Lateralization of interaural timing differences with multi-electrode stimulation in bilateral cochlear-implant users

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Abstract: Bilateral cochlear implant (BiCI) users have shown variability in interaural time difference (ITD) sensitivity at different places along the cochlea. This paper investigates perception of multi-electrode binaural stimulation to determine if auditory object formation (AOF) and lateralization are affected by variability in ITD sensitivity when a complex sound is encoded with multi-channel processing. AOF and ITD lateralization were compared between single- and multi-electrode configurations. Most (7/8) BiCI users perceived a single auditory object with multi-electrode stimulation, and the range of lateralization was comparable to single-electrode stimulation, suggesting that variability in single-electrode ITD sensitivity does not compromise AOF with multi-electrode stimulation.

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1. Introduction

Bilateral cochlear implantation is becoming more common for patients with profound deafness because significant improvements have been shown for speech-in-noise understanding and sound localization ability when patients use two vs one device (e.g., see van Hoesel and Tyler, 2003; Litovsky *et al.*, 2009). However, when compared to normal hearing (NH) listeners, speech intelligibility and localization performance is still much poorer in bilateral cochlear implant (CI) users, especially in noisy situations (e.g., see Kerber and Seeber, 2012; Loizou *et al.*, 2009). Many factors may be contributing to the poorer performance in bilateral CI users (for review, see Kan and Litovsky, 2015), but a major factor hindering good sound localization ability when listening with clinical CI processors is the limited availability of interaural time difference (ITD) cues, which is an important cue for accurate localization in NH listeners (Jones *et al.*, 2014; Macpherson and Middlebrooks, 2002; Wightman and Kistler, 1992).

While the availability of ITDs when listening with clinical CI processors is currently limited, bilateral CI users have demonstrated sensitivity to ITDs when listening to stimuli presented through specialized research processors that allow precise control of the timing of stimulation to each electrode in the right and left ear [for detailed reviews, see Kan and Litovsky (2015) and Laback *et al.* (2015)]. This sensitivity has typically been assessed using a stimulus discrimination task, whereby a subject is presented two stimuli, each containing a different ITD, and the subject's task is to identify in which direction the second stimulus was perceived relative to the first (e.g., Egger *et al.*, 2016; Kan *et al.*, 2015). This task has been useful for assessing the just noticeable difference (JND) threshold in ITDs in bilateral CI users, but is unable to characterize how well an ITD cue is being mapped to a perceived spatial location. The work

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described in this paper addresses this issue by measuring lateralization functions of perceived auditory objects when multiple electrodes are stimulated with the same ITD.

Litovsky *et al.* (2010) was the first study to report lateralization data from bilateral CI listeners, using single pairs of electrodes. In that study subjects varied in the extent to which they reported perceiving auditory objects to span the entire range of intracranial positions, and that within subject, lateralization perception varied for different places of stimulation. While this and other previous studies using single electrode stimulation have been helpful to demonstrate that bilateral CI listeners are able to detect and use ITD cues, an understanding of how ITDs are perceived when presented on multiple electrodes is needed because multi-electrode stimulation is required for good speech understanding with CIs.

To date, all studies examining ITD sensitivity with multiple electrode stimulation have measured acuity to ITDs, and have shown that ITD discrimination performance does not appear to be significantly poorer than when stimulating on single-electrode pairs alone (Egger *et al.*, 2016; Francart *et al.*, 2015; Ihlefeld *et al.*, 2014; Kan *et al.*, 2015). However, feasibility and success with multi-electrode ITD stimulation can only really be determined by understanding how ITDs presented on multiple electrodes are perceived by a listener. With single-electrode stimulation, Litovsky *et al.* (2010) reported that ITD lateralization functions can vary at different places of stimulation along the cochlear. One can hypothesize that with multi-electrode stimulation, it is possible that this variability in ITD lateralization functions might lead to an incoherent, and/or multiple, auditory object(s) being perceived. That is, for a given ITD with multi-electrode stimulation, the perceived location of the auditory object may be at a different lateral location in the head at each electrode pair. In this case, the brain may not be able to combine information from these electrodes together to form one single auditory percept in one location. Hence, in the previous studies measuring ITD JNDs with multi-electrode stimulation, subjects need not have perceived a single auditory object in order to perform an ITD discrimination task. While incoherent or multiple objects would make the JND measurement task more difficult, subjects may still be able to complete the task by using ITD information in the most salient electrode pair (Ihlefeld *et al.*, 2014). To obtain a clearer picture of whether multi-electrode stimulation is perceived as a single auditory percept, and how an ITD presented on multiple electrodes is perceptually mapped by a listener in a dimension more representative of space, this study measured lateralization functions of perceived auditory objects in bilateral CI users when multiple electrodes are stimulated with the same ITD. While the present experiment does not prevent the issues posed by the discrimination task, the measurement of lateralization functions will hopefully be able to capture additional dimensions of the perceived stimulus beyond the subjects' ability to detect whether something in the stimulus moved left or right. The lateralization task has the added value of allowing us to measure the perceived lateral positions for a range of ITDs. That is, it allows us to capture the range of ITDs that a subject is able to discern within one side of the head. Moreover, it allows us to capture whether multiple auditory objects are perceived with the given stimulus. Finally, the task provides a means of establishing whether the presence of these additional auditory objects interferes with their ability to lateralize the ITD cue. An understanding of these additional dimensions and the perceptual mapping of ITD cues is a prerequisite for determining the effectiveness of encoding ITDs on multiple electrodes, which should translate to improvements in real-world sound localization ability.

