Effects of stimulation configurations on place pitch discrimination in cochlear implants

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The present study aimed to examine the effect of electrode configuration, specifically monopolar (MP) or bipolar (BP) stimulation, on place pitch discrimination in cochlear implants (CIs). Twelve subjects implanted with the Nucleus Freedom device were presented with various pairs of stimulation across the electrode array, with varying degrees of distance between stimulation sites, and asked to judge the higher of the two in pitch. Each pair was presented either in the same mode or in different modes of stimulation for the within-mode or across-mode condition, respectively, at least 20 times. The result of the within-mode condition revealed that subjects, on average, were able to discriminate pitches significantly better in MP than in BP, with the sensitivity index (d') for adjacent channels of 1.2 for MP and 0.8 for BP. The result of the across-mode condition revealed that while individual variability existed, there was a strong tendency for CI subjects to perceive a higher pitch in BP stimulation than in MP for a similar site of stimulation. In other words, an MP channel needed to be shifted in a basal direction by as much as two electrodes on average to elicit a pitch comparable to that of a BP channel. © 2011 Acoustical Society of America.
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I. INTRODUCTION

Cochlear implants (CIs) provide auditory sensation to individuals with substantial hearing loss in which acoustic amplification has little or no benefit. The incoming acoustic signal is spectrally decomposed, and each component of the signal, from low to high frequencies, is delivered to each channel of stimulation in the electrode array. The pitch sensation is typically determined by the place of stimulation according to the tonotopical arrangement in the cochlea, e.g., stimulation at an apical site elicits a low-pitch percept. Two groups of researchers have systematically measured discrimination of stimulating electrodes and examined the percepts of “place-pitch” in CI systems (Nelson *et al.*, 1995; Collins *et al.*, 1997). While a great deal of individual variability among CI users was observed in both studies, discrimination of the stimuli on adjacent electrodes was in general difficult as quantified by the sensitivity index (d') of 1 or less; the stimuli needed to be separated by more than one electrode to be reliably discriminated from each other.

It should be noted, however, that these studies tested CI users with the Nucleus 22 device in the bipolar (BP) stimulation configuration where the current flows between two intracochlear electrodes, which are usually closely positioned. In recent CI systems, the monopolar (MP) stimulation configuration, where the current flows between one electrode inside the cochlea and another electrode outside of the cochlea, is predominantly used. It is unclear how applicable the findings

in those studies would be to examining electrode discrimination and place pitch in recently implanted patients due to the difference in stimulation configuration. It might be possible that the channel configuration has an impact on electrode discrimination and place pitch, as the MP and BP configurations differ in the spatial selectivity in the cochlea as measured physiologically (van den Honert and Stypulkowski, 1987; Bierer and Middlebrooks, 2002). Although von Wallenberg *et al.* (1995) reported that the pitch changes along the electrode array were roughly similar for both stimulation configurations, their report was based on pitch estimation rather than pairwise pitch comparison, and it was still unknown whether MP or BP stimulation would elicit pitch percepts that were better discriminated between adjacent channels. Therefore the first purpose of the present study was to address the following research question: “Would CI users be able to discriminate more place pitches across the array in BP mode or in MP mode?”

Another topic of interest in the present study was the perceptual differences in pitch between MP and BP stimuli. The pitch relations between MP and BP stimuli have not been studied and are largely unknown partly because in conventional CI systems, only one electrode configuration (either MP or BP) is selected and used for speech coding. However, it is important to understand the pitch relations in a system where both MP and BP configurations are used for speech coding, as proposed in a recent study (Kwon *et al.*, 2010). As other electrode configurations, such as tripolar stimulation or phased-array (e.g., Jolly *et al.*, 1996; van den Honert and Kelsall, 2007), are proposed and examined for future clinical applications, there is an increasing need to

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FIG. 1. Neural activation functions (Litvak *et al.*, 2007) produced by MP stimulation on electrode 10 and BP stimulation on electrodes 10 and 12. Electrode numbering is based on the conventions of Nucleus systems in which a lower number indicates a more basal location on the electrode array.

understand pitch relations between stimuli in different configurations.

