Effect of multi-electrode configuration on sensitivity to interaural timing differences in bilateral cochlear-implant users

Alan Kan,[a] Heath G. Jones, and Ruth Y. Litovsky
Binaural Hearing and Speech Laboratory, Waisman Center, University of Wisconsin—Madison,
1500 Highland Avenue, Madison, Wisconsin 53705, USA

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Recent psychophysical studies in bilateral cochlear implant users have shown that interaural timing difference (ITD) sensitivity with electrical stimulation varies depending on the place of stimulation along the cochlear array. While these studies have measured ITD sensitivity at single electrode places separately, it is important to understand how ITD sensitivity is affected when multiple electrodes are stimulated together because multi-electrode stimulation is required for representation of complex sounds. Multi-electrode stimulation may lead to poorer overall performance due to interference from places with poor ITD sensitivity, or from channel interaction due to electrical current spread. Alternatively, multi-electrode stimulation might result in overall good sensitivity if listeners can extract the most reliable ITD cues available. ITD just noticeable differences (JNDs) were measured for different multi-electrode configurations. Results showed that multi-electrode ITD JNDs were poorer than ITD JNDs for the best single-electrode pair. However, presenting ITD information along the whole array appeared to produce better sensitivity compared with restricting stimulation to the ends of the array, where ITD JNDs were comparable to the poorest single-electrode pair. These findings suggest that presenting ITDs in one cochlear region only may not be optimal for maximizing ITD sensitivity in multi-electrode stimulation.
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I. INTRODUCTION

Bilateral cochlear implants (CIs) are becoming more common for patients with profound deafness in both ears, and results to date show significant improvements in sound localization ability when using two CIs vs one CI (van Hoesel and Tyler, 2003; Litovsky *et al.*, 2009). However, performance is still much poorer compared to that seen in normal hearing (NH) listeners (Grantham *et al.*, 2007; Majdak *et al.*, 2011; Jones *et al.*, 2014), especially in noisy situations (Kerber and Seeber, 2012; Litovsky *et al.*, 2012). Data from Grantham *et al.* (2007) and Aronoff *et al.* (2010) suggest that bilateral CI users appear to be relying primarily on interaural level differences (ILDs) for sound localization along the horizontal plane with little to no reliance on interaural time differences (ITDs). This is contrary to data from NH listeners, where ITDs are weighted more heavily than ILDs (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002). The difference between CI users and NH listeners in cue weighting may be one reason for the poorer performance with bilateral CIs. Low reliance on ITDs for free-field sound localization in bilateral CI users is unsurprising because most clinical sound-processing algorithms encode acoustic sounds in a manner that is not optimal for providing useful ITD information. CI processors encode acoustic sounds by separating the incoming signal into a small number of frequency bands, typically corresponding to the number of electrodes in the implanted array (ranging from 12 to 22). Within each band, the slow-varying envelope of the signal is extracted and used to set the stimulation level for each electrode. High rate pulsatile stimulation (900 Hz or higher) is typically used to represent the envelope in each frequency band and, hence, the time-varying detail (fine structure) of the acoustic signal is not preserved. High pulse rates have been shown to reduce sensitivity to ITDs in individual pulses (Laback *et al.*, 2007; van Hoesel *et al.*, 2009), but are needed for providing a high-resolution encoding of the acoustic envelope, which is useful for speech understanding (Loizou *et al.*, 2000; Smith *et al.*, 2002; Churchill *et al.*, 2014). It is likely that ITD information in the envelopes of the signal is still encoded by the CI processors, but the usefulness of these envelope ITDs may be limited by the small dynamic range of the modulations in naturally occurring sounds or by interaural incoherence (Rakerd and Hartmann, 2010; Ihlefeld and Shinn-Cunningham, 2011; Ihlefeld *et al.*, 2014). Another possible reason for poor ITD sensitivity in bilateral CI users is that interaural differences in the insertion depths of electrode arrays are not taken into account in clinical mapping practices. Typically, electrodes of the same number are assigned the same frequency range in both ears, but interaural insertion depth differences can lead to a mismatch in the place of stimulation in the two ears, which has been shown to adversely affect perception. Under controlled conditions with direct electrical stimulation, ITD just noticeable differences (JNDs) have been shown to double with

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[a] Electronic mail: ahkan@waisman.wisc.edu

an interaural mismatch of 3 mm (Poon *et al.*, 2009; Kan *et al.*, 2013; Kan *et al.*, 2015). In addition, typical mapping procedures can often lead to non-centered or unfused auditory images (Goupell *et al.*, 2013; Fitzgerald *et al.*, 2015), which may increase the difficulty in distinguishing changes in ITD.

