* (2014), which compared ECAP Σ and pitch measures for Cochlear recipients using dual-electrode stimulation (described further in the Discussion).

Based on the findings of Hughes (2008), we hypothesized that recipients with greater amounts of spatial separation between adjacent physical-electrode SOE functions (larger Σ) would have smaller α thresholds (suggesting more intermediate virtual-channel percepts). We predicted that the two behavioral measures of pitch perception would yield similar α thresholds. Further, we hypothesized that both psychophysical tasks would be significantly correlated with ECAP Σ . As stated, finding an objective correlate to aid predicting behavioral perception of virtual channels would be more time efficient and clinically useful for pediatric recipients or others who have difficulty with pitch-related tasks.

II. METHODS

A. Subjects

Subjects were 11 Advanced Bionics recipients (8 adults, 3 teens). Four subjects were implanted with a Clarion CII device and seven with a HiRes 90 K. Eight subjects were postlingually deafened, two perilingually (C17, C25), and one prelingually (C22). All were native speakers of American English. Demographic information is available in Table I.

TABLE I. Demographic information for participating subjects. In the middle columns, time is listed as years, months (with averages in the bottom row). Time post CI was calculated from the date of psychophysical testing. SNHL = sensorineural hearing loss, + p = positioner. PTA = pure-tone average at 250, 500, and 1000 Hz. The pre-CI PTA was not available for subject C39, who transferred to our center after implantation.

Subject	Internal device, electrode array	Ear	Approximate duration of deafness	Pre-CI PTA (dB HL)	Age at CI	Age at testing	Time post CI	Etiology	Sentence Rec. (% correct), Test
C8	CII HF 1J	L	3, 0	105	55, 7	63, 11	8, 3	Sudden SNHL	98%, AzBio
C13	CII HF 1J	L	>3	110	77, 1	87, 5	9, 4	Genetic	56%, AzBio
C17 ^a	HR 90 K HF 1J	R	5, 0	77	7, 11	14, 5	6, 5	Unknown	38%, HINT
C22	HR 90 K HF 1J	L	>15	95	15, 4	18, 10	3, 5	Genetic	62%, HINT
C24	CII HF 1 + p	R	15, 0	115	67, 4	77, 6	10, 1	Unknown	62%, AzBio
C25	HR 90 K HF 1J	L	Unknown	87	11, 6	19, 7	7, 10	Usher syndrome	85%, AzBio
C26	HR 90 K HF 1J	R	13, 0	68	67, 6	71, 5	3, 10	Unknown	91%, AzBio
C29	HR 90 K HF 1J	R	2, 0	103	31, 0	35, 2	4, 2	Meningitis	90%, AzBio
C35	HR 90 K HF 1J	R	4, 0	73	84, 7	88, 2	3, 6	Unknown	63%, HINT
C39	HR 90 K HF 1J	R	0, 6	Unknown	63, 0	66, 5	3, 3	Unknown	81%, AzBio
C40	CII HF 1 + p	L	21, 0	87	59, 5	69, 9	10, 9	Genetic	70%, AzBio
MEANS			7, 4	92	46, 5	55, 8	6, 5		

^aSubject was explanted and re-implanted; time post implant is relative to the date of the initial device.

Subject C17 underwent explant/re-implant of her 90K device ~ 3.5 years before participation in this study; Table I dates were calculated using the original device, indicating total time with electrical stimulation. Speech-perception scores for sentences in quiet with the Hearing in Noise Test (HINT; Peterson and Lehiste, 1962) or AzBio Sentence Test (Spahr *et al.*, 2012) were collected from either the subject's clinical file (from the visit closest to the time of participation) or in the laboratory using the subject's everyday processor and program. This information is provided in Table I and was used to compare to virtual-channel pitch perception abilities. Speech-perception tests were presented to the CI alone in the auditory-only condition at 60 dB sound pressure level with recorded stimuli. All subjects utilized the Fidelity 120 processing strategy in their clinical programs at the time of the study. It was confirmed from the operative report that each subject had a full insertion of the electrode array. This study was approved by the Boys Town National Research Hospital Institutional Review Board under Protocol 03-07-XP, and adhered to the ethical guidelines pertaining to human subjects research.

B. Equipment setup

Pitch ranking, electrode discrimination, and ECAP SOE were measured for each subject using the Bionic Ear Data Collection System (BEDCS version 1.18.295, Advanced Bionics). All measures were performed with direct connection to the CI via a Clinical Programming Interface II and a laboratory Platinum Series Processor. A custom-designed graphical user interface created using the C# programming language overlaid BEDCS for the psychophysical measures. SoundWave version 2.0 (Advanced Bionics) was used to measure impedances at the beginning of data collection to ensure electrodes with open or short circuits were not used. None of the study participants had open or short circuits.

C. Psychophysical stimuli and procedures

Psychophysical tasks were performed for three electrode sets, which sampled the basal, middle, and apical regions of the array. For all subjects, electrodes 4 and 5 (apical), 8 and 9 (middle), and 12 and 13 (basal) were the adjacent physical electrodes simultaneously stimulated to create the virtual channels. As stated above, α values of 0 or 1 indicated the proportion of current applied to each physical electrode in the pair. For $\alpha = 0$, all current was directed to the most apical physical electrode of the pair; for $\alpha = 1$, all current was directed to the basal-most physical electrode. In the pitch tasks, α was adaptively varied to determine the smallest current difference perceptible with the apical electrode serving as the standard ($\alpha = 0$). Thus, α values approaching 0 indicate better performance, and α values approaching 1 indicate poorer performance. Stimuli were 300-ms, 1000-pps, cathodic-leading, 32- μ sec/phase, biphasic pulses presented in monopolar mode (referenced to the extracochlear monopolar case electrode). Psychophysical tasks were performed with the subject seated in front of a touch-screen monitor in a sound-treated and electrically isolated booth in the laboratory.

1. Loudness judgments

Before beginning the pitch tasks, the loudness of the stimuli were balanced to minimize loudness cues as a confounding variable for pitch measurements. First, an ascending categorical loudness scaling procedure was used to determine the subject's behavioral dynamic range. For each of the three electrode sets, categorical loudness judgments were obtained for both physical electrodes ($\alpha = 0$ and 1) to obtain reference stimuli for the more rigorous loudness-balancing task described below, and for one virtual channel at $\alpha = 0.5$. Subjects were instructed to indicate when the pulse-train stimuli were "just noticeable" (rating of 1), "loud but comfortable" (rating of 7), and the "maximum loudness level" (rating of 9) using a visual rating scale (1 = just noticeable, 10 = uncomfortably loud).