Due to the differences in the neural populations excited by MP and BP stimulation (e.g., Kral *et al.*, 1998), MP and BP stimuli in similar stimulation sites might elicit different pitch percepts. As seen in Fig. 1, illustrating neural activation functions (Rattay, 1990; Litvak *et al.*, 2007), MP stimulation excites a broad range of neural populations symmetrically from the center of the stimulated electrode, whereas BP stimulation excites two groups of nerve fibers in opposite phases and in relatively narrower ranges near the pairs of electrodes. It should be noted that these illustrations represent a highly simplified model of intracochlear voltage distributions and might be far from sufficient to explain pitch discrimination in CI users; their pitch discrimination involves not only current flows in the cochlea but also the configuration of neural survival. Presuming

that impedance distribution and neural survival are uniform across current paths, these schematic models might be helpful to predict the pitch relation between MP and BP stimulation based on the activated regions of neural populations (i.e., an activation of a more basal region would lead to a higher pitch). For example, the pitch of an MP stimulus on electrode 10 would be higher than that of a BP stimulus on electrodes 10 and 12, as the BP stimulus would create a profile of neural excitation located slightly more toward the apex, as seen in Fig. 1 (note that this is based on the electrode numbering convention in the Nucleus system, where a lower number indicates a more basal location in the electrode array). However, our observations during the pilot study were not always in line with this expectation, indicating the preceding presumptions in the model are not practical. Therefore the second purpose of the present study was to empirically investigate pitch relations between MP and BP stimulation by pairwise pitch ranking between MP and BP stimuli.

II. METHODS

A. Subjects

Twelve Nucleus Freedom users, five females and seven males, implanted with the CI24RE device and the ContourTM electrode array, participated in the study. All subjects had at least 1 yr of CI experience prior to the testing. The use of human subjects in this study was reviewed and approved by the Institutional Review Boards at the University of Utah and at The Ohio State University. Table I contains detailed subject-specific information, including patient history, phoneme identification scores obtained outside of the present study, and the channel stimulation rate used in their clinical map. All subjects were mapped with the ACETM processing strategy using the MP configuration for daily use.

B. Procedure and stimuli

To address the preceding research questions, two experimental conditions were considered: Within-mode and

TABLE I. Subjects' demographic information and identification scores of consonants and vowels, measured separately from the present study.

ID	Gender	Age at testing (years)	CI experience at testing (years)	Etiology	Phoneme ID scores (%)		Stimulation rate per channel (Hz)
					Consonants	Vowels	
S1	M	35	4	Unknown	91	93	900
S2	M	51	3	Ototoxic Drug	64	79	1800
S3	M	66	1	Unknown	44	75	900
S4	F	69	2	Autoimmune Disease	52	66	1200
S5	M	63	1	Unknown	26	26	900
S6	M	53	1	Unknown	58	77	900
S7	M	71	2	Noise Exposure	60	37	900
S8	F	73	2	Unknown	46	33	1200
S9	M	66	1	Ototoxic Drug	91	91	900
S10	F	59	2	Unknown	58	77	900
S11	F	38	1	Hereditary	61	45	900
S12	F	61	3	Ototoxic Drug	46	64	250

For consonants, the following 16 consonants were tested in the /aCa/context: b, d, g, p, t, k, z, s, m, n, f, v, θ, δ, ʒ, ʃ. For vowels, the following 10 vowels were tested in the /hVd/context: ɔ, e, ei, e:⁺, i, i:, oo, ʌ, u, u:. The stimulation rate used in the present study, as shown below, is the same as each subject's clinical setting used in everyday life.

across-mode. The subject was presented with a pair of single-channel stimuli in sequence and asked to judge the higher of the two pitches associated with each stimulation, similar to the procedure of pairwise pitch ranking used in the previous studies (Nelson *et al.*, 1995; Collins *et al.*, 1997). The duration of each stimulus was 500 ms and the inter-stimulus gap was 500 ms. In both conditions, two stimuli randomly chosen from a range of sites of stimulation specified in the following text were presented in a random order. In the within-mode condition, the stimuli were presented in the same mode, either in MP or BP. In the across-mode condition, a pair of MP and BP stimuli was presented. The pulse rate of stimulation was the same as that specified in the subject's clinical map for daily use, as specified in Table I. The presentation was at the most comfortable level—the “C-level” from the clinical map for MP stimulation and the level that produced equivalent loudness in the BP configuration. Subjects were presented with an MP stimulus at C-level and a BP stimulus in a similar stimulation site in sequence and were asked to adjust the current level of the BP stimulus in order to match the loudness of the MP stimulus. Upon completion, stimuli from all BP channels were presented in succession, and levels were adjusted as necessary until the subjects reported that they did not perceive differences in loudness across the stimuli. For MP stimulation, the phase width was 25 μ s and inter-phase gap was 8 μ s. For BP stimulation, the current level (the clinical unit used for the Nucleus system) was adjusted to produce the equivalent loudness as the C-level in MP, and if the current level reached the maximum of 255 and still did not produce sufficient loudness, the phase width was increased. In order to reduce the confounding effect of a possible difference in loudness, the actual presentation level of each stimulus was randomly reduced (“roved”) by as much as three current levels from the C-level during the pitch comparison task. Averaging across each tested channel for each participant, this was equivalent to a rove of up to 12% and 10% of the dynamic ranges of their MP and BP maps, respectively.