Table 1. Profile and etiology of subjects.

Subject	Age	Sex	Years of experience (L/R)	Etiology
IAJ	67	F	16/9	Childhood onset, unknown
IBX	70	F	4/2	Adult onset, Ototoxic medication / sensorineural
IBY	49	F	5/1	Adult onset, Unknown
IBZ	45	F	5/6	Adult onset, Unknown
ICA	53	F	3/10	Childhood onset, progressive
ICB	62	F	7/10	Childhood onset, hereditary
ICG	50	F	9/9	Childhood onset, unknown
ICI	54	F	4/3	Adult onset, unknown

2. Methods

Eight bilateral CI users with Cochlear Ltd. (Sydney, Australia) implants (CI24 and CI512 series of implants) participated in this study (see Table 1 for etiology and profile). All subjects became deaf post-lingually and have shown ITD sensitivity in other studies (Kan *et al.*, 2015; Kan and Litovsky, 2015; Litovsky *et al.*, 2012). Subjects travelled to the University of Wisconsin–Madison for testing and were paid a stipend for their participation. Testing procedures followed the regulations set by the National Institutes of Health and were approved by the University of Wisconsin's Human Subject Health Sciences Institutional Review Board.

Experiments were conducted using a pair of synchronized Laura34 speech processors (Cochlear Ltd., Sydney, Australia) connected to a laptop computer. Subject responses were recorded using a touchscreen connected to the same computer. Custom-written MATLAB (MathWorks, Natick, MA) code was used to generate stimuli and run the experiments. All stimuli were 300-ms, constant-amplitude electrical pulse trains presented at a rate of 100 pulses-per-second. The pulses were biphasic with 25-μs duration per phase, and presented via monopolar stimulation. Threshold and maximum current levels were found for all electrode pairs tested and a self-reported comfortable stimulation level within this range was used for testing.

Interaurally pitch-matched pairs of electrodes were used for these experiments and were found using methods previously described in detail in Litovsky *et al.* (2012) and Kan *et al.* (2015). To summarize the basic steps, interaurally pitch-matched pairs of electrodes were chosen using a two-step process: (1) a place-pitch magnitude estimation task was first conducted on each electrode and the results used to estimate possible pitch-matched electrode pairs across the ears; (2) a bilateral pitch comparison task was then conducted to compare various combinations of electrodes across the ears. In this task, subjects responded by indicating whether the sound of a test electrode in the ear contralateral to a reference electrode was perceived to be "much higher," "higher," "same," "lower," or "much lower" in pitch. The pair that yielded the highest number of same results was chosen as the pitch-matched pair for testing. Other rules described in detail in Litovsky *et al.* (2012) were used to choose the pitch-matched pair, if a pair could not be easily identified. Five pitch-matched pairs of electrodes, roughly spanning the length of the array, were found for each subject using this procedure (see Table 2). Finally, each left/right pair of electrodes was stimulated together, and the levels in each ear were manually adjusted by the experimenter until the subject indicated a centered auditory object, and all pairs were perceived to be at the same loudness.