2. Loudness balancing

Loudness balancing was then performed using an adaptive, double staircase procedure (Jesteadt, 1980) with α as the parameter that was adapted. Physical electrodes were first loudness balanced for each electrode region; the reference stimulus was set to the current level yielding a rating of "7" obtained from the earlier categorical loudness judgments, applied to the most apical electrode in the pair. Next, three virtual-channel conditions ($\alpha = 0.75$, 0.5, and 0.25) were loudness-balanced, again using the loudness-level of the most apical electrode in the physical-electrode pair as the reference. In the main experiments, current levels for α values intermediate to those directly loudness-balanced (i.e., determined by the adaptive procedure) were interpolated from this five-point function. For all conditions, subjects were instructed to listen to the two alternating sounds (separated by 400 ms), then match the loudness of the second stimulus with the first (reference) stimulus using up/down arrows (step size 8 μ A) on the computer screen. The current value used for loudness-balanced stimuli was the average of two repetitions for each condition.

3. Training blocks

To ensure each subject understood the pitch tasks, a short training exercise was performed without level rove for each physical-electrode pair before the first main measurement for pitch ranking or electrode discrimination. For training conditions, subjects were instructed on the task (described below) and then ten non-adaptive trials were presented for each physical-electrode pair (e.g., E9 versus E8). A pass criterion of 80% correct was used. For training scores below this criterion, further instruction and training were provided, including using physical-electrode pairs with greater spatial distance. If training determined that the physical electrodes for a condition could not be distinguished at criterion, this condition was not tested, assuming the associated virtual channels would not be discriminable. Three subjects who were initially enrolled in the study could not discriminate any of the physical-electrode pairs at the training criterion for either pitch ranking or electrode discrimination.

They were not tested in the main conditions and are not included in Table I.

4. Pitch ranking

Half the subjects began testing with pitch ranking, and half with electrode discrimination, in pseudo-random order. The main pitch-ranking task used a 2IFC adaptive procedure (3-down, 1-up) in which α was the parameter adapted. The subject was asked to choose the interval with the higher pitch. Physical-electrode pairs were tested first, followed by virtual-channel increments. Thresholds were obtained using an initial step size of $\alpha = 0.5$ until the first reversal, followed by 0.1 for the next two reversals, then 0.05 for the remaining six reversals. Threshold for each measurement was the mean of the last six reversals, which yielded an α value that estimated 79.4% correct (Levitt, 1971) on the psychometric function. For purposes of the adaptive algorithm, pitch-ranking responses were scored as correct (i.e., would be higher in pitch based on the normal tonotopic organization of the cochlea) if the subject selected the interval with more current stimulating the basal-most electrode of the pair.

As described earlier, presentation levels for each interval for each subject were determined by that subject's "7" levels from the initial categorical loudness estimates and the adaptive loudness-balancing task, plus an additional random level rove to further circumvent loudness cues. The rove spanned a total of 2 dB (in 0.25 dB steps) above and below the "7" level for that physical-electrode or virtual-channel stimulus. Subjects were instructed to ignore the changes in loudness and base their judgments only on pitch to the best of their ability. No correct-answer feedback was provided. For cases in which the subject passed the training phase of the experiment, but was not able to pitch-rank adjacent physical electrodes in an adaptive condition, a ceiling value of $\alpha > 1.0$ was assigned and that condition was not included in any averages. For each replication of conditions, the three electrode regions (basal, middle, apical) were tested in random order. Subjects alternated between pitch ranking and electrode discrimination with each replication to distribute possible learning effects or session differences over time on either task. A total of six replications were completed for all pitch-ranking conditions, with reported mean values based on those six thresholds.

5. Electrode discrimination

As for pitch ranking, a brief training session preceded the first replication of the main conditions for the electrode-discrimination task. Electrode discrimination also used an adaptive task (3-up, 1-down; α adapted), which estimated 79.4% correct. However, a 3IFC task was used and correct-answer feedback was provided after each trial. Two intervals contained stimulation on the same (reference) electrode and one interval contained stimulation on a different (test) electrode/channel. The reference electrode was always the apical physical electrode of each electrode pair, so α tracked to the smallest discriminable difference between the apical electrode in the pair and the virtual channel. Subjects were instructed to indicate which interval sounded different in

pitch, again ignoring random changes in level from interval to interval. Use of the feedback to help optimize performance was emphasized. Procedures for adapting α , adding the random level rove, and the number of replications and randomization of conditions were the same as for pitch ranking. As with pitch ranking, subjects who could not discriminate the adjacent physical electrodes (indicated by ceiling values for the majority of trials in the adaptive track) were given a score of $\alpha > 1.0$ and that measurement was omitted from the averages. Data reported for individual subjects are means based on 4–6 measurements per condition.

D. ECAP stimuli and procedures

The ECAP SOE data for the 11 subjects in the present study represent a re-analysis of a subset of data from a larger physiological study (Hughes *et al.*, 2013). Briefly, the traditional forward-masking subtraction procedure with a fixed probe and varied masker electrode (Abbas *et al.*, 2004; Hughes and Abbas, 2006a,b) was used to obtain ECAP SOE functions. The same physical probe electrodes as used for the pitch-ranking and electrode-discrimination tasks were used for the electrophysiological measures. As in the psychophysical tasks, a ten-point loudness scale was used to obtain behavioral loudness estimates for the ECAP stimuli. Masker and probe stimuli were presented at the subject's "8" (loud) rating, except when voltage compliance limits were reached or facial nerve stimulation occurred before the subject's "8" rating. The following stimulus parameters were used: single, cathodic-leading, 32- μ sec/phase biphasic pulses; 20-Hz probe rate; 1000 gain (linear multiplier); 500- μ sec masker-probe interval; monopolar stimulating reference electrode (implant case); monopolar recording reference electrode (implant case for CII, extracochlear ring electrode for 90 K); and 80 averages. The recording electrode was typically two electrode positions apical to the probe.