In order to overcome the issues surrounding clinical processors, previous studies investigating ITD sensitivity in bilateral CI users have been conducted using specialized research processors, which stimulate at single pairs of electrodes across the ears. This work has shown that ITD sensitivity is best when interaurally pitch-matched pairs of electrodes stimulated at low pulse rates are used (Laback *et al.*, 2007; van Hoesel *et al.*, 2009; Litovsky *et al.*, 2010; Litovsky *et al.*, 2012; Kan and Litovsky, 2015). As the rate of stimulation is increased, ITD sensitivity typically decreases (van Hoesel *et al.*, 2009). When stimulated at different places along the cochlea, CI users show high variability in ITD sensitivity at the different places. On average, ITD sensitivity appears to be higher at the basal end of the electrode array (Best *et al.*, 2011; Kan and Litovsky, 2015; Laback *et al.*, 2015), although there can be individual differences due to subject etiology (Litovsky *et al.*, 2010; Litovsky *et al.*, 2012). Litovsky *et al.* (2012) reported ITD JNDs for 34 bilateral CI subjects measured at 3 different places along the length of the cochlea. Sensitivity to ITDs ranged from 40 μs to over 1600 μs. In some subjects who reported having onset of deafness prior to acquiring language, ITD sensitivity was especially disrupted. While ITD sensitivity was observed in some places along the cochlear array, it was absent at other places, and in 4 out of the 34 subjects, no ITD sensitivity was observed at any of the 3 places tested.

Studies in which binaural sensitivity was measured with single interaural pairs of electrodes have clearly indicated that bilateral CI users can be sensitive to ITDs. However, it is important to determine how sensitivity is affected when multiple electrode pairs are stimulated because multi-electrode stimulation is required in order to preserve good speech understanding. Toward the goal of ultimately providing usable ITD information while maintaining good speech understanding, the current study examined ITD sensitivity in bilateral CI users when the same ITD information is presented on multiple electrodes. Understanding how overall ITD sensitivity is affected with multi-electrode stimulation is particularly important because of the high variability in ITD JNDs observed across different places of stimulation within the same subject. It is possible that overall ITD sensitivity may be lowered when electrode pairs that yield poorer ITD sensitivity are combined with electrode pairs that yield good sensitivity. Alternatively, ITD sensitivity may be unaffected by electrode pairs that yield poor sensitivity because the listener can ignore the poorer information. A third alternative is that ITD sensitivity may be increased due to summation of binaural information across a wide range of frequencies, as observed in NH listeners (Dye, 1990). In addition, it is also important to understand how stimulation on multiple electrode pairs interact with each other because the spread of current from two neighboring electrodes may interfere with the salience of ITD cues (Lu *et al.*, 2011).

A few recent studies have begun to shed light on these issues. Best *et al.* (2011) investigated ITD sensitivity in CI users in the context of binaural interference using a 100 pulse per second (pps) electrical pulse train. In NH listeners, binaural interference occurs when sensitivity to an ITD in a high-frequency "target" stimulus is disrupted by the presence of a simultaneous low-frequency interferer with an ITD set to zero. While the data showed individual differences, the authors concluded that CI users, as a group, generally showed various degrees of interference, in line with that experienced by NH listeners. The results suggest that different binaural information presented at multiple electrode places can reduce the overall sensitivity to a target binaural cue. In contrast, bilateral CI users have demonstrated some overall ITD sensitivity when stimulated at multiple sites with the same ITD. This overall sensitivity does not appear to be significantly poorer than stimulating on individual sites alone (Ihlefeld *et al.*, 2014; Egger *et al.*, 2015; Francart *et al.*, 2015). When two electrodes are stimulated, overall ITD sensitivity does not appear to be significantly affected by the presence of an electrode pair that yields poorer ITD JNDs, either with high rate (1000 pps) electrical stimulation and 100 Hz amplitude modulation (Ihlefeld *et al.*, 2014), or low rate (100 pps) stimulation (Egger *et al.*, 2015). Instead, overall ITD sensitivity appears to be influenced more by the electrode pair that yields better ITD sensitivity (Ihlefeld *et al.*, 2014). The spacing of electrode pairs appears to have little influence on overall ITD sensitivity (Egger *et al.*, 2015; Francart *et al.*, 2015), but softer presentation of the combined stimulation (Egger *et al.*, 2015) and increasing delay in stimulation between multiple channels (Francart *et al.*, 2015) can negatively affect ITD JNDs.

