Effects of Interaural Pitch Matching and Auditory Image Centering on Binaural Sensitivity in Cochlear Implant Users

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Objectives: In bilateral cochlear implant users, electrodes mapped to the same frequency range in each ear may stimulate different places in each cochlea due to an insertion depth difference of electrode arrays. This interaural place of stimulation mismatch can lead to problems with auditory image fusion and sensitivity to binaural cues, which may explain the large localization errors seen in many patients. Previous work has shown that interaural place of stimulation mismatch can lead to off-centered auditory images being perceived even though interaural time and level differences (ITD and ILD, respectively) were zero. Large interaural mismatches reduced the ability to use ITDs for auditory image lateralization. In contrast, lateralization with ILDs was still possible but the mapping of ILDs to spatial locations was distorted. This study extends the previous work by systematically investigating the effect of interaural place of stimulation mismatch on ITD and ILD sensitivity directly and examining whether "centering" methods can be used to mitigate some of the negative effects of interaural place of stimulation mismatch.

Design: Interaural place of stimulation mismatch was deliberately introduced for this study. Interaural pitch-matching techniques were used to identify a pitch-matched pair of electrodes across the ears approximately at the center of the array. Mismatched pairs were then created by maintaining one of the pitch-matched electrodes constant, and systematically varying the contralateral electrode by two, four, or eight electrode positions (corresponding to approximately 1.5, 3, and 6 mm of interaural place of excitation differences). The stimuli were 300 msec, constant amplitude pulse trains presented at 100 pulses per second. ITD and ILD just noticeable differences (JNDs) were measured using a method of constant stimuli with a two-interval, two-alternative forced choice task. The results were fit with a psychometric function to obtain the JNDs. In experiment I, ITD and ILD JNDs were measured as a function of the simulated place of stimulation mismatch. In experiment II, the auditory image of mismatched pair was centered by adjusting the stimulation level according to a lateralization task. ITD and ILD JNDs were then remeasured and compared with the results of experiment I.

Results: ITD and ILD JNDs were best (lowest thresholds) for pairs of electrodes at or near the pitch-matched pair. Thresholds increased systematically with increasing amounts of interaural mismatch. Deliberate and careful centering of auditory images did not significantly improve ITD JNDs but did improve ILD JNDs at very large amounts of simulated mismatch.

Conclusions: Interaural place of stimulation mismatch decreases sensitivity to binaural cues that are important for accurate sound localization. However, deliberate and careful centering of auditory images does not seem to significantly counteract the effects of mismatch. Hence, to obtain maximal sound localization benefits of bilateral implantation, clinical and surgical techniques are needed that take into account differences in electrode array insertion depths across the ears.

Key words: Bilateral cochlear implants, Binaural sensitivity, Interaural mismatch.

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INTRODUCTION

Surgical provision of cochlear implants (CIs) in both ears is becoming ubiquitous in many clinics; however, the outcomes thus far for binaural and spatial hearing outcomes vary tremendously across patients. The extent to which potential benefits of bilateral implantation are being realized may be affected by differences between the ears, which can arise from two different factors. First, differences in the patterns of neural survival in the two ears can lead to populations of neurons associated with different frequencies to be recruited during electrical stimulation. Second, the depth of insertion of the electrode arrays can be different in the two ears. Typical CI insertion depths* can range from 20 to 31 mm (Gstoettner et al. 1999; Helbig et al. 2012). Although it may be possible for a surgeon to approximately match the insertion depths in the two ears, this is a difficult task and small differences across the ears are common (e.g., see Pearl et al. 2014). In the present work, we focus on the effect of artificially introduced insertion depth differences between the two ears and how this can affect binaural sensitivity in bilateral CI users. Ultimately, understanding this factor will provide important insight into the causes for poor sound localization observed in many bilateral CI users.

Insertion depth differences are currently not taken into account in clinical mapping practices, in part, because of a lack of clinically feasible identification methods. Hence, the same numbered electrodes in both ears are typically assigned the same frequency range. This practice of frequency allocation, combined with interaural insertion depth differences, would lead to acoustic frequencies being sent to different places along the cochlea in the two ears. If models of binaural sound localization (Jeffress 1948; Colburn 1977) are considered, which assume that interaural time differences (ITDs) and interaural level differences (ILDs) are interaurally compared at each frequency, an interaural place of stimulation mismatch (IPM) will cause a discrepancy in the frequencies being compared. The outcome would be a distortion of the auditory spatial mapping due to an inconsistent internal mapping of ITD or ILD cues to source direction on the horizontal plane. For example, a zero ITD and ILD would not produce an auditory image that is perceived to be centered.