A custom MATLAB (Mathworks Inc., Natick, MA) program was used to mark N1 and P2 peaks to determine ECAP amplitude. ECAP amplitudes were then normalized for each subject according to the highest amplitude across the two physical-electrode probe functions within a set and separately for each region. This was done to preserve the spatial relationships among the probe SOEs being compared and to allow for SOE comparisons across electrode sets and subjects (Hughes, 2008; Hughes and Goulson, 2011; Hughes *et al.*, 2013). Following methodology from Hughes (2008), the amount of spatial separation (Σ) among each of the pairs of SOE functions was quantified. The absolute value of the difference in normalized amplitude, summed across all masker electrodes, was determined using the following formula:

$$\sum_{i=1}^{16} |a_{xi} - a_{yi}|,$$

where a_x and a_y represent the ECAP amplitudes of the two probe functions (probe electrode x compared to probe electrode y) for each masker electrode i (summed from 1 to 16; the amplitude for the recording electrode was interpolated

FIG. 1. Illustration of the hypothesis that greater ECAP SOE separation (Σ) for adjacent probe electrodes is associated with lower (better) α thresholds (left panel, subject C26) and less ECAP SOE separation (Σ) is associated with higher (poorer) α thresholds (right panel, C35). Normalized ECAP SOE functions are plotted for the basal probe set for each subject (probe 12, filled circles; probe 13, unfilled). Dotted vertical lines indicate the spatial separation (Σ) between adjacent SOE functions. ECAP Σ and α thresholds for pitch ranking (PR) and electrode discrimination (ED) are indicated in the top right corner of each panel. As hypothesized, subject C26 had greater ECAP SOE separation ($\Sigma = 3.97$), with better α thresholds ($\alpha = 0.17$ for pitch ranking, $\alpha = 0.45$ for electrode discrimination). C35 had less ECAP SOE separation ($\Sigma = 1.46$), with poorer α thresholds ($\alpha = 0.97$ for pitch ranking, and $\alpha = 0.96$ for electrode discrimination).

because ECAPs could not be recorded for the masker on the recording electrode). The resulting value is expressed as the ECAP separation index (Σ). Larger Σ values correspond to greater spatial separation among SOE functions.

It was hypothesized that greater spatial separation among adjacent probe electrodes (larger Σ values) would be correlated with better virtual-channel resolution using current steering (smaller α thresholds). To illustrate this hypothesis, Fig. 1 displays individual SOE functions for subjects C26 and C35 for the basal electrode set. Filled circles indicate apical probe 12, open circles are basal probe 13, and dotted vertical lines at each masker electrode represent the separation between adjacent probe functions (the sum of which is the separation index). Each subject's ECAP Σ and α values for pitch ranking and electrode discrimination (first and second values, respectively) are included at the top of each plot. Consistent with the hypothesis, subject C26 had greater spatial separation (less overlap) among adjacent physical electrodes ($\Sigma = 3.97$), and smaller α values ($\alpha = 0.17$ for pitch ranking, and $\alpha = 0.45$ for electrode discrimination), indicating better spectral resolution of virtual channels compared with subject C35. For C35, the physiological spatial separation was minimal ($\Sigma = 1.46$), signifying greater overlap among neural excitation patterns, and α values were larger ($\alpha = 0.97$ for pitch ranking, and $\alpha = 0.96$ for electrode discrimination), indicating poorer virtual-channel resolution than subject C26. It was therefore hypothesized that the two measures would be negatively correlated among the group data, with greater spatial separation associated with smaller α thresholds.

III. RESULTS

The first goal of this study was to compare performance for pitch ranking and electrode discrimination in the same subjects. For comparison to previous studies, which most commonly report α values for thresholds, the obtained α values are presented and analyzed. The data are then converted

to d' to directly compare performance across tasks, given pitch ranking used a 2IFC procedure and electrode discrimination used 3IFC (see Goehring *et al.*, 2014). Table II shows pitch-ranking and electrode-discrimination thresholds (α) for individual subjects for the three electrode regions. Individual pitch-ranking thresholds ranged from $\alpha = 0.09$ to $\alpha > 1.0$; individual electrode-discrimination thresholds ranged from $\alpha = 0.34$ to $\alpha > 1.0$. Group means and standard errors (SEs) for α are summarized at the bottom of Table II. Mean α values do not include subjects with thresholds > 1.0 , because those subjects could not perceive virtual channels (as in Donaldson *et al.*, 2011). Assigning a value of 1.0 for these instances could have skewed the mean in cases when pitch ranking or electrode discrimination were actually > 1.0 . Mean pitch-ranking α thresholds for the basal, middle, and apical electrode regions were 0.53, 0.54, and 0.57, respectively. Mean electrode-discrimination thresholds were higher (poorer) at 0.69, 0.68, and 0.75 for basal, middle, and apical regions, respectively. The basal and middle electrode regions produced similar mean performance for pitch ranking; however, there were two subjects (C13, C25) who could not pitch rank adjacent physical electrodes for the basal region ($\alpha > 1.0$). For the middle and apical regions, all 11 subjects were able to effectively pitch rank the physical electrodes. Mean electrode-discrimination thresholds were poorer compared with mean pitch-ranking thresholds. The basal and middle electrode regions produced similar mean performance ($\alpha = 0.69$ for basal, and $\alpha = 0.68$ for middle). There were five instances (across four subjects) for electrode discrimination in which adjacent physical electrodes could not be discriminated ($\alpha > 1.0$).

There were large individual differences across subjects in both psychophysical tasks. Two subjects performed exceptionally well; C26 and C29 had the smallest (best) pitch ranking thresholds of $\alpha = 0.09$ (both for the middle region), indicating excellent resolution of virtual channels. In contrast, other participants struggled with the tasks. Subject C17's thresholds for pitch ranking and electrode

TABLE II. Pitch ranking and electrode discrimination thresholds (α), and ECAP separation indices (Σ) for each subject. Pitch ranking and electrode discrimination α values approaching 0 indicate better performance. Psychophysical thresholds designated as “>1.0” indicate the subject could not rank or discriminate the adjacent physical electrodes. These values were excluded from the means and standard errors (SE). NR = no ECAP response.