All BP stimuli in this study were presented in a “BP +1” mode of stimulation, as it was the most commonly used mode for BP electrode configurations in clinical applications of Nucleus systems. The “BP +1” mode utilized a bipolar pair between every other electrode—for example, stimulation between electrodes 20 and 22 or between 1 and 3, corresponding to the most apical or basal channel of stimulation, respectively. In this paper, these channels will be denoted by (20,22) or (1,3).¹ For the sake of consistency, MP stimulation will be denoted in this paper by the active electrode and “M,” such as (22,M) or (1,M).

Although complete pitch ranking matrices including pitch comparisons between all possible stimulation pairs were obtained in the previously discussed studies (Nelson *et al.*, 1995; Collins *et al.*, 1997), the results for pairs consisting of distantly-spaced channels were not further used in the analysis of the sensitivity index (d'). Therefore in the present study, the focus was to examine pitch relations between channels that were roughly in similar stimulation sites, e.g., four electrodes apart in most subjects for the within-mode condition.² Each pair of channels was repeated at least 20

times. All subjects received an informal practice session, not exceeding 15 minutes, including repeated presentations of distant and close electrode pairs and clear instructions to attend to the pitch differences while ignoring other cues such as possible loudness differences. Feedback was provided to seven subjects (S3, S6, S7, S9, S10, S11, and S12) for the within-mode condition based on the tonotopical ordering. The effects of feedback did not appear to be critical.

While within-mode pitch relations have been investigated by previous studies, place-pitch relations between MP and BP stimuli are relatively unknown and therefore substantially more stimuli pairs covering a wider range of separations between channels were selected for testing in the across-mode condition than in the within-mode condition. Each channel of stimulation was paired with as many as five to seven other stimulation channels. This produced a total of about 150 to 250 tested pairs in the across-mode condition.

C. Data analysis plans

For the within-mode condition, the sensitivity index (d') was obtained from the pairwise pitch ranking scores, consistent with the previous studies (Nelson *et al.*, 1995; Collins *et al.*, 1997). The cumulative d' was obtained in each subject and mode as a function of electrode site from the apical end and was used to evaluate the subjects' gross discrimination abilities at different sites. The d' s were compared for MP and BP stimulation to examine whether electrode configuration had a significant impact on place pitch discrimination.

For the across-mode condition, the percent scores of pitch ranking in each BP channel were arranged as a function of the paired MP channel. It was of particular interest to establish the pitch relation between MP and BP channels when they were stimulated at nearby sites. If it was determined purely by stimulating electrodes, as mentioned in Sec. I, (10,12) should be perceived higher than (12,M), showing a percent score above 50%, and lower than (10,M), showing a score below 50% [as mentioned earlier, (12,M) is more apically located than (10,M)]. Therefore (11,M), which is at the location of the geometric centroid of electrodes 10 and 12, should be the most similar in pitch to (10,12) with a score of about 50%. In reality, the closest match occurred at a site shifted either apically or basally from this prediction. In order to quantify the pitch shift, the percent results were fitted to a sigmoid function, and the site of the MP channel that produced 50% was obtained for each BP channel. The trend of the pitch shifts was compared and further analyzed across subjects and places of stimulation.

III. RESULTS

A. Within-mode condition

Table II is the matrix of pairwise pitch ranking results in MP for S6. The matrix is organized from apical (top/left) to basal channels (bottom/right). The (i,j)-th item in the matrix indicates the percentage of responses that the row stimulus was reported higher than the column stimulus. For example, for 100% of the trials, (14,M) was perceived higher than (20,M), while in only 60% of the trials, (14,M) was

TABLE II. Pitch ranking results in MP for S6.

	(22,M)	(21,M)	(20,M)	(19,M)	(18,M)	(17,M)	(16,M)	(15,M)	(14,M)	(13,M)	(12,M)	(11,M)	(10,M)	(9,M)	(8,M)	(7,M)	(6,M)	(5,M)	(4,M)	(3,M)	(2,M)
(21,M)	45																				
(20,M)	85	65																			
(19,M)	70	70	55																		
(18,M)	70	90	85	70																	
(17,M)	100	100	95	95	75																
(16,M)	90	100	100	90	85	55															
(15,M)		100	90	90	90	70	85														
(14,M)			100	100	95	95	70	60													
(13,M)				100	80	80	80	75	75												
(12,M)					100	90	95	85	60	65											
(11,M)						90	90	85	80	75	55										
(10,M)							100	80	75	85	65	60									
(9,M)								100	100	90	80	70	60								
(8,M)									100	100	85	80	80	90							
(7,M)										90	90	100	80	95	95						
(6,M)											90	100	100	95	95	80					
(5,M)												100	100	100	95	80	60				
(4,M)													90	100	95	100	70	55			
(3,M)														90	100	100	90	80	60		
(2,M)															100	90	90	80	75	85	
(1,M)																90	100	95	75	80	60