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* It should be noted that the place of stimulation is affected by a number of different factors not just physical insertion depth. Differences in electrode designs and physical placement in the cochlea can lead to different medial-to-lateral positions, which would greatly affect the set of spiral ganglion cells that are actually stimulated by interaural electrodes of the same number. As such, insertion angle is a more accurate measure of insertion depth compared with insertion depth reported in millimeters because it better correlates with the places of stimulation. However, in the text, we have opted to refer to insertion depth in millimeters because it is intuitively easier to understand compared with insertion angle.

We recently reported the effect of IPM on binaural auditory image fusion and sound source lateralization in bilateral CI users (Kan et al. 2013). In that study, IPM was deliberately introduced in a single pair of electrodes, by always stimulating the same electrode in one ear and systematically varying the electrode stimulated in the contralateral ear. Experiments began with interaural pitch matching was used to select the pair of electrodes perceived to have the best match in pitch. This technique assumes that electrodes with the same perceived pitch are exciting the same areas along the cochlea in the two ears. It has been shown that interaural pitch matching can identify pairs with good ITD sensitivity, although this may depend on the patient's etiology and amount of neural survival (Long et al. 2003; van Hoesel 2004; Litovsky et al. 2010, 2012). Binaural fusion was measured as a function of IPM using a 10-category fusion scale. This scale was devised to capture the (i) number, (ii) location, and (iii) compactness of perceived auditory images. In addition, perceived intracranial location (i.e., lateralization) of auditory images was measured for ITD and ILD values intended to produce images spanning right to left ear. The task involved subjects reporting the number of auditory images and perceived lateral position of each auditory. With increasing amounts of IPM, subjects reported a decrease in binaural fusion and an increase in the number of auditory images. In addition, the auditory image was perceived to be off-center, even though the stimulus had a zero ITD and ILD. When a nonzero ITD was applied, the ability to perceive changes in the lateral position of the auditory image was decreased significantly with increasing interaural mismatch, to the point where different ITDs were not perceptually mapped to different locations. In contrast, subjects typically retained the ability to perceptually map changes in ILDs to different locations, even in the presence of large interaural mismatches. However, the ILD mapping was distorted toward one side of the head. Thus, the mapping of lateral position with changes in ILD did not pass through the center of the head when ITD was set to zero.

The lack of binaural fusion and lateralization of the auditory image at large amounts of IPM may explain the decrease in ITD sensitivity observed in a number of studies directly measuring ITD just noticeable differences (JNDs) in CI users with right-left discrimination tasks. Long et al. (2003), Wilson et al. (2003), and van Hoesel (2004) all showed that a pair of pitch-matched electrodes across the ears was more likely to have the best ITD JNDs and that there was a monotonic decrease in sensitivity with interaural electrode pairs that were less similar in pitch. Poon et al. (2009) showed that there is approximately a 3.4-mm range along the cochlea, whereby ITD sensitivity was within a factor of 2 of the lowest ITD JND. This suggests that there may be some degree of tolerance in the amount of mismatch for ITD sensitivity.

To date, the effects of IPM on ILD sensitivity has not been directly measured in bilateral CI users. In normal-hearing (NH) listeners, the effect of IPM on ILD sensitivity has been examined using Gaussian-enveloped tones with different bandwidths to simulate different amounts of current spread (Goupell, Stoelb, et al. 2013) and using interaurally uncorrelated, 1/3-octave narrowband noise to simulate incoherence between the ears (Francart & Wouters 2007). As with ITD sensitivity in CI users, ILD JNDs increased with increasing interaural mismatch in the NH listeners.

Because IPM is not typically taken into account by current clinical mapping practices and surgical techniques, and ILDs are considered to be an important cue for sound localization in bilateral CI users (Grantham et al. 2007; Aronoff et al. 2010), it is also important that the effects of IPM on ILD sensitivity be understood in CI users. Hence, in this study, we systematically investigated the effect of IPM on both ITD and ILD sensitivity, in the same bilateral CI subjects. In addition, we investigated whether "centering" of the auditory image in the presence of IPM can improve sensitivity to ITDs and ILDs. The results in Kan et al. (2013) showed that CI users perceive an off-centered auditory image with mismatch, which may explain the increase in ITD and ILD JNDs. This is because in NH listeners, smaller JNDs have been found for ITDs with centered tones and narrowband transients (Yost 1974; Hafter et al. 1975) and for ILDs with centered tones (Domnitz & Colburn 1977; Yost & Dye 1988). Hence, it was hypothesized that adjusting the stimulation levels in each ear to produce a centered auditory image might be an alternative way to improve sensitivity to ITDs and ILDs. In particular, this might be a more clinically feasible way of accommodating for IPM with existing tools, without the need to do pitch matching across the ears. Overall, the results of this study extends our knowledge of the effects of IPM on binaural sensitivity in CI users and highlight that IPM considerations may need to be taken into account in clinical practices, to maximize binaural sensitivity in bilaterally implanted patients.