The current work addresses questions regarding approaches for maximizing ITD sensitivity by identifying the most suitable locations on the electrode array for presenting ITD information. This decision is especially interesting when we have knowledge of ITD sensitivity with single pairs of electrodes for each participant at different places of stimulation along the electrode array. Because ITD sensitivity in NH listeners is best at low frequencies, and the cochlea is most sensitive to low frequencies at the apex (Robles and Ruggero, 2001), it has been generally assumed that ITD information should be presented to bilateral CI users at the apical end of the electrode array with multi-electrode stimulation (van Hoesel and Tyler, 2003; Hochmair *et al.*, 2006; Churchill *et al.*, 2014). However, unlike NH listeners whose cochleae do not vary much in neural health, in CI users there is high variability among the patient population as to which places of stimulation show good ITD sensitivity. Thus, one cannot assume that apical electrodes should be the only electrodes to carry ITD information because these electrodes may not be the most ITD sensitive. Hence, in this study, we investigate a number of different possibilities for choosing the electrodes that carry ITD information in order to determine which configuration of electrodes maximizes ITD sensitivity. Our investigations focused on the following possibilities: (1) ITD carrying electrodes should be located toward the apical end of the electrode array for reasons discussed above; (2) ITD carrying electrodes should be located at the basal end of the electrode array because bilateral CI users as a group have typically shown slightly better ITD sensitivity with basal stimulation; (3) the electrodes that yield the best ITD sensitivity should be used in order to maximize overall ITD sensitivity; (4) ITD information should be distributed along the electrode array in order to minimize interference from spread of current; and/or (5) ITD information should be presented along the entire electrode array, and the brain will be able to extract the most potent information for maximizing ITD sensitivity.

II. METHODS

A. Listeners

Eleven bilateral CI users with Cochlear Ltd. (Sydney, Australia) implants (CI24 and CI512 series of implants) participated in this study. Table I shows the profile and etiology of the CI users; all were postlingually deaf and had shown ITD sensitivity at low stimulation rates in other studies. Subjects traveled to the University of Wisconsin-Madison for testing and were paid a stipend for their participation. All experimental 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.

B. Equipment and stimuli

A personal computer running MATLAB software (Mathworks, Natick, MA) was used to generate stimuli and run the experiments using custom written code. A pair of synchronized Laura34 speech processors (Cochlear Ltd., Sydney, Australia) were used to deliver the stimuli directly to the subject's implants. Subject responses were recorded using a touchscreen connected to the personal computer. All stimuli were 300-ms duration, constant amplitude pulse trains presented at a rate of 100 pps. The pulses were biphasic with a 25 μs phase duration and presented via monopolar stimulation.

C. Electrode selection

Five interaurally pitch-matched pairs of electrodes were chosen for each subject. The five pairs were chosen to roughly span the length of the electrode array at the following locations: base, mid-base, mid, mid-apex, and apex. Loudness maps were created for each subject at the beginning of testing to ensure safe and comfortable stimulation levels. It should be noted that the 100 pps rate for the test stimuli is much lower than the rates used in the participants' clinical processors. This low pulse rate was chosen because previous studies have shown that CI users are more sensitive to ITDs at low rates (Laback *et al.*, 2007; van Hoesel *et al.*, 2009). For each subject, the threshold (*T*), comfortable (*C*), and maximum comfortable (*M*) levels of all the electrodes were determined with psychophysical testing whereby the subject reported the perceived loudness of a 100 pps constant amplitude pulse train at a current level chosen by the experimenter. *T* was defined as the current level required so that a sound could just be heard. *C* was defined as the level at which stimulation was comfortably loud and the level at which the subject reported that s/he would be willing to listen to the stimulation all day. *M* was defined as the highest current level that stimulation could occur without it being uncomfortably loud. Once established, *C* levels were compared across electrodes by sequentially playing 300-ms pulse trains on each electrode with an inter-stimulus interval of 100-ms and adjustments were made to ensure that all *C* levels at all electrodes were perceived to be at an equally comfortable loudness.

Pitch-matched pairs were found using the methods described in Litovsky *et al.* (2010) and Litovsky *et al.* (2012). First, a place-pitch magnitude estimation task was conducted whereby subjects were presented stimuli at a single, randomly chosen electrode in either the left or right ear. Subjects responded by rating the perceived pitch of the stimulus on a scale from 1 (low pitch) to 100 (high pitch). Each electrode was tested ten times. The results of the place-pitch magnitude estimation task were used to estimate possible pitch-matched electrode pairs across the ears, which informed the experimenter which electrode pairs to use in the following direct pitch comparison procedure. Second, a two-interval, five-alternative forced choice bilateral pitch comparison task was conducted using the estimated pairs. On each trial, the subject was presented with a sound in one ear followed by a sound in the other ear. Subjects were asked to respond by indicating whether the second sound was perceived to be "much higher," "higher," "same," "lower," or "much lower" in pitch compared to the first sound. These categories were assigned values of 2, 1, 0, −1, and −2, respectively, and a metric, μ, was calculated by summing the

TABLE I. Profile and etiology of CI Listeners.