Lateralization functions were measured using established methods previously described in detail in Litovsky *et al.* (2010) and Kan *et al.* (2013). To summarize, subjects indicated the perceived lateral location of the stimulus by indicating the point on a response bar that spanned the width of a cartoon image of a face. If multiple auditory objects were perceived, subjects ranked the dominance of auditory objects and indicated the perceived lateral location of the most dominant (primary) auditory object in the topmost bar, and the locations of secondary auditory objects in the lower bars. Subjects could repeat the presentation of the stimulus as many times as needed to decide on the intracranial location of the auditory objects. The responses were converted into an arbitrary set of values ranging from 0 to 1, where 0, 0.5, and 1 represented the leftmost, center, and rightmost locations in the head, respectively. On each trial, an ITD of 100, 200, 400, and 800 μs was applied to the stimulus. Each ITD value

Table 2. Electrode pairs tested and their corresponding ITD JND thresholds (in μs) from Kan *et al.* (2015), and ULR expressed as a percentage of the possible range across the head. NM denotes non-measureable thresholds.

	Base				Mid-base				Mid				Mid-Apex				Apex			
	L	R	JND	ULR	L	R	JND	ULR	L	R	JND	ULR	L	R	JND	ULR	L	R	JND	ULR
IAJ	6	8	392	29.3	10	12	353	25.7	14	14	328	37.9	16	19	237	38.5	19	21	396	42.5
IBX	4	4	198	9.3	8	9	164	10.4	12	13	183	6.6	16	17	300	3.0	20	22	504	0.3
IBY	4	7	246	78.2	8	11	242	72.4	12	12	353	50.5	16	14	312	58.7	20	18	394	50.1
IBZ	4	4	691	84.2	5	5	667	42.8	8	6	662	64.5	10	10	916	9.6	12	12	522	77.0
ICA	3	4	303	31.6	8	10	301	29.7	14	14	508	18.4	16	15	NM	13.3	18	19	NM	7.9
ICB	4	4	83	79.5	8	9	92	82.5	12	12	114	59.8	15	14	171	54.1	18	18	203	34.7
ICG	6	6	139	59.9	8	8	153	66.1	12	10	175	72.1	16	14	289	72.8	20	18	398	52.7
ICI	2	4	109	94.8	4	8	158	87.9	8	10	155	93.2	12	16	335	65.4	18	18	405	49.6

was tested ten times, in both directions. In this paper, left- and right-leading ITDs are denoted by negative and positive ITD values, respectively.

Lateralization functions were first measured separately for each of the five pitch-matched pairs, followed by different multi-electrode configurations. A series of three-electrode configurations were tested, where the pitch-matched electrode pairs stimulated were located along the electrode array at (1) apex, mid-apex, mid [Apical-3]; (2) base, mid-base, mid [Basal-3]; (3) the three electrode pairs with the best ITD sensitivity[1] out of the five tested individually [Best-3]; and (4) base, mid, apex [Separated-3]. In addition, a five-electrode configuration [All-5] was also tested. These configurations were the same as those used in Kan *et al.* (2015). In all multi-electrode configurations, electrode pairs were sequentially stimulated in apex-to-base order, where the time between the onsets of each pulse in successive electrodes was 70 μs.

3. Results

Figure 1 shows the lateralization functions from all of the subjects for the five multi-electrode configurations, sorted by a range of lateralization in the All-5 configuration. The lateralization functions were derived by fitting a three-parameter logistic function of the form

$$p(\text{ITD}) = \frac{L_m}{1 + e^{-m(\text{ITD}-\text{shift})}}, \tag{1}$$

to the mean perceived location at each ITD, where m is the steepness of the curve, shift is the bias in the responses, and L_m is the curves maximum value which was constrained to be at a maximum of 1. The following observations can be made from the data: (i) Only subject IAJ reported hearing two auditory objects with multi-electrode stimulation, though the prevalence of the secondary auditory object was typically low and varied for the different multi-electrode configurations (All-5: 2%; Base-3: 5%; Separated-3: 13%; Apical-3: 29%).[2] It is notable that while two auditory objects were perceived by IAJ, the lateralization of the primary auditory object appears to be relatively unaffected by the presence of the secondary auditory object in the Separated-3 and All-5 conditions, as demonstrated by lateralization functions that span locations from left to right as a function of ITD. (ii) Most subjects demonstrated a reasonably