MATERIALS AND METHODS

Subjects

A total of nine, postlingually deafened, adult bilateral CI users participated in this study. Due to time constraints, subjects IAZ and IBW did not complete experiment 2. Table 1 shows the profile and etiology of the CI users. All had Cochlear Ltd. (Sydney, Australia) implants (CI24 and CI512 models). These implants have 22 intra-cochlea stimulation electrodes spaced approximately 0.75-mm apart and 2 extra-cochlea ground electrodes. The electrodes are numbered 1 to 22 starting from the most basal electrode to the most apical electrode. All subjects traveled to the University of Wisconsin–Madison for testing and participated in these tests over 2 to 3 days. Subjects were paid a stipend for their time. All experimental procedures followed the regulations set by the National Institutes of Health and were approved by the University of Wisconsin's Human Subjects Institutional Review Board.

Equipment and Stimuli

A personal computer running MATLAB (MathWorks, Natick, MA) was used to generate stimuli and run the experiments. The stimuli were 300 ms, and constant amplitude pulse trains presented on either a single electrode or an interaural pair of electrode. Pulses were biphasic with a 25-μs phase duration, 8-μs phase gap, and presented via monopolar stimulation. Compared with typical stimulation rates, a relatively low stimulation rate was used (100 pulses per second). This is because CI users typically show greater ITD sensitivity at lower pulse rates (van Hoesel et al. 2009; Litovsky et al. 2012). The stimuli were presented directly to the subject's implants using a pair of synchronized L34 processors (Cochlear Ltd., Sydney, Australia). Subjects responded on a touchscreen connected to the personal computer.

Calibration

Methods for obtaining loudness maps and selecting testing electrodes were the same as that described in Kan et al. (2013).

TABLE 1. Profile and etiology of subjects

ID	Age	Sex	Years CI Experience (L/R)	Implant (L/R)	Etiology
IAJ	65	F	14/7	CI24M/CI24R	Unknown
IAZ	77	M	5/3	CI24RE/CI24RE	Unknown
IBD	81	M	12/12	CI24M/CI24M	Meniere's/noise/hereditary
IBF	59	F	3/5	CI24RE/CI24RE	Hereditary
IBK	71	M	7/1	CI24R/CI24RE	Hereditary/noise
IBO	46	F	<1/3	CI512/CI24RE	Otosclerosis
IBQ	79	F	8/5	CI24RE/CI24R	Meniere's
IBW	55	F	4/18	CI24RE/CI512*	Ototoxic medication
IBX	70	F	2/1	CI24RE/CI512	Ototoxic medication/sensorineural hearing loss

**Note: IBW was reimplanted 2 yr before testing. Before this, she had a CI22 in her right ear.*

Briefly, threshold (T), comfortable (C), and maximum comfortable (M) levels were obtained for each electrode by having the subject report the perceived loudness of a constant amplitude pulse train presented at a current level chosen by the experimenter. T was defined as the threshold of audibility of electrical stimulation, C was the stimulation level that was comfortably loud and that the subject could tolerate listening to all day, and M was the highest stimulation level without it being uncomfortably loud. These measures formed the loudness map for the subject. Adjustments were made to C levels such that all electrodes were perceived to be of equal loudness before proceeding.

Two interaural pitch-matching tasks were used to find a pitch-matched pair at electrodes across the ears for testing. First, a place-pitch magnitude estimation task was conducted using a method of constant stimuli. Subjects were presented stimulation on a randomly chosen even-numbered electrode in either their left or their right ear and responded by rating the perceived pitch of the stimulus on a scale from 1 (low pitch) to 100 (high pitch). Each even-numbered electrode was tested 10 times, giving a total of 220 stimulus presentations (11 Electrodes × 2 Ears × 10 Repetitions). The results of the place-pitch magnitude estimation task were used as a guide to estimate pitch-matched electrode pairs across the ears for the next task. Second, a bilateral pitch comparison task was conducted to find pairs of perceptually pitch-matched electrodes across the ears. The bilateral pitch comparison task was a two-interval, five-alternative forced choice task. In each trial, the subject was presented with a sound in one ear and then a sound in the other ear. They were asked to respond whether the second sound was "much higher," "higher," "same," "lower," or "much lower" in pitch compared with 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 enumerated responses. Subjects could repeat 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 electrode on the right 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. For the following experiments, a matched pair near the middle of the electrode array was used for testing and was tested to ensure a single, fused auditory image in the center of the head was perceived when stimulated.