Subject	Pitch ranking (α)			Electrode discrimination (α)			ECAP separation index (Σ)		
	Basal	Middle	Apical	Basal	Middle	Apical	Basal	Middle	Apical
C8	0.31	0.59	0.31	0.49	0.69	0.72	1.61	2.40	1.53
C13	>1.0	0.32	0.62	>1.0	0.40	0.80	4.09	2.24	0.93
C17	0.96	0.93	0.97	0.98	>1.0	0.97	1.64	2.29	4.81
C22	0.59	0.80	0.88	0.86	0.85	0.85	2.73	1.95	2.18
C24	0.90	0.80	0.94	0.96	0.49	>1.0	3.87	3.52	4.57
C25	>1.0	0.71	0.43	>1.0	0.89	>1.0	1.10	2.37	1.04
C26	0.17	0.09	0.12	0.45	0.74	0.45	3.97	2.00	0.89
C29	0.34	0.09	0.27	0.74	0.76	0.85	1.83	1.95	1.69
C35	0.97	0.86	0.96	0.96	0.97	0.97	1.46	2.45	0.76
C39	0.25	0.19	0.17	0.34	0.49	0.56	2.24	1.72	0.88
C40	0.25	0.55	0.57	0.44	0.54	0.58	NR	2.74	1.33
MEAN	0.53	0.54	0.57	0.69	0.68	0.75	2.45	2.33	1.87
SE	0.11	0.10	0.10	0.09	0.06	0.06	0.38	0.19	0.49

discrimination were all equal to or greater than $\alpha = 0.93$, indicating this subject had difficulty with ranking and discriminating the adjacent physical electrodes. Subject C25 could not rank or discriminate the physical electrodes for three out of six replications (across the two psychophysical tasks). Also, as noted earlier, three additional subjects could not meet training criterion and were not tested in the main psychophysical tasks.

In order to compare to results of previous studies, an analysis of α values are presented first. To test whether virtual-channel resolution (α) was significantly different across the *psychophysical tasks* (pitch ranking or electrode discrimination) and *electrode regions* (basal, middle, or apical), a two-way repeated measures analysis of variance (RM-ANOVA) was performed. For this analysis, participants with α values >1.0 were not included because it was of interest to compare performance for α across the tasks and regions. Therefore, only the seven subjects with α thresholds for each of the tasks/regions were included in the analysis (C8, C22, C26, C29, C35, C39, and C40). A Bonferroni correction was used to adjust for multiple comparisons. Results revealed a significant main effect of the psychophysical test, indicating significantly lower (better) α thresholds for pitch ranking than for electrode discrimination ($F[1,6] = 10.60$, $p = 0.02$). There was no significant main effect of electrode region ($F[2,12] = 2.46$, $p = 0.13$), and no significant interaction between test and region ($F[2,12] = 0.34$, $p = 0.72$).

As noted earlier, however, the goal of the study was to directly compare performance on the two tasks; thus, procedural differences should be considered. Therefore, the α data were converted to d' using values from [Hacker and Ratcliff \(1979\)](#) for the 79.4% correct estimated in the adaptive procedures for 2IFC (1.14 for pitch ranking) and 3IFC (1.61 for electrode discrimination). All subjects were included in this analysis (using $\alpha = 1.0$ for ceiling values when converting to d'). The d' data are shown in Table III. A two-way RM-ANOVA was performed with *psychophysical task* and *electrode region* as within-subject factors. Bonferroni corrections were applied for the multiple comparisons. Results

indicated no significant difference for d' across psychophysical task ($F[1,10] = 0.42$, $p = 0.53$) or electrode region ($F[2,20] = 0.53$, $p = 0.60$), and there was no significant interaction between task and region ($F[2,20] = 0.80$, $p = 0.46$). In sum, although analyses using α values showed better performance for pitch ranking than for electrode discrimination, the d' analysis, which considered procedural differences, showed no significant difference between the two tasks. Further, note that neither mean α values nor d' values were significantly different across the basal, middle, or apical electrode regions.

Although it was not an *a priori* goal to compare virtual-channel resolution to speech perception, all participants used the same speech-processing strategy (Fidelity 120), which allowed for such a comparison. Further, previous studies have compared speech-recognition scores to α ; therefore, it was of interest to perform similar analyses in the present study ([Donaldson et al., 2011](#); [Snel-Bongers et al., 2012](#)).

TABLE III. Pitch ranking and electrode discrimination thresholds in d' for each subject. The α data were converted to d' using values from [Hacker and Ratcliff \(1979\)](#) for the 79.4% correct for 2IFC (1.14 for pitch ranking) and 3IFC (1.61 for electrode discrimination). SE = standard error.

Subject	Pitch ranking (d')			Electrode discrimination (d')		
	Basal	Middle	Apical	Basal	Middle	Apical
C8	0.27	0.52	0.27	0.30	0.43	0.45
C13	0.88	0.28	0.54	0.62	0.25	0.49
C17	0.84	0.82	0.85	0.61	0.62	0.60
C22	0.52	0.70	0.77	0.54	0.53	0.53
C24	0.79	0.70	0.82	0.60	0.31	0.62
C25	0.88	0.63	0.38	0.62	0.55	0.62
C26	0.15	0.08	0.11	0.28	0.46	0.28
C29	0.30	0.08	0.23	0.46	0.47	0.53
C35	0.85	0.75	0.84	0.60	0.60	0.60
C39	0.22	0.17	0.15	0.21	0.31	0.35
C40	0.22	0.48	0.50	0.27	0.34	0.36
MEAN	0.54	0.47	0.50	0.46	0.44	0.49
SE	0.10	0.09	0.09	0.05	0.04	0.04

Figure 2 shows each subject's mean psychophysical thresholds for pitch ranking (left panel) and electrode discrimination (right panel) plotted against percent-correct scores on sentences in quiet to determine whether smaller α values were correlated with better speech perception (scores from Table I). For each subject, the mean α value (calculated from the basal, middle, and apical means) was used. Mean values were calculated in two ways. First, means did not include values of $\alpha > 1.0$ (consistent with Donaldson *et al.*, 2011). These data are shown in the top row of Fig. 2. For the second analysis, means included values of $\alpha > 1.0$ by assigning a value of 1.0 (as in Snel-Bongers *et al.*, 2012), and are displayed in the bottom row. Each subject is identified by a unique symbol, detailed in the legend. Pearson product moment correlations were performed to assess the relation between the speech-perception scores and mean α . For the analysis excluding >1.0 values from the mean, a significant correlation was observed between sentences in quiet versus pitch-ranking α ($r = -0.76$, $p = 0.006$). Although the trend was similar for electrode discrimination, it was not significant ($r = -0.44$, $p = 0.18$). For the analysis including >1.0 values, there was a significant correlation between sentences in quiet and electrode discrimination α ($r = -0.65$, $p = 0.03$), but not for pitch ranking ($r = -0.56$, $p = 0.07$). In summary, subjects with better scores on sentences in quiet tended to have smaller (better) psychophysical thresholds.