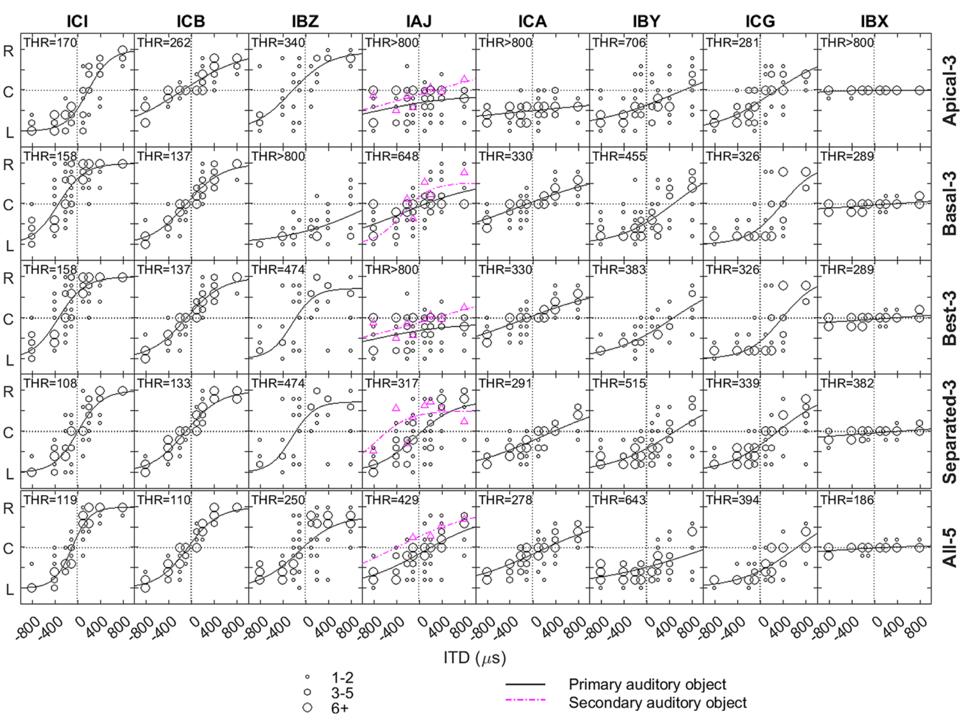

Fig. 1. (Color online) Lateralization functions are shown for all subjects for the different multi-electrode configurations tested. Subjects are sorted by their range of lateralization in the All-5 configuration. Primary auditory object responses were binned into 11 locations, 5 on each side plus center, and the size of the circle in each plot represents the number of responses at each location bin. The location of secondary auditory objects is denoted by triangles. The mean locations for the primary and secondary auditory object were fit by a three-parameter logistic function, as shown by the solid and dashed lines, respectively. An estimate of the left/right ITD discrimination threshold (THR), is shown in the upper left corner for each configuration.

good mapping of ITD to perceived lateral location in at least one of the multi-electrode conditions. Typically, this was the Separated-3 condition. This can be seen by the clustering of responses for a given ITD. (iii) The ability to map ITDs to an intercranial location within the full range of the head varied with subjects. For subjects ICI, ICB, IBZ, IBY, and ICG, the full range of left-to-right lateralization was achieved within the physiologically relevant range of ITDs (approximately -700 to $700\,\mu$s) with most of the multi-electrode configuration. For subjects IAJ and ICA, a partial range of left-to-right lateralization was achieved within the range of ITDs tested, and subject IBX had difficulty with lateralization of the auditory object in all configurations.