Electrode Selection

Experiments were conducted using the matched pair found using the procedure described earlier and simulating "mismatched" pairs by holding one of the electrodes in the matched pair fixed and varying the electrode used on the contralateral side. Table 2 shows the electrode pairs used for each subject. In the following, Δ is used to denote the number of electrodes away from the matched pair, where $\Delta = 0$ is defined as the matched pair, negative values of Δ means the left ear electrode used is more basal than the right ear electrode of the matched

TABLE 2. Electrode pairs for "matched" and "mismatched" conditions

Δ	−8			−4			−2			0			2			4			8		
	L	R	Adj	L	R	Adj	L	R	Adj	L	R	Adj	L	R	Adj	L	R	Adj	L	R	Adj
IAJ	14	22	ND	14	18	5	14	16	−2	14	14	8	14	12	3	14	10	ND	14	6	ND
IAZ	5	14	—	9	14	—	11	14	—	13	14	—	15	14	—	17	14	—	21	14	—
IBD	12	20	5	12	16	10	12	14	8	12	12	1	12	10	2	12	8	0	12	4	−7
IBF	4	13	ND	8	13	3	10	13	3	12	13	−2	14	13	3	16	13	9	20	13	ND
IBK	8	18	1	8	14	0	8	12	4	8	10	4	8	8	6	8	6	9	8	2	−11
IBO	12	20	−7	12	16	1	12	14	10	12	12	8	12	10	6	12	8	0	12	4	−7
IBQ	6	7	0	10	7	3	12	7	1	14	7	−2	16	7	2	18	7	7	22	7	ND
IBW	14	22	—	14	18	—	14	16	—	14	14	—	14	12	—	14	10	—	14	6	—
IBX	8	17	0	8	13	8	8	11	−1	8	9	0	8	7	−10	8	5	0	8	1	4

Negative Δ values imply the left ear electrode (L) was closer to the base of the cochlea, and positive Δ values imply the right ear electrode (R) was more basal. The amount of adjustment (Adj) in CU needed to center the auditory image in experiment II is shown, where negative and positive adjustments imply the C level in the left and right ear was reduced, respectively. Electrode pairs where a centered auditory image could not be determined are marked ND. Subjects IAZ and IBW did not complete experiment II, and no adjustment are shown for those pairs.

pair and positive values of Δ means the right ear electrode is more basal than the left ear electrode of the matched pair. In this study, Δ = 0, ±2, ±4, and ±8 were tested, yielding a total of seven Δ conditions.

Procedure

Two experiments were conducted. In experiment I, ITD and ILD sensitivity were measured as a function of simulated IPM. These conditions were tested to examine the effect of the clinical situation where acoustic information for the same frequency range are assigned to the same numbered electrodes in both ears, irrespective of the amount of insertion depth difference in the two ears. A left-right discrimination task was performed using a two-interval, two-alternative forced choice procedure in which either a non-zero ITD or ILD was presented in the stimulus in the left or right direction in the first interval and in the opposite direction in the second. Subjects responded by indicating the direction of the sound in the second interval. Typical ITD values were ±100, ±200, ±400, and ±800 μs and ILD values were ±2, ±5, and ±10 current units (CUs), although these were varied for some subjects depending on their sensitivity to these cues. ITDs were applied by delaying the stimulation in the ear contralateral to the intended direction of the sound. Similarly, ILDs were applied by reducing the stimulation level at the contralateral ear. Each ITD/ILD was presented 40 times (20 times left direction and 20 time right direction) at each Δ. Percent correct scores were fit with a psychometric function (Wichmann et al. 2001a, 2001b) and the ITD and ILD JND calculated at the 71.1% point on the psychometric function. The JNDs reported in this article have been doubled to match JND values that are typically reported for discrimination tasks with a center reference. It should be noted that level roving was not included in the test paradigm because centeredness of auditory images can change as a function of level due to different dynamic ranges and loudness growth functions between the ears (Goupell, Kan, et al. 2013), and this may confound interpretation of results.

