Effect of mismatched place-of-stimulation on binaural fusion and lateralization in bilateral cochlear-implant users[a)]

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Bilateral cochlear implants (CIs) have provided some success in improving spatial hearing abilities to patients, but with large variability in performance. One reason for the variability is that there may be a mismatch in the place-of-stimulation arising from electrode arrays being inserted at different depths in each cochlea. Goupell *et al.* [(2013b). J. Acoust. Soc. Am. **133**(4), 2272–2287] showed that increasing interaural mismatch led to non-fused auditory images and poor lateralization of interaural time differences in normal hearing subjects listening to a vocoder. However, a greater bandwidth of activation helped mitigate these effects. In the present study, the same experiments were conducted in post-lingually deafened bilateral CI users with deliberate and controlled interaural mismatch of single electrode pairs. Results show that lateralization was still possible with up to 3 mm of interaural mismatch, even when off-center, or multiple, auditory images were perceived. However, mismatched inputs are not ideal since it leads to a distorted auditory spatial map. Comparison of CI and normal hearing listeners showed that the CI data were best modeled by a vocoder using Gaussian-pulsed tones with 1.5 mm bandwidth. These results suggest that interaural matching of electrodes is important for binaural cues to be maximally effective.
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I. INTRODUCTION

Bilateral implantation of cochlear implants (CIs) can give users significant improvements in sound localization ability compared to their ability when using only one CI. In Litovsky *et al.* (2009), 14 out of 17 subjects (82%) demonstrated improvement in free-field sound localization ability in the horizontal plane with just three months of experience with bilateral CIs. For these 14 subjects, the average root-mean-square (RMS) localization error was 26.1° with a standard deviation (SD) of 12.0° when two implants were used. In contrast, when only one implant was used, the average RMS error was 61.5° (SD = 14.4°). However, compared to normal hearing (NH) subjects, localization accuracy of bilateral CI users is still much worse and there is a large variability in performance among CI users. For example, in Grantham *et al.* (2007), the average RMS localization error in the free-field along the horizontal plane for 22 CI users was 30.8° (SD = 10°) compared to only 6.7° (SD = 1.1°) for nine NH subjects. Similarly, in Majdak *et al.* (2011), average RMS localization error in a virtual auditory space (VAS) setup for five CI users was 20.7° (SD = 2.9°) compared to 12.4° (SD = 2.2°) for ten NH subjects. The gap between NH listeners and CI users is even greater when localizing in the presence of noise. Litovsky *et al.* (2012) showed that bilateral CI users require a high (>10 dB) signal-to-noise ratio (SNR) for localization performance to be near that achieved in quiet for CI users, while NH subjects maintained comparable performance in quiet and at SNR of −5 dB. Kerber and Seeber (2012) showed that at an SNR of −3 dB, most bilateral CI users were unable to identify the side of a target sound source.

While NH subjects make use of interaural time (ITDs) and level differences (ILDs) for sound localization along the horizontal plane (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002), there is increasing evidence that CI users may only be relying on ILDs. In Grantham *et al.* (2007), CI users showed a significant increase in free-field localization error for low-pass filtered noise compared to wide-band noise but no difference in performance for high-pass noise compared to wide-band noise, suggesting that localization of noise bursts is primarily based on high-frequency ILDs and not low-frequency ITDs. Aronoff *et al.* (2010) used VAS techniques to determine the relative contribution of ITD and ILD to sound localization in CI users. By modifying head-related transfer functions to present stimuli that varied in ITDs or ILDs separately, they found that when ITDs were varied and ILDs held constant, sound localization performance was significantly poorer compared to free-field localization. In contrast, when ILDs were varied and ITDs held constant, localization performance was comparable to free-field localization, suggesting that ILDs are the dominant cue used for sound localization in CI users. In contrast, ITDs are the dominant cue for sound localization in the horizontal plane in NH listeners (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002), and this difference may be a reason for the performance difference observed between NH and CI subjects.