Subject	Age	Sex	Years of experience (left/right)	Etiology
IAJ	67	F	16/9	Childhood onset, unknown
IBK	73	M	8/2	Adult onset, hereditary/noise
IBN	68	M	4/13	Childhood onset, unknown
IBQ	81	F	7/10	Adult onset, Meniere's
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
ICB	62	F	7/10	Childhood onset, hereditary
ICG	50	F	9/9	Childhood onset, unknown
ICI	54	F	4/3	Adult onset, unknown
ICM	60	F	3/2	Adult onset, progressive

enumerated responses. Subjects could listen to the sounds as many times as they needed before making a response. Twenty trials were collected for each pair tested and the pair with a total μ closest to zero was chosen as the "matched" pair. If there were multiple pairs with $\mu = 0$, then the pair closest in electrode number was chosen. For some subjects, it was sometimes the case that no pair of interaural electrodes sounded the same, but rather one of the tested pairs had a bimodal distribution of responses with the right electrode being perceived higher in pitch for approximately half of the trials and lower for the other half. In this case, this pair was chosen as the "matched" pair. Five pitch-matched pairs, spanning the length of the array, were found using this procedure.

Because concurrent stimulation on multiple electrodes is often perceived as being louder than stimulation on each electrode individually, the *C* levels of the five pitch-matched pairs were reduced by 10%–15% of their dynamic range. The reduced levels were used in the single-electrode conditions and ensured that when all five electrode pairs were stimulated together, the perceived loudness was at a comfortable level. Care was taken to ensure that the individual electrode pairs were still perceived to be the same loudness at this reduced level by playing the five electrode pairs sequentially and having the subject indicate if any of the pairs were louder than the other. Louder electrode pairs were reduced in level to match the level of all pairs. Finally, each left/right pair was stimulated simultaneously and the subject was asked to indicate the perceived lateral location of the auditory image on a picture of a face. The levels were adjusted manually to ensure that a centered auditory image was perceived for each of the five pitch-matched pairs separately. Table II shows the electrode pairs used by each subject for these experiments.

D. Task

ITD JNDs were measured using a two-interval, two-alternative forced choice task. In the first interval, an ITD pointing either to the left or right was applied to the stimuli. In the second interval, an ITD of the same magnitude was applied but in the opposite direction to that of the first. Subjects responded by indicating the direction of the second interval relative to the first. A method of constant stimuli was used in this experiment where ITDs of 100, 200, 400, and 800 μs were tested. Additional ITD values were added during the testing for subjects who had thresholds outside of this range. Each ITD was tested 40 times, 20 left-right, and 20 right-left.

TABLE II. Electrode pairs. (L, left; R, right.)

	Base		Mid-base		Mid		Mid-apex		Apex	
	L	R	L	R	L	R	L	R	L	R
IAJ	6	8	10	12	14	14	16	19	19	21
IBK	6	6	11	10	14	13	15	16	18	22
IBN	4	8	8	13	12	16	15	18	18	20
IBQ	8	1	12	3	14	7	16	9	20	11
IBX	4	4	8	9	12	13	16	17	20	22
IBY	4	7	8	11	12	12	16	14	20	18
IBZ	4	4	5	5	8	6	10	10	12	12
ICB	4	4	8	9	12	12	15	14	18	18
ICG	6	6	8	8	12	10	16	14	20	18
ICI	2	4	4	8	8	10	12	16	18	18
ICM	4	5	8	8	12	14	16	15	18	18

ITD sensitivity was first measured separately for each of the five pitch-matched pairs, followed by different configurations consisting of three pairs of electrodes. The three-electrode configurations tested had the following electrode combinations: (1) apex, mid-apex, mid (apical-3); (2) base, mid-base, mid (basal-3); (3) the three electrode pairs with the best ITD sensitivity out of the five tested individually (best-3); and (4) base, mid, apex (separated-3). Finally, ITD sensitivity was measured when all five electrodes were stimulated (all-5). In the multi-electrode cases, electrode pairs were sequentially stimulated in apex-to-base order in which the onset of a pulse between each successive electrode pair was 70 μs.

E. Analysis

Percent correct scores for each ITD tested were corrected for bias by estimating the hit rate probabilities for each stimulus interval, P_1 (left-right) and P_2 (right-left) and bracketing within the range of $1/N$ and $1 - 1/N$ to prevent numeric instabilities, where $N = 40$, which equals the number of trials per ITD. d'-scores were then calculated by: $d' = \sqrt{2} \times [z(P_1) + z(P_2)]/2$. The d'-scores at each ITD were fit with a straight line passing through the origin, and ITD JNDs were estimated as the point where the line intersected $d' = 1$. It should be noted that the ITD JNDs reported in this article are 50% smaller than JND values that are typically reported for discrimination tasks with a center reference.