The second objective of this study was to compare pitch ranking and electrode discrimination to the ECAP separation index (Σ) to determine whether either of the psychophysical

FIG. 2. Speech perception scores for sentences in quiet (percent correct), plotted as a function of performance for pitch ranking (left panel) and electrode discrimination (right panel). Data are mean α values averaged across electrode regions. In the top row, mean values do not include $\alpha > 1.0$. In the bottom row, the mean includes the values with $\alpha > 1.0$, using 1.0 as an estimate. Each subject is identified by a unique symbol.

tasks was correlated with ECAP spatial separation. It was hypothesized that greater spatial separation for adjacent probe electrodes (larger Σ values) would be negatively correlated with better virtual-channel resolution (smaller α thresholds). The α values were used instead of d' to facilitate comparisons to earlier studies. The right-most section in Table II displays the ECAP separation indices (Σ) for each subject, with means and SEs across subjects at the bottom. For subject C40, no measurable ECAP response could be obtained for the basal set. Group mean ECAP Σ values were 2.45, 2.33, and 1.87 for the basal, middle, and apical electrode regions, respectively. Thus, spatial separation was smallest for the apical set, and largest for the basal set. To determine whether the ECAP spatial separation (Σ) itself was significantly different across electrode regions (basal, middle, or apical) a one-way RM-ANOVA was performed. Results revealed no significant main effect of electrode region ($F[1,9] = 0.83$, $p = 0.39$) on ECAP Σ , consistent with the larger data set previously reported by Hughes *et al.* (2013).

Figure 3 displays scatter plots of group mean pitch-ranking thresholds (α) versus ECAP separation indices (Σ) for basal, middle, and apical electrode regions (top to bottom, respectively). C40's basal set was excluded due to the lack of measurable ECAPs. Labeled data points above the horizontal dotted line ($\alpha = 1$) in the top panel indicate the two subjects who could not pitch rank the adjacent physical electrodes. Regression analyses and Pearson product moment correlations were used to test the significance of the relation between the ECAP separation index (Σ) and pitch-ranking α . The solid regression line and correlation coefficients represent subjects in which psychophysical thresholds of $\alpha > 1.0$ were excluded from the analysis. If the proposed hypothesis were supported, results would show a *negative* correlation between ECAP Σ and pitch-ranking α . Instead, a significant *positive* correlation was observed for the apical electrode region ($r = 0.60$, $p = 0.05$). This correlation, however, is driven by two data points in the upper right corner of the graph. There were no significant correlations for the basal or middle comparisons (basal: $r = -0.18$, $p = 0.68$; middle: $r = 0.52$, $p = 0.10$). A sub-analysis was conducted in which data for subjects with $\alpha > 1.0$ were included in the comparison between basal pitch-ranking α and ECAP Σ (1.0 was substituted for α in these cases). This analysis is represented by the dashed regression line in the top panel of Fig. 3. Results only show a minimal change in the correlation coefficients from the original analysis, excluding the 1.0 values ($r = -0.08$, $p = 0.82$). Figure 4 displays scatter plots showing group electrode-discrimination thresholds (α) versus ECAP separation indices (Σ), plotted as in Fig. 3. No significant correlations were observed between electrode-discrimination α and ECAP Σ for any of the electrode regions in which subjects with 1.0 values were excluded (basal: $r = -0.11$, $p = 0.79$; middle: $r = -0.24$, $p = 0.50$; apical: $r = 0.50$, $p = 0.17$). As with pitch ranking, an analysis was conducted to examine the effect of including subjects with values of $\alpha > 1.0$. Correlation coefficients were not altered significantly when these values were added (basal: $r = -0.05$, $p = 0.90$; middle: $r = -0.23$, $p = 0.51$, apical: $r = 0.50$, $p = 0.12$).

FIG. 3. Mean pitch ranking thresholds (α) as a function of normalized ECAP separation indices (Σ) for basal, middle, and apical electrode regions (top to bottom, respectively). Subjects who could not pitch rank the adjacent physical electrodes ($\alpha > 1.0$) are indicated by the circles above the dotted line at $\alpha = 1.0$, and are labeled with the corresponding subject number. The solid regression line and Pearson correlation values labeled on the graph represent the ECAP versus pitch ranking α comparison without the $\alpha > 1.0$ subjects. The dashed regression line in the basal panel reflects the subjects in which $\alpha > 1.0$ were included in the analysis. These corresponding r - and p -values are listed in the text.

There were several instances in which ECAP Σ was similar across subjects and electrode regions, but α varied considerably (see Table II). This is illustrated in Fig. 5 for three subjects: C13, C17, and C25 (across panels) for the middle physical-electrode set (electrode 8 is the filled circle;

FIG. 4. Mean electrode discrimination thresholds (α) versus normalized ECAP separation indices (Σ) for basal, middle, and apical regions (top to bottom, respectively). Formatted as in Fig. 3.

electrode 9 is unfilled). Separation indices (Σ ; denoted in each panel) were similar across the three subjects, ranging from 2.24–2.37; however, α for pitch ranking was more varied across subjects ($\alpha = 0.32$ for C13, $\alpha = 0.93$ for C17, and $\alpha = 0.71$ for C25). Likewise, electrode-discrimination thresholds also varied considerably for these participants ($\alpha = 0.40$ for C13, $\alpha > 1.0$ for C17, and $\alpha = 0.89$ for C25). In summary, there was no significant correlation between ECAP Σ and the psychophysical data for pitch ranking and electrode discrimination for any of the electrode regions evaluated, which did not support the hypothesis. Therefore, ECAP spatial

FIG. 5. Example showing similar ECAP separation indices (Σ) across the middle probe region for three participants (C13, C17, and C25, labeled left to right in the figure), but with various levels of performance on the psychophysical tasks (α values). Separation indices (Σ) and α values are given in the top right corner of each panel for pitch ranking (PR) and electrode discrimination (ED). Probe 8 is the filled circle; probe 9 is unfilled. Dotted vertical lines indicate the amount of spatial separation (Σ) between the two SOE functions.

separation patterns did not predict behavioral perception of virtual channels in the current study across the basal, middle, or apical electrode regions.