In experiment II, we examined whether significant improvements can be made to ITD and ILD sensitivity in the presence of IPM by centering the auditory image. The conditions tested investigated the need for interaural pitch matching to maximize binaural sensitivity for bilateral CI users. C levels for sound image centering were found using a lateralization task (see Kan et al. 2013). In this task, subjects responded by selecting the number of sound sources they perceived (1, 2, or 3, corresponding to full, non-, and partial fusion) and then marking the perceived lateral position of each sound source on a set of colored bars imposed onto the picture of a face. The number of colored bars available depended on the number of sounds heard. If subjects heard multiple sounds, they were instructed to rank the perceived dominance of the sounds and respond with the most dominant (primary) source on the topmost bar. Subjects could repeat the stimulus as many times as needed before making their decision. The locations of the markers in the colored bars were converted into an arbitrary set of values ranging from −10 to +10, where −10 represented the leftmost location in the head, 0 the center, and +10 the rightmost location in the head. Subjects received bilateral stimulation with the stimulation level reduced from C in either one of the ears, thereby introducing a possible ILD in the stimuli between the two ears. Typical ILDs were 0, ±2, ±5, and ±10 CU. For two (IBO and IAJ) of the nine subjects, ILDs were increased to ±20 CU to account for the subject's dynamic range and perceived laterality in response to the various levels selected for the two ears. Negative and positive adjustments imply a reduction from C level in the right ear and left ears, respectively. Each condition was presented 20 times in a random order. A cumulative Gaussian function was used to fit the data and used to estimate the current units in each ear needed to elicit a centered image. The amount of adjustment applied for each subject's C levels is shown in Table 2. ITD and ILD JNDs were then measured using the centered matched and mismatched pairs with the left/right discrimination task described earlier.

RESULTS

The group result from the direct pitch comparison task is shown in Figure 1, plotted as the absolute value of the pitch-matching metric, μ, and as a function of mismatch Δ. It can be seen that the direct pitch comparison task has the capacity to identify an interaural pair of electrodes that subjects report as having the most similar perceived pitch (μ ≈ 0). In addition, for these electrode pairs, as the contralateral electrode is changed away from the one that produced best pitch matching, μ increases systematically, indicating a systematic decline in the number of same responses.

In experiment I, we investigated the effect of IPM on ITD and ILD JNDs. The results are shown in Figure 2A and B, respectively. Large intersubject variability can be seen in ITD JNDs with IBF having JNDs <200 μs for all Δ between ±4, while JNDs for IBW were always above 800 μs. Similarly, large intersubject variability can be seen in ILD JNDs with IBD having JNDs less than 2 CU for all Δ between ±4, while IBW showed much larger JNDs (>12 CU for all Δ). When JNDs were normalized by the JND obtained at Δ = 0 for each subject, ITD JNDs can be seen to be lowest around Δ = 0 and increase substantially for values of Δ beyond ±4 (Fig. 2C). However, normalized ILD JNDs consistently stay within about two times that of the JND at Δ = 0 for most values of Δ (Fig. 2D). Friedman test was conducted to examine ITD and ILD JNDs as a function

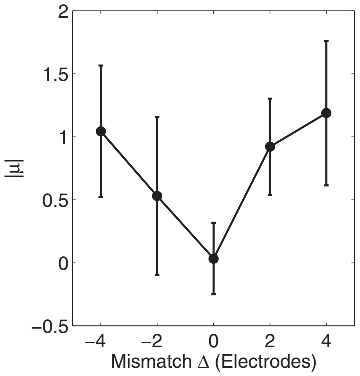

Fig. 1. Change in the metric, μ, as a function of mismatch is shown. The metric, μ, was calculated as the sum of responses to whether the second sound was "much higher," "higher," "same," "lower," or "much lower" in pitch compared with the first sound, which were assigned values of 2, 1, 0, −1, and −2, respectively. A value of zero means that the pitch of the electrode pair stimulated was perceived to be the same across the ears, and increasing values of μ imply that the perceived pitch was increasingly different.