Each item in the matrix indicates the percentage of responses that the row stimulus was higher than the column stimulus. Each item represents the score after at least 20 trials.

perceived higher than (15,M). In this matrix, the percent scores decreasing from left to right in each row demonstrate pitch relations consistent with the tonotopic organization. While pitch relations of S6, as shown in Table II, mostly followed such expectations, in some subjects deviations—so-called “pitch reversals”—were observed, indicated by scores below 50% (see the Sec. IV B).

The d' was obtained from the percent score for each pair using the published table (Hacker and Ratcliff, 1979). The cumulative d' was computed by summing d' s across pairs of adjacent channels. Following the convention used in the earlier studies (Nelson *et al.*, 1995; Collins *et al.*, 1997), the d' for the 100% score was approximated to 3.3. Although the d' for adjacent channels is not limited and could easily exceed 3.3 in some subjects through the process of subdividing (Kwon and van den Honert, 2006), this approximation was necessary to facilitate comparison of the cumulative d' s across subjects. Thus due to this approximation, the maximum cumulative d' was 69.3 (3.3×21) for MP and 62.7 (3.3×19) for BP. Figure 2 displays the plot of cumulative d' (from an apical-to-basal direction) for each subject. These plots visualize subjects' abilities to discriminate electrodes based on place pitch along the electrode array. The steeper the growth of the d' s, the more sensitive the subject is to place pitch. The abscissa of the graph is the active electrode of the basal channel in the pair: for MP pairs, 21 to 1 indicate the pairs from (21,M)-(22,M) to (1,M)-(2,M); for BP pairs, 19 to 1 indicate the pairs from (19,21)-(20,22) to (1,3)-(2,4). The cumulative d' for the entire array is the final value of the graph, e.g., 58.5 for S1 in the MP mode, and is displayed in Table III. In addition, each cumulative d' function was line-fitted, as shown in Fig. 2, and the slope of each line, corresponding to the mean d' per electrode for adjacent channels, is included in Table III.

A wide range of variability in place pitch discrimination appears in Fig. 2 and Table III. Some subjects, such as S1

and S2, showed good performance, whereas S5, S10, and S11 showed relatively poor discrimination. In all subjects except for S9, both the cumulative d' s and the slopes of the line were greater in MP than in BP, indicating that the subjects were generally more sensitive to the pitch difference in MP than in BP. The average of mean d' per electrode was 1.24 and 0.83 for MP and BP, respectively. This difference was significant as shown in the analysis of covariance (using MATLAB Statistical Toolbox version 7.2) producing a significant interaction between the slope and mode of stimulation ($p = 0.0065$). For comparison, the data reported in Nelson *et al.*'s study (1995), obtained in BP mode, were reconstructed to make Table IV. A similar degree of variability across subjects was seen. The mean cumulative d' for pairs of adjacent channels across subjects was 16.6 for the present study and 14.5 for Nelson *et al.*'s study. A two-sample t-test conducted with cumulative d' s indicated that the difference was not significant ($p = 0.6394$), which was also expected by coincidentally the same mean value of d' per electrode in the present study (Table III) and Nelson *et al.*'s study (Table IV). Note that the mean slopes in Tables III and IV are indicated in terms of d' per electrode for an easy comparison as opposed to d' per millimeter used in Nelson *et al.* (1995). Our rationale for using d' per electrode is discussed in Sec. IV A.

From Fig. 2, it seems that, while place pitch discrimination ability in each subject might not be uniform across the array, no particular trend is found that indicates better performance in the apical or basal region. However, it is notable that, in several subjects, S4 and S12, (and S2 only for BP), discrimination degraded as the channels moved from middle to basal locations, and no subject in the present study showed the opposite trend.

Poor neural survival around mid-to-basal locations might be suspected in S12, as she usually complained about insufficient high frequency sounds from her implant. In S2,

FIG. 2. Cumulative d' s for adjacent channels, in an apical-to-basal direction, for the within-mode condition. The results are line-fitted, and the slope of each condition is indicated in Table III. Each marker indicates the cumulative d' between the channel denoted by the abscissa and all of the more apical channels, e.g., the cumulative d' for active electrode 1 indicates the cumulative d' between (1,3) and (20,22). Note that the y axis is not the same for each row of plots.

on the other hand, where the results of MP and BP showed the most pronounced contrast, the neural survival was not a likely cause as he showed almost perfect pitch discrimination in MP across the entire array.