III. RESULTS

Individual ITD JNDs are shown in Fig. 1. Figure 1(A) shows ITD JNDs for the single-electrode condition. The single-electrode data are consistent with most reports on bilateral CI users, whereby variability in ITD JNDs is observed across the subject population. Here, JNDs were as low as 35 μs (within normal hearing range) in one subject (IBK, Base) and above 900 μs in others (IBN, Mid; IBZ, Mid-Apex). Across the different places of stimulation, there was no systematic change in ITD JNDs in this subject group. For some subjects (e.g., ICB, ICG, ICI, IBX), ITD JNDs appeared to decrease from apex to base, although subjects such as IBN and IBQ showed no systematic trend across the cochlear places. On average, ITD JNDs were 382 μs, 338 μs, 334 μs, 260 μs, and 247 μs from apex to base. Friedman's test with Bonferroni correction revealed that, across the group, ITD JNDs in the Apex condition was significantly higher than JNDs in the Mid-Base and Base conditions [$\chi^2(4,11) = 14.04$, $p = 0.007$].

Figure 1(B) shows ITD JNDs for the multi-electrode configuration. It can be seen that subjects with lower ITD

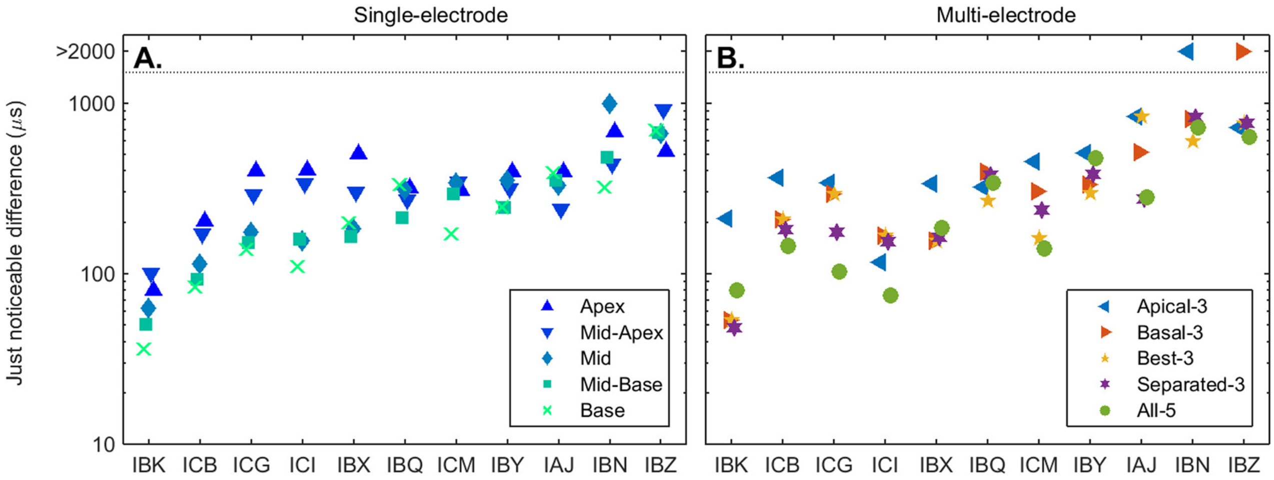

FIG. 1. (Color online) ITD JNDs are shown for each subject individually. Different symbols are used to represent the different single- and multi-electrode conditions. Subjects are sorted by lowest to highest based on the mean JND across all single-electrode conditions.

JNDs in the single-electrode conditions [Fig. 1(A)] were also the subjects who had lower ITD JNDs in the multi-electrode conditions [Fig. 1(B)]. In the three-electrode configurations, variability in ITD JNDs exist across the subject population, although most subjects demonstrated poorest ITD JNDs with the Apical-3 (average: 564 μs) and Basal-3 (average: 475 μs) configurations, while ITD JNDs were slightly better with the Best-3 (average: 344 μs) and Separated-3 (average: 324 μs) configurations. Friedman's test with Bonferroni correction found no significant difference in ITD JNDs between all three-electrode configurations [$\chi^2(3,11) = 7.69$, $p = 0.05$]. For the All-5 configuration, ITD JNDs were on average lower than the three-electrode configurations (average: 289 μs). However, there was no multi-electrode configuration that consistently yielded the lowest ITD JNDs across the entire group of listeners. Figure 2 shows a box plot of the ITD JNDs for each multi-electrode configuration. A Friedman's test with Bonferroni correction comparing all multi-electrode configurations revealed a significant difference between the Apical-3 and the All-5 configurations [$\chi^2(4,11) = 11.64$, $p = 0.02$], indicating that ITD JNDs were generally higher when only the apical-most locations were stimulated, and the All-5 configuration typically yielded the lowest ITD JNDs among the group of subjects.