IV. DISCUSSION

To our knowledge, this study was the first to examine both pitch-ranking and electrode-discrimination tasks using current steering in the same subject sample. As described above, the majority of previous studies have evaluated virtual-channel perception using a 2IFC, pitch-ranking task (Donaldson *et al.*, 2005; Firszt *et al.*, 2007; Koch *et al.*, 2007; Donaldson *et al.*, 2011). Pitch-ranking data from the current study were similar to data reported in Donaldson *et al.* (2011). Individual α values from Donaldson *et al.* and the current investigation ranged from $\alpha = 0.09$ to $\alpha > 1.0$ across electrode regions, indicating significant variability in individual pitch-ranking abilities across subjects and even within a subject. Mean α thresholds were slightly lower (better) for the middle and apical electrode regions in Donaldson *et al.*, while basal values were similar to those in the present study (Donaldson *et al.*, 2011: basal $\alpha = 0.53$, middle $\alpha = 0.34$, apical $\alpha = 0.44$; current study: basal $\alpha = 0.53$, middle $\alpha = 0.54$, apical $\alpha = 0.57$; see Table II). Both studies used similar methodology and a stimulus level rove to reduce loudness cues. Because earlier work by Firszt *et al.* (2007) and Koch *et al.* (2007) did not use a level rove, it is possible that the performance levels reported in those studies may be an overestimation of subjects' actual abilities. Further, mean α thresholds were not reported in those studies, thus making it difficult to compare those results to the present study.

For electrode discrimination, Snel-Bongers *et al.* (2012) examined intermediate virtual-channel percepts using a 3IFC electrode-discrimination task with a level rove, as did the present study. Their thresholds ranged from approximately $\alpha = 0.25$ to $\alpha = 1.0$ [values estimated from Fig. 5(A) of Snel-Bongers *et al.*, 2012]. This is comparable to the current study ($\alpha = 0.34$ to $\alpha > 1.0$). Additionally, Snel-Bongers *et al.* examined speech-perception scores in relation to electrode-discrimination α , although they compared α to phonemes correct, whereas the present study compared α to percent correct for sentences in quiet. Both studies observed significant correlations between speech-perception scores

and α , indicating that participants with better speech-perception scores tended to have better resolution of intermediate virtual channels. For the present study, depending on how the mean α value was calculated for the comparison (see Fig. 2), either pitch ranking or electrode discrimination were significantly correlated with α . Although this finding is noteworthy, it was not within the scope of this study to examine, in depth, the relation between speech perception and α . Such examinations remain an opportunity for further study.

For electrode discrimination (3IFC), the analysis of raw α values yielded significantly larger α values (poorer performance) than for pitch ranking (2IFC). However, no significant difference was found when data were converted to d' using standard corrections for multiple-interval, forced-choice tasks. This strongly suggests that procedural differences were the dominant factor governing subjects' performance, and need to be considered when comparing performance across studies with different tasks, as well as different subject populations. Although the "oddity" task and feedback for the 3IFC electrode-discrimination task might, in general, be considered less difficult, perhaps the use of the random level rove made an additional interval more difficult than for 2IFC. Overall, these findings are consistent with our previous study, which compared pitch ranking and electrode discrimination in the Cochlear Corporation device for dual-electrode mode (Goehring *et al.*, 2014). Specifically, no difference in performance was observed across the two behavioral tasks when data were converted to d' in that study.

Overall, the pitch tasks were difficult for most of the subjects. Several participants could not pitch rank or discriminate the adjacent physical electrodes, with seven instances of α values > 1.0 , and three subjects who could not pass the training procedures for inclusion in the study (i.e., could not rank or discriminate the adjacent physical electrodes for any of the electrode regions). On the other hand, two subjects (C26 and C29) performed exceptionally well on pitch ranking with $\alpha = 0.09$ for the middle electrode pair, suggesting the possibility of multiple intermediate percepts. Interestingly, both had fairly high (poor) α thresholds for electrode discrimination of the middle electrode pair ($\alpha = 0.74$ for C26, $\alpha = 0.76$ for C29). Both subjects demonstrated excellent performance on the AzBio sentences in

quiet ($\geq 90\%$; see Table I). Duration of deafness does not appear to explain the high speech perception scores and excellent middle-region virtual-channel resolution for pitch ranking for these two subjects, as subject C29 had a relatively short duration of deafness (2 years), whereas C26 was deaf for 13 years prior to implantation (see Table I). As a comparison to C26, subject C24, who was deaf for 15 years, performed more poorly on the pitch tasks and also had poorer speech-recognition performance (62% on sentences). Subject C26, however, had more residual hearing before implantation [pre-CI pure-tone-average (PTA) of 68 dB hearing level (HL); see Table I] than C24 (PTA of 115 dB HL). The highest speech-perception scores were for C8, who performed relatively well on the pitch tasks (α values ranged from 0.31 to 0.72). Duration of deafness for C8 was minimal (3 yr), but pre-CI PTA was high at 105 dB HL. It is clearly difficult to discern exactly which factors may play a role in a particular subject's performance on the pitch tasks. As explained by [Frijs et al. \(2009\)](#), if the electrical fields of the two electrode contacts do not overlap with simultaneous stimulation, there will not be sufficient excitation of the intermediate neurons and, thus, no virtual-channel perception. Thus, the present study, in addition to those previously cited ([Donaldson et al., 2005](#); [Firszt et al., 2007](#), [Koch et al., 2007](#); [Donaldson et al., 2011](#); [Snel-Bongers et al., 2012](#)), highlight the large variability for spectral resolution of virtual channels among CI recipients.

In terms of the effect of electrode region, there were no significant differences across the basal, middle, and apical regions on virtual-channel perception in the current study for either task (see Table II). [Donaldson et al. \(2011\)](#) indicated that $\alpha = 0.5$ translates to at least one intermediate virtual-channel percept between the adjacent physical electrodes. When this definition is applied to the results of the present study, mean α values (from Table II) indicated that subjects could pitch rank at least one intermediate virtual channel for each of the electrode regions (basal, middle, and apical; α values ranging from 0.53–0.57). For electrode discrimination, mean α values indicated subjects could discriminate less than one intermediate channel across the regions (α values ranging from 0.68–0.75). Previous studies have shown poorer perception of virtual channels for basal-region electrodes with current steering for pitch ranking tasks ([Firszt et al., 2007](#); [Koch et al., 2007](#); [Donaldson et al., 2011](#)). In the present study, mean basal and middle α thresholds were not significantly different than apical thresholds for both pitch ranking and electrode discrimination. Our results suggest that, on average, virtual-channel thresholds assessed using current steering do not vary significantly across the electrode array for either pitch ranking or electrode discrimination.