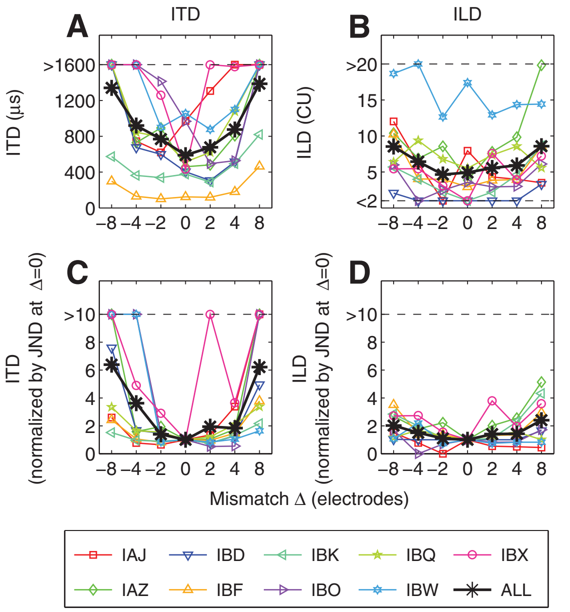

Fig. 2. Just noticeable differences (JNDs) for interaural time differences (ITDs) and interaural level differences (ILDs) as a function of mismatch (Δ) are shown in panels (A) and (B), respectively. Group average is shown by stars. ITD and ILD JNDs normalized by JND at the pitch-matched pair (Δ = 0) is shown in (C) and (D), respectively.

of Δ. Significant differences (where $p < 0.05$) were found for ITD JNDs [$\chi^2(6) = 35.26$, $p < 0.005$], where Wilcoxon signed-rank tests with Bonferroni correction revealed that $\Delta = -8$ was significantly worse than $\Delta = -4, -2, 0,$ and 2, and $\Delta = 8$ was significantly worse than $\Delta = -2, 0, 2,$ and 4. Significant differences were also found for ILD JNDs [$\chi^2(6) = 17.16$, $p = 0.009$], where post hoc analysis with Wilcoxon signed-rank tests with Bonferroni correction applied showed that ILD JNDs for $\Delta = -2$ were significantly better than that of $\Delta = -8$, 4, and 8. In addition, ILD JNDs at $\Delta = 0$ was significantly better than that of $\Delta = -8$.

In experiment II, we investigated whether significant improvements can be obtained by centering the auditory image due to IPM. The amount of adjustment applied for each subject is shown in Table 2. For some subjects such as IAJ and IBF, a centered image could not be determined at large amounts of mismatch. These electrode pairs were not tested. On average, the amount of adjustment needed was about 4 CU, with larger adjustments required at larger amounts of mismatch. The ITD and ILD JNDs measured after centering are shown in Figure 3A and B, respectively. On average, ITD JNDs were similar to those obtained in experiment 1. However, some improvement can be seen in ILD JNDs, particularly at $\Delta = \pm 8$. The average amount of improvement obtained from centering the auditory image is shown in Figure 3C and D. On average, ITD JNDs did not improve and showed some decline for $\Delta = -4$ and $\Delta = 8$ electrodes. However, improvement in ILD JNDs can be seen at $\Delta = \pm 8$. The Friedman test was conducted to compare ITD JNDs at each Δ between the two experiments. No significant differences were found (all $p > 0.1$). In contrast, the Friedman test conducted to compare ILD JNDs between the two experiments found a significant improvement in ILD JNDs in experiment 2 for $\Delta = +8$ ($p = 0.02$).

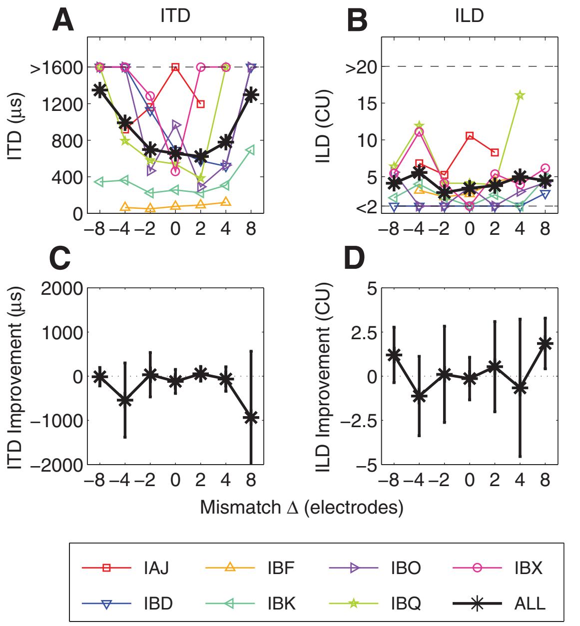

Fig. 3. Just noticeable differences (JNDs) obtained after auditory image centering. JNDs are shown as a function of mismatch (Δ) is shown in (A) and (B) for interaural timing differences (ITDs) and interaural level differences (ILDs), respectively. Group average is shown by stars. The improvement in ITD and ILD JNDs due to auditory image centering is shown in (C) and (D), respectively.