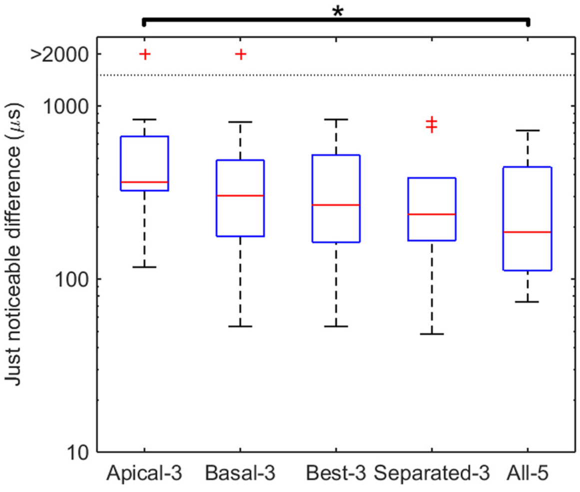

FIG. 2. (Color online) Box plot showing the median, 25th and 75th percentiles, and outliers (+) for each multi-electrode configuration. The asterisk denotes a significant difference between configurations.

Figure 3 shows the ITD JNDs obtained in the multi-electrode configurations normalized by the worst [Fig. 3(A)] and best [Fig. 3(B)] single-electrode ITD JNDs, where worst and best refers to the pair of electrodes in each configuration that yielded the highest and lowest ITD JNDs, respectively. While large inter-subject differences can be seen in Fig. 3(A), a Wilcoxon signed rank test found no significant difference between the Apical-3, Basal-3, and Best-3 configurations and the electrode pair that yielded the worst ITD JND ($p > 0.05$), suggesting that confining stimulation to either end of the electrode array leads to poorer overall ITD sensitivity. However, it should be noted that for the Best-3 configuration, five subjects (IBK, ICB, ICG, ICI, IBX) had the same electrode pairs chosen for the Best-3 and Basal-3 configurations. If these subjects were excluded, the Best-3 configuration yielded ITD JNDs that were on par with or better than the worst single-electrode pair. Only subject IAJ performed poorly when using the Best-3 electrode configuration. IAJ's poor ITD sensitivity with the Best-3 configuration may be due to the fact that two of the Best-3 electrodes were the apex and mid-apex pairs, which led to similar performance between the Best-3 and Apical-3 configurations. In contrast, the Separated-3 and All-5 configurations yielded ITD JNDs that were significantly better than the worst single-electrode pair as revealed by a Wilcoxon signed rank test ($p < 0.05$), suggesting that distributing ITD information along the length of the array vs confining ITD information to one end of the array leads to improved ITD sensitivity beyond that yielded by the worst single-electrode pair.

Comparing multi-electrode configurations with the best single-electrode pair, Wilcoxon signed rank tests revealed significant differences between all multi-electrode conditions and the single-electrode pair that yielded the best ITD JND ($p < 0.05$). It can be seen from Fig. 3(B) that all multi-electrode configurations had ITD JNDs