With regard to the second goal of this study, which was to determine whether ECAP spatial separation (Σ) for adjacent physical electrodes could be used to predict performance on the pitch ranking and/or electrode discrimination tasks for virtual channels, no significant correlations were found between the psychophysical and electrophysiological measures for any of the three electrode regions (Figs. 3 and 4). [Hughes \(2008\)](#) found a significant correlation between

the ECAP separation index (Σ) and pitch ranking; however, that study examined the relations for physical electrodes spaced one to six electrodes apart. In [Goehring et al. \(2014\)](#), the comparison between physical-electrode and dual electrode pitch data and ECAP Σ were positively correlated as hypothesized; however, only two of the comparisons across tasks and electrode regions were significantly correlated (middle pitch ranking, apical electrode discrimination). In the present study, the use of current steering allowed for a detailed comparison between ECAP Σ for adjacent physical electrodes versus α . Data from the present study suggest that either the separation index (Σ) or the ECAP measures themselves are not sensitive enough to predict perceptual pitch changes associated with virtual-channel stimulation between adjacent physical electrodes.

There may be a number of reasons why the ECAP and psychophysical measures did not correlate as hypothesized. First, different stimuli were used for the ECAP and psychophysical measures. ECAPs were recorded with single-pulse stimuli, whereas psychophysical measures were obtained with pulse-train stimuli. Because ECAPs generally require higher current levels to evoke a response, there can be greater spread of excitation in the cochlea compared with lower current levels for psychophysical tasks. A study by [Hughes and Stille \(2008\)](#), using a forward-masking paradigm, showed that excitation patterns for ECAP measures were broader than those obtained for psychophysical (pulse-train) measures. Therefore, the ECAP may be less sensitive for measuring overlap of neural excitation patterns produced by relatively high-level stimulation of closely spaced electrodes such as adjacent physical electrodes. This limitation should not discourage future studies from examining comparisons between electrophysiological and psychophysical measures, given the high potential clinical utility of electrophysiological measures that could predict behavioral measures. Further, only three electrode comparisons were examined for each subject; it may be that within-subjects comparisons involving a larger number of electrode sets would show a stronger correlation between the pitch and ECAP data.

One issue is that the ECAP Σ metric may be limited in its ability to capture certain neural mechanisms that may contribute to perception. A brief review of how the metric is obtained helps clarify this point. With the forward masking subtraction paradigm, the largest ECAP response is obtained when the masker and probe are on the same electrode (maximum overlap of neural excitation patterns); however, responses may be reduced or absent for larger separations between masker and probe electrodes (no overlap) as in the case of basal and/or apical maskers. Normalization of the raw ECAP amplitudes is performed to allow for within- and across-subject comparisons. Finally, the difference in normalized masker amplitudes between the adjacent ECAP SOE functions provides the final separation index (Σ) value. Individual nerve survival patterns will affect the ECAP response. For subjects with poorer nerve survival, there may be more zero-amplitude measures for masker electrodes that are farther from the probe (equating to a smaller separation index, Σ). However, for subjects with better neural survival,

but less separation among adjacent electrodes, the separation index may also be small. This issue was illustrated in Fig. 5 for three subjects. All three had similar ECAP separation indices (Σ). Subject C13 (far left) had a greater number of measurable ECAP responses (all amplitudes >0) at all masker electrodes, but had less separation among adjacent probe electrodes. For C17 (middle) and C25 (right), there were more zero-amplitude measures for basal masker electrodes, which may suggest poorer nerve survival in these subjects. It should also be noted that C17 had an uneven profile compared to the more uniform SOE function for C13 and C25. As explained in Hughes *et al.* (2013), more uniform responses may reflect better or more intact nerve survival patterns among adjacent electrodes. Despite having similar separation indices (Σ), each subject's ability to detect intermediate virtual channels varied considerably from excellent detection of virtual channels for C13, to poorer performance for C17. Subject C13 may have better or more evenly distributed nerve-survival patterns that contributed to better performance on the psychophysical tasks compared with that for C17; however, the separation index did not capture this aspect. Therefore, the ECAP Σ may be limited in its ability to identify certain neural mechanisms that may account for performance differences on behavioral measures.

Although this study showed that the separation index (Σ) calculated for adjacent PEs was not correlated with α thresholds, Snel-Bongers *et al.* (2012) examined several other measures to determine whether any of them could predict the number of intermediate virtual channels with current steering. ECAP SOE width (as described above), electrical field imaging, electrode contact distance to the medial wall, channel interaction (3IFC psychophysical task), and phoneme scores (also discussed above) were compared to virtual-channel (α) thresholds obtained using a 3IFC discrimination task. Their psychophysical channel-interaction measure was correlated with α for 5 of the 12 subjects. None of the other measures, however, strongly predicted the number of intermediate channels. Therefore, the present study joins others thus far in finding no correlation between the ECAP SOE and psychophysical data for intermediate virtual-channel stimulation (Busby *et al.*, 2008, using dual-electrode mode; Snel-Bongers *et al.*, 2012, using current steering).

In summary, the present study showed that pitch ranking and electrode discrimination, when analyzed as d' , produce equivalent outcomes with current steering for Advanced Bionics recipients. Psychophysical procedures similar to previous studies were used (Donaldson *et al.*, 2011; Snel-Bongers *et al.*, 2012). Our obtained threshold values (α) are reasonably consistent with previous work for subjects with devices capable of current steering, given different subject populations across studies. When the two psychophysical measures were compared to the ECAP separation index (Σ ; Hughes, 2008) to determine if the objective measure could be used to predict performance on the behavioral tasks, ECAP spatial separation was not predictive of α thresholds for any of the electrode regions. This may be the result of broader excitation patterns produced by the electrophysiological measures due to higher stimulus levels, or a

limitation of the metric (separation index, Σ). Increasing spectral resolution for cochlear-implant recipients remains a goal for all devices, indicating further research is needed regarding how both behavioral (subjective) and physiological (objective) measures can assess these abilities.

ACKNOWLEDGMENTS

The authors thank Gina Diaz, Lisa Stille, and Katelyn Glassman for assistance with data collection; Prasanna Aryal for development of the data collection program; Leo Litvak (Advanced Bionics) for BEDCS support; Walt Jesteadt and Gail Donaldson for consultation, and Kendra Schmid for statistical support. This study was supported by the National Institute on Deafness and Other Communication Disorders (NIDCD) Grants Nos. R01 DC009595 and P30 DC04662. The content of this project is solely the responsibility of the authors and does not necessarily represent the official views of the NIDCD or the National Institutes of Health.