Another reason for the difference in performance between CI and NH subjects is that in CI users the peripheral auditory inputs to the binaural system at the two ears may be

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dissimilar in frequency. In contrast, inputs to the NH binaural system from the two ears are assumed to be well matched (Carr and Konishi, 1990; Yin and Chan, 1990; Stern and Trahiotis, 1992). There are at least two factors that can account for the interaural frequency dissimilarity in CI users. First, the survival of spiral ganglion neurons may differ between the ears, creating areas that cannot receive electrical stimulation, also known as "dead regions" (Nadol, 1997; Kawano *et al*., 1998; Moore *et al*., 2000). Since current CI technology is designed to take advantage of the tonotopic organization of the cochlea and its pattern of innervation, dead regions along the cochlea are likely to disrupt the intended innervation pattern. This can lead to unintended differences in inputs to the binaural systems from the two ears, and has the potential to degrade sound localization performance. Second, implantation depths of electrode arrays at the two cochleae may be dissimiliar. The cochlea is assumed to be approximately 35 mm in length, and typical CI insertion depths range from 20 to 30 mm (Ketten *et al*., 1998; Gstoettner *et al*., 1999). While it may be possible for a surgeon to approximately match the insertion depths across the ears, CI insertion depths in the left and right ears may vary by several millimeters. Such variations would lead to differences in the anatomical place of stimulation in each ear for electrodes of the same number. In this situation, there would be an *interaural frequency mismatch* across the ears for binaural information that is meant to be presented at the same characteristic frequency.

This paper examines the effect of controlled, deliberate interaural mismatch in the place of stimulation on the ability of bilateral CI users to utilize ITDs and ILDs. This issue is of importance, both scientifically and clinically, because the effects of mismatch on ITDs and ILDs are poorly understood. Scientifically, an investigation on the effect of mismatch on ITDs and ILDs will improve our understanding of the robustness of these cues and tolerance for mismatched frequency inputs at the level of neural coding. Clinically, a clearer understanding of mismatch may affect the precision with which CI processors in the two ears are programmed, so that future clinical practices might provide an improvement in sound localization abilities of CI users.

There have been a few studies examining the effect of mismatch on binaural sensitivity in both NH subjects and CI users. Studies in CI users have used special synchronized research processors to present their stimuli. To date, only ITD just noticeable differences (JNDs) have been measured as a function of different interaural electrode pairings across the ears (Long *et al*., 2003; Wilson *et al*., 2003; van Hoesel, 2004). Since the exact implantation depths of the electrode array in each ear is difficult to ascertain, pitch comparison testing was also conducted in these studies, using the same interaural pairs of electrodes. It is reasonable to assume that electrodes which excite the same area of the cochlea in each ear would have similar pitches. The results of these studies showed that a pair of similarly pitched electrodes across the ears was more likely to show sensitivity to ITDs and that there was a monotonic decrease in sensitivity when the pair of electrodes was less pitch-matched. Data from four CI users presented in Poon *et al*. (2009) showed that there is approximately a 3.4 mm range along the cochlea whereby ITD sensitivity is on average within a factor of 2 of the lowest ITD JND. These results appear to be consistent with current physiological models of the binaural system that assumes that ITDs are processed in a coincidence matrix with matched frequency inputs (Jeffress, 1948; Joris *et al*., 1998) and would suggest that interaural frequency mismatch in CI users would lead to reduced ITD sensitivity. However, the results from Poon *et al*. also suggest that there is a degree of tolerance in the amount of mismatch for ITD sensitivity. The spread of current from a stimulating electrode should have a role in ameliorating the effects of mismatch since a wide population of auditory fibers are responding to the stimulation and thus there is an overlap in the area of excitation across the ears (van Hoesel, 2004; Blanks *et al*., 2008; Goupell *et al*., 2013b).