To compare the extent of lateralization between single- and multi-electrode stimulation, we calculated the utilized lateral range (ULR) of the primary auditory object for each subject individually, expressed as a percentage of the total available lateralization range. The ULR was calculated by taking the difference in the lateral location of the auditory object estimated using Eq. (1) for $\text{ITD} = -700$ and $+700\,\mu$s, and multiplying by 100. The ULR provides a conservative estimate of the perceptual range of the auditory object with physiologically relevant ITD values, but may underestimate the actual range perceived by the CI user because there is typically some variability in the perceived lateral position of an auditory object (Kan *et al.*, 2013). The median ULRs for each multi-electrode configuration were: Apical-3: 44.9%, Basal-3: 48.5%, Best-3: 67.2%, Spread-3: 67%, and All-5: 49.6%. Friedman's test comparing ULRs across all multi-electrode configurations found a significant difference between the Apical-3 and Separated-3 conditions ($\chi^2 = 10.56$, $p = 0.03$). Figure 2 shows the ULR calculated for each multi-electrode configuration compared against the largest ULR obtained from the single-electrodes[3] that made up each of the multi-electrode configuration. Bilateral CI users demonstrated a high variability in ULRs across subjects, ranging from subject IBX who showed a very small ULR for all configurations to ICI who was able to lateralize the auditory object for the full range of ITDs. However, for most subjects' single- and multi-electrode ULRs were relatively comparable. This can be seen by the fact that most data points either fell on, or close to, the dotted line. Wilcoxon signed rank tests found no significant differences in ULRs when comparing multi-electrode configurations with the single electrode pair that yielded the largest lateralization range, except for the Apical-3 condition where the difference in ULRs approached significance ($p = 0.05$). More subjects showed a decrease in ULRs in the Apical-3 configuration, compared to other multi-electrode configuration. This can be more clearly seen in Fig. 3, where the ULRs for multi-electrode configurations has been normalized by the largest ULR of the single-electrode pairs making up the multi-electrode configuration. It can be seen that in most conditions, median performance is on par with that of single-electrode stimulation, but for some subjects (namely, IAJ and ICA) the Separated-3 condition led to a significant increase in ULRs. A comparison of median performance across the different multi-electrode configurations suggests that there was a drop in ULRs in the Apical-3 configuration when compared to the best single electrode pair within the group.

To quantify the subjects' ability to map ITDs to discriminable lateral locations, a left/right ITD discrimination threshold was estimated from the lateralization function using the method described in Litovsky *et al.* (2010). The estimated thresholds are shown in the top left-hand corner of each plot in Fig. 1. The threshold estimates the smallest ITD that would lead to a discriminable difference between two locations

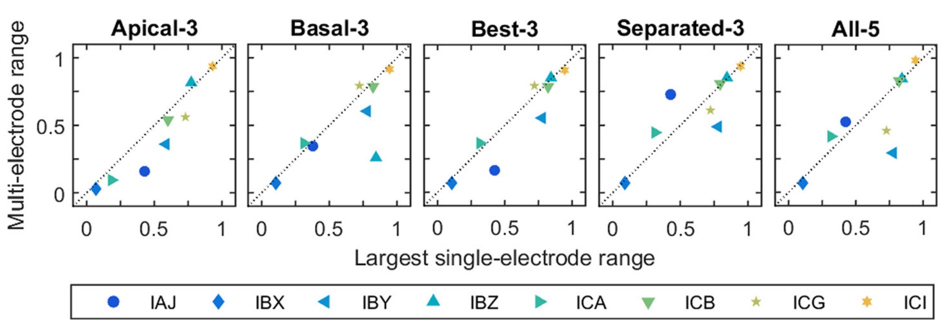

Fig. 2. (Color online) A comparison of the ULR between multi- and the largest single-electrode configurations is shown. The largest single-electrode range was determined from the lateralization functions of the single-electrode pairs that made up the multi-electrode configuration. The dotted line indicates where the single- and multi-electrode ULRs are the same. Data points that fall on the dotted line along the main diagonal indicate similar ULRs for both single- and multi-electrode configurations, while data points that fall below the line indicate smaller ULRs for multi-electrode stimulation.

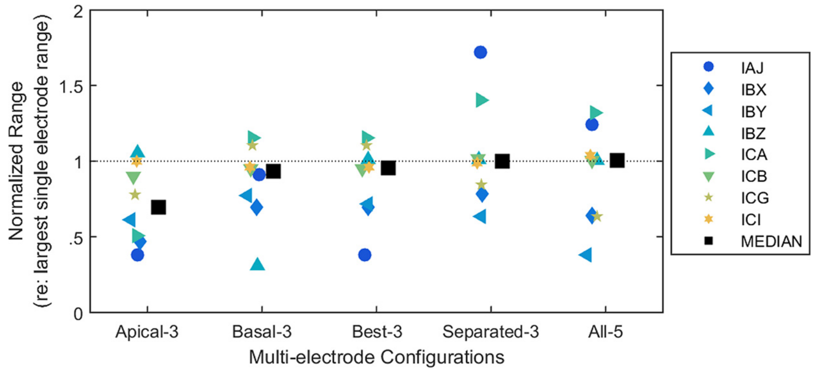

Fig. 3. (Color online) The normalized range for all multi-electrode configurations is shown, where the different symbols denote individual results and the black square denotes the group mean. A normalized range of 1 implies equivalent ULRs between single- and multi-electrode stimulation, while a normalized range less than 1 shows poorer performance.