¹Fidelity 120 is a virtual-channel speech-processing strategy in which the number of spectral bands (filters) can be potentially increased from 16 (with standard HiRes speech processing) to 120. For Fidelity 120, a maximum of 15 electrode pairs in the array includes an additional 8 stimulating sites between each pair.

- Abbas, P. J., Hughes, M. L., Brown, C. J., Miller, C. A., and South, H. (2004). "Channel interaction in cochlear implant users evaluated using the electrically evoked compound action potential," *Audiol. Neurotol.* **9**, 203–213.
- Brendel, M., Buechner, A., Krueger, B., Frohne-Buechner, C., and Lenarz, T. (2008). "Evaluation of the Harmony sound processor in combination with the speech coding strategy HiRes 120," *Otol. Neurotol.* **29**, 199–202.
- Busby, P. A., Battmer, R. D., and Pesch, J. (2008). "Electrophysiological spread of excitation and pitch perception for dual and single electrodes using the Nucleus Freedom cochlear implant," *Ear Hear.* **29**(6), 853–864.
- Busby, P. A., and Plant, K. L. (2005). "Dual electrode stimulation using the Nucleus CI24RE cochlear implant: Electrode impedance and pitch ranking studies," *Ear Hear.* **26**, 504–511.
- Collins, L. M., and Throckmorton, C. S. (2000). "Investigating perceptual features of electrode stimulation via a multidimensional scaling paradigm," *J. Acoust. Soc. Am.* **108**(5), 2353–2365.
- Collins, L. M., Zwolan, T. A., and Wakefield, G. H. (1997). "Comparison of electrode discrimination, pitch ranking, and pitch scaling data in postlingually deafened adult cochlear implant subjects," *J. Acoust. Soc. Am.* **101**(1), 440–455.
- Donaldson, G. S., Dawson, P. K., and Borden, L. Z. (2011). "Within-subjects comparison of the HiRes and Fidelity 120 speech processing strategies: Speech perception and its relation to place-pitch sensitivity," *Ear Hear.* **32**(2), 238–250.
- Donaldson, G. S., Kreft, H. A., and Litvak, L. (2005). "Place-pitch discrimination of single-versus dual-electrode stimuli by cochlear implant users," *J. Acoust. Soc. Am.* **118**(2), 623–626.
- Firszt, J. B., Holden, L. K., Reeder, R. M., and Skinner, M. W. (2009). "Speech recognition in cochlear implant recipients: Comparison of standard HiRes to HiRes 120 sound processing," *Otol. Neurotol.* **30**, 146–152.
- Firszt, J. B., Koch, D. B., Downing, M., and Litvak, L. (2007). "Current steering creates additional pitch percepts in adult cochlear implant recipients," *Otol. Neurotol.* **28**(5), 629–636.
- Frijns, J. H. M., Kalkman, R. K., Vanpoucke, F. J., Snel Bongers, J., and Briare, J. J. (2009). "Simultaneous and non-simultaneous dual electrode stimulation in cochlear implants: Evidence for two neural response modalities," *Acta Otolaryngol.* **129**, 433–439.
- Goehring, J. L., Neff, D. N., Baudhuin, J. L., and Hughes, M. L. (2014). "Pitch ranking, electrode discrimination, and physiological spread-of-excitation using Cochlear's dual-electrode mode," *J. Acoust. Soc. Am.* **136**(2), 715–727.
- Hacker, M. J., and Ratcliff, R. (1979). "A revised table of d' for M-alternative forced choice," *Percept. Psychophys.* **26**(2), 168–170.

- Hughes, M. L. (2008). "A re-evaluation of the relation between physiological channel interaction and electrode pitch ranking in cochlear implants," *J. Acoust. Soc. Am.* **124**(5), 2711–2714.
- Hughes, M. L., and Abbas, P. J. (2006a). "The relation between electrophysiological channel interaction and electrode pitch ranking in cochlear implant recipients," *J. Acoust. Soc. Am.* **119**, 1527–1537.
- Hughes, M. L., and Abbas, P. J. (2006b). "Electrophysiologic channel interaction, electrode pitch ranking, and behavioral threshold in straight versus perimodiolar cochlear implant electrode arrays," *J. Acoust. Soc. Am.* **119**, 1538–1547.
- Hughes, M. L., and Goulson, A. (2011). "Electrically evoked compound action potential measures for virtual channels versus physical electrodes," *Ear Hear.* **32**(3), 323–330.
- Hughes, M. L., and Stille, L. J. (2008). "Psychophysical versus physiological spatial forward masking and the relation to speech perception in cochlear implants," *Ear Hear.* **29**(3), 435–452.
- Hughes, M. L., Stille, L. J., Baudhuin, J. L., and Goehring, J. L. (2013). "ECAP spread of excitation with virtual channels and physical electrodes," *Hear. Res.* **306**, 93–103.
- Jesteadt, W. (1980). "An adaptive procedure for subjective judgments," *Percept. Psychophys.* **28**(1), 85–88.
- Koch, D. B., Downing, M., Osberger, M. J., and Litvak, L. (2007). "Using current steering to increase spectral resolution in CII and HiRes 90K users," *Ear Hear.* **28**(2), 38S–41S.
- Levitt, H. (1971). "Transformed up-down methods in psychoacoustics," *J. Acoustic. Soc. Am.* **49**(2), 467–477.
- Peterson, G. E., and Lehiste, I. (1962). "Revised CNC lists for auditory tests," *J. Speech Hear. Disord.* **27**, 62–70.
- Saoji, A. A., Litvak, L. M., and Hughes, M. L. (2009). "Excitation patterns of simultaneous and sequential dual-electrode stimulation in cochlear implant recipients," *Ear Hear.* **30**(5), 559–567.
- Snel-Bongers, J., Briare, J. J., Vanpoucke, F. J., and Frijns, J. H. M. (2012). "Spread of excitation and channel interaction in single- and dual-electrode cochlear implant stimulation," *Ear Hear.* **33**(3), 367–376.
- Spahr, A. J., Dorman, M. F., Litvak, L. M., Van Wie, S., Gifford, R. H., Loizou, P. C., Loisel, L. M., Oakes, T., and Cook, S. (2012). "Development and validation of the AzBio sentence lists," *Ear Hear.* **33**(1), 112–117.
- Zwolan, T. A., Collins, L. M., and Wakefield, G. H. (1997). "Electrode discrimination and speech perception in postlingually deafened adult cochlear implant subjects," *J. Acoust. Soc. Am.* **102**, 3673–3685.