DISCUSSION

While the number of bilateral CI users continues to increase worldwide, little is known about best-practice models for clinical mapping of electrode arrays in the two ears. Current clinical mapping practices generally treat each ear as a monaural system and do not deliberately match the stimulation across the two ears in any particular manner. Although bilateral patients are likely to have differences in the insertion depths of electrode arrays, this is not a factor that has been taken into account in clinical mapping approaches. The general approach is to allocate a predetermined frequency range to each electrode based on the electrode number, regardless of its actual positioning. This can lead to an IPM and cause limitations in the processing of binaural cues in the brain. The effect of IPM on binaural sensitivity was demonstrated in the results from experiment I, where ITD and ILD JNDs were typically lowest (best) for electrode pairs that were offset by no more than two electrodes (1.5 mm) from the pitch-matched pair. However, when interaural mismatch was eight electrodes spacing apart (6 mm along the cochlea), JNDs increased to about six times the JND obtained at $\Delta = 0$. This is consistent with results in other studies in both NH listeners (Blanks et al. 2008; Goupell, Stoelb, et al. 2013) and bilateral CI users (Long et al. 2003; Wilson et al. 2003; van Hoesel 2004; Poon et al. 2009; Kan et al. 2013). In particular, Kan et al. (2013) showed that when $\Delta = \pm 8$ electrodes, CI users were unable to perceive changes in lateral position of an auditory image when ITDs were imposed onto the stimuli. In addition, the significant increase in ITD JND at $\Delta = \pm 8$ electrodes may be due to a decrease in auditory image fusion or the perception of an off-center auditory image (Goupell, Stoelb, et al. 2013; Kan et al. 2013). Our results showed that, for ITD JNDs to stay fairly small, that is, no greater than twice that of the lowest ITD

JND, the largest tolerable amount of mismatch is about four electrodes (3 mm). This amount is similar to that observed in Kan et al. (2013) and Poon et al. (2009). Most importantly, prior studies have only focused on ITDs, and our results here show that similar trends were observed for both ITD and ILD JNDs. The effect of interaural mismatch on ILDs raises important considerations when clinical mapping is conducted because ILDs are the most robust and dependable cues available to bilateral CI users. There has not been any attention paid to effect of interaural mismatch on ILDs, but results of this study alert us to the fact that such attention is desirable if binaural hearing abilities are to be maximized in bilateral CI users.

Very little data are available on the range of insertion depth differences prevalent in the clinical population. In the present study, mismatches within about 2 to 3 mm seem to be relatively common, whereas only one of nine subjects had a large amount of interaural mismatch across the ears. Of the several dozen subjects tested in our research group to date (e.g., Litovsky et al. 2012), pitch-matching tasks revealed about 10% of subjects having interaural mismatches ≥3 mm. Although large mismatches seem to be rare, ITD JNDs for mismatched pairs beyond 2 electrode spaces (about 1.5 mm) can often be outside the physiological range of human hearing (i.e., larger than the ITD generated with the width of a human head or larger than about 700 μs). This would make ITDs weak or unusable for sound localization within a hemifield. Hence, for maximizing ITD sensitivity, these results argue for the need to more carefully consider matching of interaural place of stimulation in clinical practice. It should be noted that the spread of excitation associated with monopolar stimulation may possibly help to alleviate some of the problems associated with IPM. If we consider models of binaural hearing where binaural cues are compared on a frequency by frequency basis, the spread of current associated with monopolar stimulation will activate a large area of the cochlea on both sides, meaning that even with some mismatch, there would be an area of overlap between the two ears for which binaural comparisons can be made. For other forms of polarity stimulation (e.g., tripolar stimulation), where the aim is to reduce the area of excitation along the cochlea, IPM will likely be a greater issue because the area of overlap between the two ears will be smaller. In addition, the recent introduction of different length arrays (Zeng et al. 2008) will likely have a substantial impact on IPM for a person who receives a long array in one ear and a short array in the other. The results of this work help to shed some light on the potential impact of having different length arrays in the two ears on one's ability to use binaural cues.