In NH subjects, ITD thresholds as a function of mismatch have been measured using amplitude-modulated (AM) signals (Henning, 1974; Nuetzel and Hafter, 1981; Blanks *et al*., 2007; Blanks *et al*., 2008). The consistent trend in the results from these studies has been that with increasing mismatch, ITD JNDs increased. Francart and Wouters (2007) studied the effect of interaural frequency mismatch on ILD JNDs with narrowband noises. As with ITD JNDs, ILD JNDs also increased with increasing mismatch. A more comprehensive study was conducted by Goupell *et al*. (2013b), who investigated the effect of interaural frequency mismatch on binaural fusion, lateralization and discrimination of both ITDs and ILDs in NH subjects using Gaussian-pulsed tones of different bandwidths. When ITDs or ILDs were zero, small-to-moderate amounts of interaural mismatch led to a lateral shift of the auditory image, while large mismatches led to non-fusion of the auditory image in some listeners. When ITDs and ILDs were applied, mismatch caused a reduced range of lateralization, particularly for ITDs. In addition, lateralization curves were increasingly distorted compared to lateralization curves obtained for interaurally matched stimuli. As with previous studies, ITD and ILD JNDs were also found to increase with increasing mismatch. These results highlight the importance of matched frequency inputs across the ears for binaural sensitivity.

In this study, we have followed the approach of Goupell *et al*. (2013b) in order to examine the effect of interaural mismatch on binaural sensitivity in CI users. First, the effect of mismatch on binaural image fusion was investigated. Data from Goupell *et al*. (2013b) showed that, when ITDs and ILDs are set to zero and there is no interaural mismatch, the sounds at the ears are typically fused into a single auditory percept located in the center of the head. With increasing mismatch, the amount of frequency overlap between the ears will be reduced and this may lead to only partial fusion or non-fusion of the sounds which could lead to the perception of multiple auditory images. Second, if one assumes that binaural cues are processed in a coincidence matrix with matched frequency inputs, then it is reasonable to predict that mismatched inputs will have an effect on the use of ITDs and ILDs for sound source location. Hence, the effect of mismatch on ITD and ILD lateralization was investigated in the same CI users, in which subjects reported the intracranial position of perceived sound sources for various ITDs or ILDs. This method allows a more direct measure of the effect of interaural frequency mismatch on the perceived lateral position of an auditory image, which we believe to be more informative than discrimination measures because there is a more direct mapping of localization in space to lateralization for a wide range of ITDs and ILDs.

II. METHODS

A. Subjects

Nine post-lingually deafened, bilateral CI users with CI24 and CI512 family of implants (Cochlear Ltd., Sydney, Australia) participated in this study. These implants have an array of 22 intra-cochlear stimulation electrodes with a 0.75 mm inter-electrode spacing and two extra-cochlear ground electrodes. In these CIs, electrodes are numbered 1 to 22 starting from the most basal electrode to the most apical electrode.

Subjects traveled to the University of Wisconsin-Madison for testing and participated in these tests over 2–3 days. Subjects were paid a stipend for their time. Table I shows the profile and etiology of the CI users. 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.

B. Equipment and stimuli

A personal computer running MATLAB (MATHWORKS, Natick, MA) software was used to generate stimuli and run the experiments. A Nucleus Implant Communicator (Cochlear Ltd., Sydney, Australia) was used to deliver bilaterally synchronized, electrically pulsed signals directly to a subject's implants. The pulses were biphasic with a 25 μs phase duration, 8 μs phase gap and presented via monopolar stimulation mode. All stimuli for these experiments were 300 ms, constant amplitude pulse trains presented at a rate of 100 pulses per second (pps), either on a single electrode or on an interaural pair of electrodes. This rate of pulsatile stimulation was lower than the typical stimulation rates used in clinical CI processors (Wilson *et al.*, 1991). However, since the aim of this study was to understand the effect of binaurally mismatched stimulation on perception, it was essential to start with conditions that maximize sensitivity to binaural cues, in particular ITDs which are known to be better at low stimulation rates (van Hoesel *et al.*, 2009). Subject responses were obtained using a touchscreen monitor connected to the personal computer.