B. Across-mode condition

A typical example of the results of pairwise pitch ranking for MP-BP pairs for S6 is displayed in Table V. Unlike the within-mode condition, the matrix shows the results across both upper and lower diagonal areas. Presuming that the pitch ranking followed the tonotopic arrangement, in a *row-wise* inspection of the results (i.e., how the pitch relation changed for a given BP stimulus as the paired MP stimulus

is varied), the scores should decrease from the left to right (in the apical-to-basal direction). If the score is substantially high or low (above 75% or below 25%, for example), we could determine that the pitch of one is consistently higher or lower than the other. If the score is in mid-range, the perceived pitches would be similar for the pair.

From Table V, pitch relations in some rows are consistent with the expectation from the sites of stimulation. For example, the pitch was in the following order from low to high: (19,M) < (17,19) < (17,M); i.e., (17,19) was perceived higher in pitch than (19,M) 85% of the time and higher than (17,M) 20% of the time. However, in many rows, pitch relations deviated from this expectation as the pitch of a BP

TABLE III. Summary of within-mode condition results in the present study, in terms of total cumulative d' s for adjacent channels and mean slopes of the lines in Fig. 2 indicating d' per electrode for MP and BP stimulation.

	$\Sigma d'$		Mean slope (d' /electrode)	
	MP	BP	MP	BP
S1	58.6	41.4	2.94	2.04
S2	60.2	23.9	2.88	1.16
S3	30.7	13.1	1.35	0.55
S4	28.4	20.2	1.35	1.11
S5	9.9	6.6	0.77	0.39
S6	14.7	7.8	0.78	0.46
S7	25.2	20.3	1.16	1.07
S8	14.2	16.5	0.65	0.80
S9	25.6	25.1	1.32	1.31
S10	11.9	8.5	0.57	0.36
S11	7.8	4.9	0.37	0.27
S12	13.3	11.0	0.77	0.45
Mean	25.0	16.6	1.24	0.83

TABLE IV. Total cumulative d' s for adjacent channels in a BP within-mode condition, reconstructed from Figs. 3 and 4 in Nelson *et al.* (1995).

	$\Sigma d'$	Mean slope (d' /electrode)
RFM	39	2.37
JRK	25	1.20
WZM	27	1.70
AJA	24	1.25
JPB	19	1.25
KKS	5	0.32
TVB	5	0.37
VVK	7.5	0.37
EES	6	0.44
JWB	4	0.11
RRR	4.5	0.09
DVS	7.5	0.52
mean	14.5	0.83

Cumulative d' s were read from the figures, and the mean slopes were calculated from the slopes in their figures (d' /mm) multiplied by 0.75, which is the distance between electrodes in mm on the arrays tested by Nelson *et al.*

TABLE V. Pitch ranking results in the across-mode condition for S6 for illustration.

	(22,M)	(21,M)	(20,M)	(19,M)	(18,M)	(17,M)	(16,M)	(15,M)	(14,M)	(13,M)	(12,M)	(11,M)	(10,M)	(9,M)	(8,M)	(7,M)	(6,M)	(5,M)	(4,M)	(3,M)	(2,M)	(1,M)
(20,22)	15	30	15	10	32	7	20	10	0													
(19,21)	100	90	75	80	44	10	27	20	20	10												
(18,20)	90	100	95	80	76	40	35	20	7	30	10											
(17,19)	80	100	80	85	72	20	50	15	27	13	10	30										
(16,18)	90	100	100	90	72	60	60	45	30	7	20	0	47									
(15,17)		70	70	100	90	95	85	60	45	45	40	27	35	60								
(14,16)			80	80	100	90	90	75	55	40	25	47	56	30	0							
(13,15)				90	93	100	90	70	48	50	40	10	20	27	0	30						
(12,14)					80	60	80	80	84	75	70	60	44	33	20	10	0					
(11,13)						80	80	100	73	80	70	25	32	45	20	13	20	0				
(10,12)							80	80	100	100	90	70	60	60	40	13	7	0	0			
(9,11)								60	70	80	100	85	68	80	45	25	7	20	0	0		
(8,10)									100	80	100	87	76	90	75	35	25	0	10	0	0	
(7,9)										80	100	80	90	95	65	55	20	35	10	10	0	10
(6,8)											100	100	75	73	95	80	85	35	20	10	0	10
(5,7)												100	100	90	80	70	80	85	55	35	27	20
(4,6)													100	100	80	90	70	80	85	10	30	20
(3,5)														100	100	100	100	65	80	85	35	35
(2,4)															100	100	80	80	45	80	85	50
(1,3)																100	100	53	67	20	80	85