across the midline. The measure takes into account the slope of the lateralization function, as well as the underlying variance in the perceived locations. Both of these factors affect the discriminability of lateral locations. The slope characterizes the rate of change in ITD before lateral positions are discriminable, and the variance captures the internal noise in the lateral position judgments. Hence, thresholds would be smallest for a subject with a large ULR and small variance, and largest for a subject with a small ULR and large variance. It should be noted that this method is likely to yield thresholds that are higher than that obtained using two-interval methods because there is no reference location for a judgment comparison in the lateralization task. Median thresholds for each of the multi-electrode conditions were: Apical-3: 523 μs, Basal-3: 328 μs, Best-3: 328 μs, Separated-3: 328 μs, and All-5: 264 μs. Friedman's test found no significant differences between the thresholds of the multi-electrode configurations ($\chi^2 = 7.11$, $p = 0.13$).

4. Discussion

The current study addresses the question of whether the same ITD information presented on multiple electrode pairs would lead to a coherent auditory object being perceived in a single, lateral location in spite of the known variability in ITD sensitivity at different places along the cochlea in bilateral CI users. Our results showed that the majority of subjects reported perceiving a single auditory object that systematically varied in its intra-cranial location as a function of ITD. This implies that the variable sensitivity measured at different places along the length of the cochlear does not seem to have a large effect on the grouping of electrodes with the same ITD information into a single coherent auditory object. This is a significant result because it suggests that even if ITD information were transmitted at places along the cochlea with poorer ITD sensitivity, bilateral CI users will still be able to use other cues, such as a common onset or periodicity of the rates within the stimulus to group electrodes together to form a single, coherent auditory object. For one subject, multiple auditory objects were perceived with multi-electrode stimulation. It should be noted that the prevalence of the perceived secondary auditory object was typically low, except for the Apical-3 configuration where in 29% of trials a secondary auditory object was perceived. It is likely that this subject was more sensitive to the inharmonic relationship of the places of stimulation with multi-electrode stimulation, and hence was more likely to report hearing multiple auditory objects compared to other participants.

The results also showed that the range of lateralization with multi-electrode stimulation was typically on par with that of the largest single-electrode lateralization range. This result is consistent with previous literature that showed that ITD sensitivity was also comparable between single- and multi-electrode stimulation (Egger *et al.*, 2016; Francart *et al.*, 2015; Ihlefeld *et al.*, 2014; Kan *et al.*, 2015). In addition, a comparison of different multi-electrode configurations showed that confining the ITD information to the apical end of the electrode array appears to reduce the lateral range of the auditory object. This is consistent with the results of Kan *et al.* (2015), which showed that ITD sensitivity was also poorer when ITD information was confined to the apical end of the electrode array with multi-electrode stimulation. At present, it is unclear why ITD sensitivity is typically poorer in this region. In contrast, the results found in this study suggest that spreading the ITD information along the length of the electrode array can lead to improved lateralization in some subjects, a result that is also consistent with that found in Kan *et al.* (2015). This adds additional support to the notion that spreading ITD information along the length of the electrode array, rather than restricting ITD information to the apical end of the array, may be more beneficial for bilateral CI users.

5. Conclusion

This work examined the extent to which the same ITD presented on multiple interaural electrode pairs was perceived as a coherent auditory object at a single lateral location by bilateral CI users. Results suggest that lateralization with single- and multi-electrode stimulation are comparable, and that spreading ITD information along the length of the electrode array appears to be more beneficial than restricting ITD information to the apical end of the array. Overall, these findings provide additional evidence supporting the notion that ITD sensitivity can be restored to bilateral CI users with carefully controlled, multi-electrode stimulation.

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[1]ITD sensitivity was determined for these electrode pairs in other studies. Details can be found in Litovsky *et al.* (2012) and Kan *et al.* (2015). ITD JND thresholds for these electrode pairs, as measured using a two-interval discrimination task, are provided in Table 2.

[2]It should be noted that for subject IAJ, the Best-3 and Apical-3 configurations are identical. That is, the single-electrode pairs that yielded the lowest ITD JNDs were the Apex, Mid-Apex, and Mid pairs.

[3]The single electrode ULRs are shown in Table 2.

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