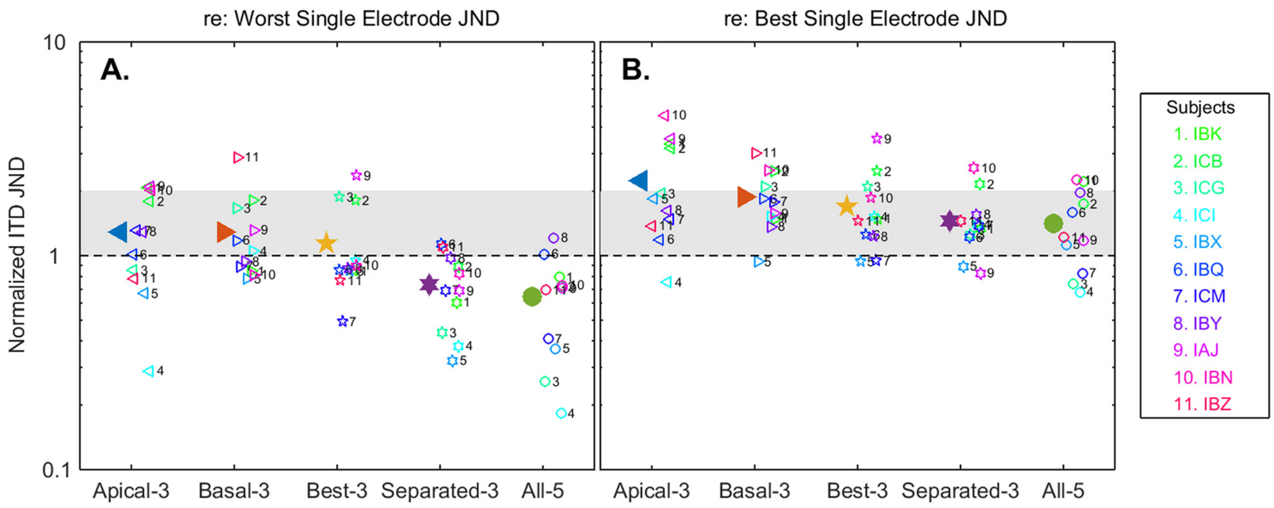

FIG. 3. (Color online) Multi-electrode ITD JNDs normalized by the worst and best single-electrode ITD JND. The worst and best single electrodes are defined as the pairs comprised in the multi-electrode configuration with the highest and lowest ITD JNDs, respectively. A normalized ITD JND value of 1 indicates similar performance between the multi-electrode configuration and single electrode. A normalized ITD JND value of < 1 indicates better performance than the single-electrode case. The shaded area indicates multi-electrode ITD JNDs that are within twice that of the ITD JND obtained in the single-electrode case. The filled symbol represents the group average, while the unfilled symbols represent individual results.

poorer than the pair yielding the best JND. However, ITD JNDs for multi-electrode configurations were typically within about twice the ITD JND of the pair yielding best performance. Assuming a doubling of the ITD JND yielded by the best single-electrode pair is a reasonable upper bound for poor performance, the Separated-3 and All-5 configurations yielded acceptable performance for most subjects, while the Apical-3, Basal-3, and Best-3 configurations yielded acceptable performance for more than half of the subjects. This implies that while ITD JNDs for the Apical-3 and Basal-3 configurations were similar in performance to the worst single-electrode pair, they were still within a reasonable limit.

IV. DISCUSSION

With increasing numbers of patients being implanted with bilateral CIs, improving the efficacy of bilateral CI stimulation is becoming an important area of research. A significant gap in sound localization performance exists between NH listeners and bilateral CI patients, which has typically been attributed to the fact that ITD cues are not presented in a reliable manner by the clinical processors. In theory, ITD cues may be available in the signal envelope, but CI users do not appear to be relying on these cues for free-field localization. Past research has focused primarily on ITD sensitivity with stimulation at single electrode pairs along the cochlear array, but the impact of multi-electrode stimulation on ITD sensitivity has not yet been fully explored. The current study examined ITD sensitivity when different multi-electrode configurations were used to present the same ITD information. This work is important for the design of new speech coding strategies that optimize availability of binaural cues to CI users, and it sheds light on how the auditory system combines ITD information presented at multiple cochlear sites.

Previous work measuring ITD sensitivity at different places along the cochlea with single electrode pairs has shown that within a subject there can be high variability in sensitivity along different places in the cochlea (van Hoesel *et al.*, 2009; Litovsky *et al.*, 2012). The data collected on single pairs of electrodes in this present study are consistent with prior reports. The general trend observed in the group data is that stimulation in basal electrode pairs produced better ITD sensitivity with decreasing sensitivity at progressively more apical stimulation. However, individual differences still existed and were non-monotonic as a function of cochlear place in some subjects. These observations are consistent with previous works (Best *et al.*, 2011; Ihlefeld *et al.*, 2014; Kan and Litovsky, 2015; Laback *et al.*, 2015). While the precise reasons for the variability in ITD sensitivity across the group are unknown, one might speculate that ITD sensitivity is related to the survival of spiral ganglion cells along the cochlea. This may account for the variability in sensitivity when stimulating at different places along the cochlea within the same patient, but does not explain the general population trend of better ITD sensitivity at the base because the spiral ganglion cell survival rate is typically better at the apex than the base (Pfingst *et al.*, 2011).

When multiple electrodes were stimulated, our results showed no significant difference in ITD sensitivity for groups of electrodes either at the apical or basal ends of the electrode arrays (Apical-3 and Basal-3 conditions). What appeared to be of significant benefit to ITD sensitivity was to have ITD information presented at multiple places of stimulation distributed along the length of the electrode array (Separated-3 and All-5 conditions). However, a different approach has been taken with speech coding strategies that have been proposed for introducing ITD information in CI processors. These strategies have typically focused on having lower stimulation rates at the most apical channels, while maintaining higher stimulation rates on basal channels (van Hoesel and Tyler, 2003; Hochmair *et al.*, 2006; Churchill *et al.*, 2014). These approaches may have, as discussed above, assumed that in order to improve ITD sensitivity low rates should be used at the apical end of the array because ITD sensitivity is best at low frequencies in NH listeners and at low rates in CI users. Similarly, these approaches also assume that speech information requires high rates of stimulation, which would be better suited for presentation near the basal region of the electrode array. However, our current results suggest that a different approach whereby ITD information is distributed along the full length of the array may be more beneficial for maximizing ITD sensitivity. What remains unclear is how ITD information should be introduced along the array without compromising speech intelligibility. One possible solution is to stochastically jitter the timing of pulses when using high pulse rates. The use of periodic high rate pulse trains is believed to lead to adaptation of the auditory nerve, but the introduction of aperiodicity in the pulse train has been shown to restore some ITD sensitivity (Laback and Majdak, 2008). However, random jittering may have an effect on speech understanding and will require further research.