Each item in the matrix indicates the percentage of responses that the row stimulus in BP was higher than the column stimulus in MP. Each item represents the score after at least 20 trials. For readers' convenience, the stimulus pairs with the similar sites of stimulation are marked in shaded cells

channel was often higher than that of the MP channel on the basal side. For example, (18,20) was perceived higher than (18,M) 76% of time and (9,11) was perceived higher than (9,M) 80% of the time. In those examples, the BP pitch was shifted higher (or in the basal direction) by one electrode in the pitch scale of MP channels. In some rows, the basal shift of BP pitch was more than one electrode: the pitch of (15,17) was shifted basally by four electrodes compared to MP channels as it was not lower than the pitch of MP channels until (11,M). These pitch shifts occurred in all subjects. In order to quantify the patterns of pitch shifts, the row-wise scores, i.e., pitch ranking scores of a fixed BP stimulus, were plotted as a function of the paired MP stimulus, and curve-fitted with a sigmoid function, as shown in Fig. 3. The point on the abscissa crossing a 50% score indicates the point where BP and MP channels hypothetically produce equivalent pitches in a statistical sense. In this example of (10,12) in S6, the 50%-crossing point is 9.4, and the amount of pitch

FIG. 3. Sigmoid function fitted to the across-mode pitch ranking scores of a fixed BP stimulus, (10,12), in S6. The point on the abscissa, 9.4, crossing a 50% score indicates the point where BP and MP channels hypothetically produce an equivalent pitch in a statistical sense. The amount of pitch shift in this case is 1.6 electrodes (from the reference location of electrode 11).

shift is 1.6 electrodes as the crossing point would have been 11 had no shift occurred.

Figure 4 displays the results of pitch shifts for each fixed BP channel. The positive ordinate values indicate basal shifts and negative values indicate apical shifts. Most pitch shifts occurred in the basal direction. This indicates that CI subjects tend to perceive a BP stimulus as higher in pitch than expected from the site of excitation compared with an MP stimulus at a similar location. In some subjects, the amount of shift was often as large as three or four electrodes. The trend of basal shifts was particularly strong around the middle sites of the electrode array as shifts were often reduced on either end of the electrode array and sometimes became apical shifts as seen in S2, S8, and S12. Exceptions to this trend were seen in two subjects. In S11, apical shifts occurred in the middle of the electrode array. In S4, shifts were near zero (except for the most apical channel), indicating that the prediction from activation functions, as mentioned in Sec. I, in fact, successfully fits the result in this subject. Figure 5 displays the amount of shift in each BP channel averaged across all subjects and shows basal shifts of about two electrodes for BP channels from (16,18) through (4,6). This indicates that for a given electrode location, there is a tendency for a BP stimulus to be perceived as higher in pitch than an MP stimulus.

IV. DISCUSSION

A. Electrode discrimination data in the literature

The result of the within-mode condition indicates that electrode configuration (MP or BP) has a significant effect on pitch discrimination. Except for one subject (S9), all subjects were better able to discriminate place pitch in MP than in BP stimulation. The mean d' for discrimination of adjacent channels was 1.24 and 0.83 for MP and BP,

FIG. 4. The pitch shift, in electrodes, for fixed BP stimuli, obtained from curve-fitted results in the across-mode condition, as illustrated in Fig. 3. A positive pitch shift indicates that for a given BP channel, the MP channel that produces an equivalent pitch is in a more basal location, e.g., a pitch shift of 2 for (13,15) indicates that the MP channel that produces an equivalent pitch, is (12,M).

respectively. Even if the mean d' was the same for MP and BP, the cumulative d' would be greater for MP than for BP because there are more channels available in MP. Therefore the difference in mean d' between MP and BP punctuates the advantages of MP stimulation in pitch percepts; not only does MP have more total channels, it allows for more sensitive discrimination between channels. Interestingly, the previous data (Nelson *et al.*, 1995; Collins *et al.*, 1997) obtained with BP stimulation were not significantly different from the present data with BP stimulation. This indicates that the differences in the device type (Nucleus-22 versus Nucleus-Freedom) and the electrode array (the straight “banded” array versus Contour™ array) do not have an impact on place pitch discrimination.