To the authors' knowledge, currently there are no clinical tools available for identifying differences in electrode insertion depths between the ears. The use of postoperative CT scans has been suggested for clinical mapping procedures (Noble et al. 2013) and may also be useful for estimating the difference in insertion depths of electrode arrays. From CT scans, one would be able to quickly determine whether there are large mismatches in the interaural insertion depths. However, smaller mismatches would be difficult to observe and new tools will need to be developed to assist in estimating the differences. If CT scans are not available, an alternative method such as pitch matching (e.g., Long et al. 2003; van Hoesel 2004; Laback et al. 2007; Litovsky et al. 2012) may be feasible for achieving the goal of mitigating effects of IPM. Because pitch-matching methods provide an informed way of enabling binaural sensitivity (i.e., interaural pairs found by this method within about two electrodes [1.5 mm] of the pair yielding best ITD and ILD sensitivity, see Fig. 2), this method may be preferred. However, finding pitch-matched pairs for all combination of electrodes can be time-consuming, and methods for streamlining the process are needed. Although specialized tools are currently not available, it may be possible that a clinician can conduct a simple interaural electrode comparison by stimulating an electrode on the left and right, sequentially, with the clinical software. The patient can give a verbal response of whether electrodes are higher, lower, or the same pitch, in a procedure similar to mapping practices. A few different electrode comparisons along the array would provide a rough estimate of the interaural difference in terms of number of electrodes, which could then be used to adjust the frequency allocation tables in each ear. Objective measures such as electrically evoked auditory brainstem responses may also possibly provide a method for adjusting frequency allocation tables (Smith & Delgutte 2007); however, differences in the electrode pairing using electrically evoked auditory brainstem response results and pitch-matching methods have been observed (He et al. 2012).

It was hypothesized that centering the reference position of the auditory image may allow subjects to discriminate smaller ITDs and ILDs because smaller JNDs have been found for ITDs with centered tones and narrowband transients (Yost 1974; Hafter et al. 1975) and for ILDs with centered tones (Domnitz & Colburn 1977; Yost & Dye 1988) in NH listeners. However, experiment II showed that centering of the auditory image did not significantly improve ITD or ILD JNDs, except for $\Delta = 8$. This is largely consistent with the results in NH listeners from Goupell, Stoelb, et al. (2013), which found no significant improvement in JNDs after imposing interaural offsets to counteract off-centered auditory images. The lack of significant improvement may be due to the fact that best sensitivity for ITDs and ILDs with a centered auditory image only occurs when place of stimulation along the cochlea is similarly matched across the ears. In other words, binaural sensitivity is best only when inputs from the same frequency channels are compared directly. In addition, when larger areas of the cochlea are excited either via spread of current in electrical stimulation or acoustic stimuli with sufficient bandwidth, it might be that considerably large level adjustments need to be made before a significantly noticeable improvement in JNDs can be observed. In Koehnke et al. (1995), which used 1/3-octave noise bands, offsets of 12 to 24 dB were needed before significant changes in binaural sensitivity were observed.

Auditory image centering was considered a possible alternative to pitch matching as a way to improve binaural sensitivity because it might be more easily achievable with existing clinical tools. Results from experiment II showed that it is unlikely that ITD sensitivity can be improved by auditory image centering in the presence of mismatch. However, significant improvements were found in ILD JNDs at $\Delta = +8$, suggesting that perceptual centering of the auditory image may help ensure good ILD sensitivity. While it is unclear how much of an effect centering will have in the case of multielectrode stimulation (as in the case of clinical processors), we can hypothesize that for a single broadband sound source, the centering of all mismatched interaural electrode pairs will provide a common reference location for the same input ILD, which should lead to a general improvement in localization of the sound. In the case of competing sound sources, the utility of centering is less clear and warrants further investigation. It should also be noted that a centered auditory image can vary as a function of loudness growth between the two ears (Goupell, Kan, et al. 2013), which suggests that clinicians might need to find centered auditory images at a number of points along the loudness growth function to maximize ILD sensitivity for a range of auditory inputs.

Centering of auditory images may be an important consideration in current clinical practice when large IPM is suspected or present because ILDs are considered the primary cue for sound localization with current clinical processors (Grantham et al. 2007; Aronoff et al. 2010). Although the results of these experiments demonstrate that ILD sensitivity is less susceptible to the effects of small amounts of IPM (≤3 mm), ILD sensitivity can be improved through centering when IPM is large. Results from Kan et al. (2013) suggest that any substantial IPM will be perceived as a lateral bias of the sound source's perceived location toward the ear with shallower electrode insertion, which implies that centering of auditory images is likely to be beneficial for sound localization in CI users. However, CI users' ability to use ITDs is believed to be marred by the independent processing of current speech processors, the use of high stimulation rates and lack of low-frequency ITDs (van Hoesel 2004; Litovsky et al. 2012). Should the fidelity with which speech processors deliver ITDs to CI users be improved, the results of these experiments demonstrate the importance of bilateral mapping practices that take into account insertion depth differences, to maximize both ITD and ILD sensitivity.

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