It is interesting to note that no significant difference was found between the Separated-3 and All-5 configurations. This result suggests that the spacing of electrode pairs did not affect overall ITD sensitivity in this experiment. This is in agreement with the findings of Francart *et al.* (2015) and Egger *et al.* (2015). More importantly, the lack of a difference between the Separated-3 and All-5 configuration would suggest that ITD sensitivity is not greatly improved by increasing the number of electrodes. This implies that only a small number of ITD carrying electrodes may be necessary to transmit ITD information, as long as the electrodes used are distributed along the length of the array.

ITD sensitivity in bilateral CI users has been shown to decline at softer stimulation levels (van Hoesel, 2007). While the loudness of single electrode stimulation would have been softer than the multi-electrode configurations, the stimulation on the best single-electrode pair usually yielded ITD JNDs that were lower than obtained with multi-electrode stimulation, suggesting that the differences observed were not related to loudness. This result is in contrast to that found in Ihlefeld *et al.* (2014) and Egger *et al.* (2015), where ITD JNDs obtained via stimulation on two electrodes were found to be similar to that obtained via the best single-electrode pair. In these prior studies, only two electrode pairs were stimulated. We speculate, with only two electrodes, it may have been easier for the subject to determine which of the electrode pair is more reliable, and be able to attend to the more ITD sensitive pair and simply ignore the poorer pair. In our case, where three or more electrode pairs are being stimulated, the best electrode pair may be more difficult to determine and follow. One might speculate that given more than two electrodes, subjects may combine information from all electrodes. Following the analysis from Ihlefeld *et al.* (2014), we can attempt to predict multi-electrode d'-scores by

$$d'_{\text{multi}} = \sqrt{\sum_{i=1}^{n} (d'_i)^2}, \qquad (1)$$

where d'_i is the individual d'-score from the n single-electrode pairs making up the multi-electrode configuration. ITD JNDs can then be estimated by finding the point where the line $d' = 1$ intersected with a straight line fit to the calculated d'_{multi}-scores. Figure 4 shows the estimated ITD JNDs vs the ITD JNDs measured in each multi-electrode configuration. In all configurations, it can be seen that our predictions underestimated the ITD JND for most of the subjects. These results suggest that ITD information presented at the different electrode places may not be uniformly weighted by the listener and that other factors may be influencing overall ITD sensitivity when multiple electrodes are stimulated.

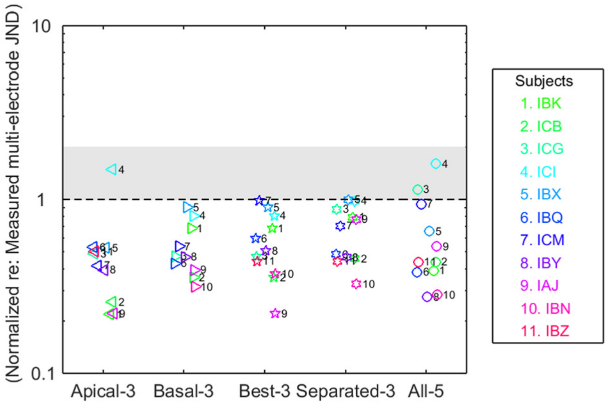

FIG. 4. (Color online) Estimated ITD JND normalized by measured multi-electrode ITD JND. A normalized JND value of 1 indicates that the predicted ITD JND is the same as the measured multi-electrode ITD JND, while a value of < 1 indicates that the JND is underestimated. Each symbol represents the result for an individual subject.

V. CONCLUSION

This work examined how overall ITD sensitivity is affected when different configurations of electrodes are stimulated with the same ITD information. While our overall results would suggest that stimulating on a single-electrode pair will likely yield the best ITD sensitivity, multi-electrode stimulation is necessary for good speech understanding and the encoding of complex sounds. Reasonable ITD sensitivity can still be obtained with multi-electrode stimulation, although the configuration of electrodes chosen for stimulation can have a significant effect on performance. Presenting ITD information along the length of the electrode array appeared to be most beneficial, while stimulating on only half the electrode array led to much poorer ITD sensitivity. Overall, these findings suggest that strategies that limit low stimulation rates to the apical end of the electrode array may not be optimal for maximizing ITD sensitivity in bilateral CI users.

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