In light of the present result and discussion in the preceding text, it is important to recognize the differences in electrode configuration when comparing results across studies. Recent studies have reported pitch discrimination of virtual channels (Donaldson *et al.*, 2005; Kwon and van den Honert, 2006; Firszt *et al.*, 2007) and discrimination of stimuli on multiple channels (Laneau and Wouters, 2004). These studies essentially capitalized upon the CI users’ abilities to discriminate between adjacent channels, presuming sufficiently good ability to carry out such demanding tasks. The results from

these studies generally indicate a far better ability in pitch discrimination than implied by the earlier studies in the 1990s (Nelson *et al.*, 1995; Collins *et al.*, 1997) that had suggested that discrimination between adjacent channels was not always reliable ($d' < 1$). The present result demonstrating better discrimination in MP than in BP reconciles the discrepancy and suggests that electrode configurations be taken into careful consideration when interpreting conclusions across studies.

It is worth noting that Laneau and Wouters (2004) reported relatively better performance in electrode discrimination with four Nucleus-24 subjects. When converting to the d' s for adjacent channels, as their results were represented in terms of just noticeable differences, they are roughly in the range of 1.5 and 3.3, corresponding to cumulative d' s for the entire array of approximately 31.5 and 69.3, respectively, after multiplying each by 21. Compared with Table III in this paper, these d' s appear to be relatively overestimated. First, the relatively smaller number of subjects in ($N=4$) Laneau and Wouters’s study (2004) might have led to a sampling bias. Second, a procedural difference should also be noted. In their study, only 8 pairs of stimuli were presented to subjects in two sites of stimulation as opposed to about 100 pairs in the present study and far more pairs in studies by Nelson *et al.* (1995) and Collins *et al.* (1997). With the reduced diversity in the stimuli, the subjects might have shown better performance to the extent that factors of attention influenced the results.

In previous studies (Nelson *et al.*, 1995; Collins *et al.*, 1997; Laneau and Wouters, 2004), discrimination was described in terms of d' per millimeter in the electrode array (d'/mm), calculated with 0.75 mm for the spacing between electrodes in the Nucleus banded array. The description of discrimination per unit distance (mm) might be potentially useful to make comparisons with other electrode arrays with different electrode spacing. However, the Contour™ array in the present study, which has been used in clinical

FIG. 5. The mean pitch shift in electrodes across subjects for fixed BP stimuli, from Fig. 4.

applications predominantly for the last decade or so, has a pre-curved structure and, after insertion, the electrodes in the apical region are placed closer toward the modiolus than those in the basal region. Therefore with a wild difference in the curvature of the electrode array *in situ*, the results described in terms of distance on the electrode array in two different types of electrode arrays are not directly comparable. Furthermore, the distance between electrodes in a Contour™ array is not uniform—electrodes are more narrowly spaced in the apical side than in the basal side, i.e., the distance between the most apical electrodes is only half of that between the most basal electrodes. For readers' reference, here are the values of d' per mm calculated from the technical specification of the Contour™ array (personal communication with Cochlear Ltd.): 2.22 for MP and 1.55 for BP, although these should be taken with caution for the reasons discussed in the preceding text.

B. Pitch reversals

A pitch reversal refers to a phenomenon where the perceived pitch is the opposite of the expectation from the tonotopical relations of the sites of stimulation for a stimulus pair in the same electrode configuration. While pitch reversals occurred in several subjects and were discussed in two earlier studies (Nelson *et al.*, 1995; Collins *et al.*, 1997), they were not given as significant consideration in recent studies (Laneau and Wouters, 2004; Donaldson *et al.*, 2005; Kwon and van den Honert, 2006; Firszt *et al.*, 2007). In fact, in the recent literature, the terms “place pitch discrimination” and “electrode discrimination” were often used interchangeably, largely discarding the phenomenon of pitch reversals. Therefore an in-depth analysis was conducted to examine pitch reversals in the present study.

First, without considering statistical significance, there were 54 (17 for MP and 37 for BP) occurrences of judging a higher pitch for the apical channel than the basal channel (i.e., the percent score below 50% in the within-mode result as seen in Table II), of a total of 480 cases of pairs of adjacent channels (21 pairs for MP and 19 pairs for BP in all 12 subjects). This seems roughly similar to the occurrences seen in the previous studies (Nelson *et al.*, 1995; Collins *et al.*, 1997). However, it was necessary to verify whether the scores below 50% represented true pitch reversals and not random variations. As each score could be considered as the result of a binomial process $B(20, 0.5)$ —i.e., 20 observations and a probability of 0.5 with a null hypothesis that the pitch judgment was random, a criterion of a score of 15% or less was established below which the null hypothesis was rejected within a 99% confidence interval. Only 6 cases (of 54) in four subjects (S5, S7, S8, and S12) met this criterion. This does not necessarily mean that the other 48 cases were not pitch reversals but that the number of observations was insufficient to support statistical significance. Therefore further testing was conducted with three subjects (S7, S9, and S12) without feedback in which pairs with scores of 20% or 25% were presented in another 20 trials. In a total of 40 observations, the criterion score became 27.5%, and the statistical power to examine significance increased. Despite this

TABLE VI. The stimulus pairs with scores substantially below 50% as determined by a 99% confidence interval.

Subject	Stimulus pair	Score (%)
S5	(21,M) and (22,M)	10
	(20,M) and (21,M)	5
S7	(18,20) and (19,21)	5
	(13,15) and (14,16)	5
	(6,8) and (7,9)	8
S8	(7,9) and (8,10)	10
S12	(12,14) and (13,15)	20
	(1,M) and (2,M)	18

The scores were obtained from the results matrices, as illustrated in TABLE II. The lower the score, the more strongly the pitch percept was the opposite of the tonotopical order. These cases represent a clear indication of pitch reversals.

extended effort, only two more cases, one in S7 and another in S12, were identified as pitch reversals. Table VI displays the eight cases of pitch reversals with the scores—the cases are fairly evenly distributed between MP (3 cases) and BP (5 cases), and it appears pitch reversals occur across the entire array without a particular pattern of site of stimulation.

To summarize, while the occurrences of pitch reversals in the present study appear similar to the previous studies, most of the occurrences do not qualify as pitch reversals based on a 99% confidence interval, suggesting that they might occur less frequently than indicated by earlier studies. Although the phenomenon of pitch reversals cannot be completely disregarded, as it occurred with statistical significance in four subjects in the present study, their implications in clinical applications are unclear at this point.

C. Consideration of relevant acoustic models and other caveats

Stimulation on each channel in CIs is often considered equivalent to a band-limited signal in acoustic hearing, as electrical stimulation presumably excites a neural population, restricted in a range, similar to acoustic hearing based on tonotopic organization. A band of noise in acoustic hearing elicits a pitch percept close to the edge of the spectrum of the signal (von Békésy, 1961; Small and Daniloff, 1967; Klein and Hartmann, 1981). Laneau *et al.* (2006) argued, from an experiment measuring discrimination of noise bands in normal hearing while varying the slope of the edges and comparing the discrimination data obtained with CI listeners (Laneau and Wouters, 2004), that the slope of the edge of excitation in electric hearing would be equivalent to 40 dB/octave in acoustic noise bands. However, considering that the noise with a cut-off slope of 40 dB/octave can produce very high pitch strength, almost as high as a slope of 144 dB/octave (Fastl, 1980), it is unclear whether CI listeners perceptually associate a channel of stimulation with a signal with high pitch strength. Their data in 2004 might have been overestimated as discussed earlier; the actual slope is likely to be shallower, and possibly substantially shallower, in CI users showing poor discrimination.

Finally, it should be noted that the variability observed in the present results might be partially attributed to a

confounding effect of loudness on pitch judgment. We have observed, during the pilot study, instances of a strong influence of unbalanced loudness. Despite the instruction to ignore any possible differences in loudness, some subjects tended to associate a louder stimulus with a higher-pitch stimulus. Admittedly, loudness balancing in the present study was imperfect, and the roving of presentation level of each stimulus might have compensated for the imperfection. At the same time, some of the variability of the data might be attributed to any loudness differences caused by the use of roving.

V. CONCLUSIONS

- (1) CI subjects in the present study showed better discrimination of place pitch in MP than in BP stimulation. When the result of BP stimulation was considered, subjects' overall discrimination in terms of the cumulative d' in the present were not significantly different from previous findings in the literature using BP stimulation (Nelson *et al.*, 1995; Collins *et al.*, 1997). This accounts for the results of relatively better discrimination in more recent studies using MP stimulation (Laneau and Wouters, 2004; Donaldson *et al.*, 2005; Kwon and van den Honert, 2006; Firszt *et al.*, 2007).
- (2) In a direct pairwise comparison of MP and BP stimuli, the subjects tended to perceive a higher pitch sensation in BP than in MP for a similar site of stimulation, requiring the MP stimulation to be shifted in a basal direction by as much as two electrodes, on average, to elicit a similar pitch.
- (3) The approximation of the edge of excitation from electrical stimulation to 40 dB/octave in acoustic noise bands (Laneau *et al.*, 2006) is likely to be overestimated. The actual slope depends on the individual CI user and is likely to be shallower.

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¹In the literature, sometimes only one electrode is specified when referring to a BP stimulus. That notation is not suitable in the present paper in which numerous pairs of MP and BP stimuli are compared because choosing only one electrode might cause an unnecessary bias in the analyses and presentations of the results.

²In three subjects (S6, S10, and S12), pairs with wider separation were tested, up to six electrodes apart, producing a total of 111 pairs for MP, as seen in Table II, and 99 pairs for BP.

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