C. Calibration

1. Loudness mapping

Loudness maps were created for each subject at 100 pps. Threshold (T), comfortable (C), and maximum comfortable (M) levels of all electrodes were determined by asking the subject to report the perceived loudness of a constant amplitude pulse train at a current level chosen by the experimenter. T was defined as the threshold of audibility of electrical stimulation, C was the stimulation level which was comfortably loud and one that the subject could tolerate listening to for long periods of time, and M was the highest stimulation level that a subject could tolerate without it being uncomfortably loud. After loudness maps were obtained, the C levels were compared across electrodes by first sequentially playing 300 ms pulse trains on overlapping blocks of five electrodes with an inter-stimulus interval of 100 ms. Adjustments were made until all C levels within each block were perceived to be of equal loudness. In each subsequent block of five electrodes, two electrodes from the previous group were maintained as a reference for the loudness balancing. A final sweep of all electrodes was made at the end to ensure all electrodes were the same perceived loudness. This approach was developed after considerable pilot testing, and ensured that electrodes nearby one another as well as electrodes at opposite ends of the electrode array were tested with loudness balanced current levels.

2. Selection of electrode pairs

In order to study the effect of interaural frequency mismatch on binaural sensitivity, pitch matching methods were used to find a pitch-matched pair across the ears. This is a common technique in bilateral CI studies (e.g., see Long *et al.*, 2003; van Hoesel, 2004; Litovsky *et al.*, 2010; Litovsky *et al.*, 2012) and has been shown to often yield an interaural pair of electrodes that has best sensitivity to ITDs (Poon *et al.*, 2009). It is likely, but not necessarily, that a perceptually pitch-matched pair across the ears would have

TABLE I. Profile and etiology of subjects.

Subject	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[a]	Ototoxic medication
IBX	70	F	2/1	CI24RE/CI512	Ototoxic medication/sensorineural hearing loss

[a]IBW was re-implanted 2 years prior to testing. Prior to this, she had a CI22.

approximately the same place of stimulation in the left and right cochlea. Pitch matching was assessed using a two-step process. In the first step, a place-pitch magnitude estimation task was conducted using a method of constant stimuli (Litovsky *et al.*, 2012). The amplitude of the stimuli was set to *C* level. Subjects could repeat the presentation of stimuli as many times as they needed prior to making a decision (typically subjects listened to the stimuli once or twice). They responded by rating the perceived pitch of the stimulus on a scale from 1 (low pitch) to 100 (high pitch), and were instructed to use the same scale for both ears. Several training trials were given prior to testing in order to familiarize the subjects with the task and to encourage them to use the full scale. Even-numbered electrodes in the two ears were tested ten times each, in random order, yielding a total of 220 stimulus presentations (11 electrodes × 2 ears × 10 repetitions). The results of this step were used to select electrodes for further testing in the next task.

In the second step, a bilateral pitch comparison task was conducted to find pairs of perceptually pitch-matched electrodes across the ears. An interaural pair of electrodes that received, on-average, the same rating in the first step was chosen as an estimate of a pitch-matched pair. Typically, the left ear electrode was held constant and the right ear electrode was tested with the estimated pitch-matched electrode and neighboring electrodes (two higher in number, two lower in number) in a two-interval, five-alternative forced choice task. On each trial, the task was to compare the perceived pitch in the two ears directly; hence the subject was presented with a sound in the left ear on the fixed electrode and then a sound in the right ear on one of the test electrodes. Subjects could repeat the sounds as many times as necessary before making a decision (typically once or twice). They responded by answering whether the second sound was "much higher," "higher," "same," "lower," or "much lower" in pitch compared to the first sound. These categories were given values of 2, 1, 0, −1, and −2, respectively, and a metric, μ, was calculated by summing the enumerated responses. Each pair of electrodes was tested 20 times 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. In the following experiments, a "matched" pair near the middle of the electrode array was used for testing.

3. Sound image centering

Prior to imposing non-zero ITDs and ILDs on the stimuli, it was important to verify that a subject perceived a single, fused auditory image in the center of the head when stimulated at *C* level on the "matched" pair. This was done by conducting a lateralization task. 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, respectively) 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 loudness difference in the stimuli between the two ears. Typical adjustments were 0, ±2, ±5, and ±10 current level units (CU), though these were adjusted depending on the subject's dynamic range and the subjective laterality in response to the different levels. 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 estimate the CUs in the two ears that were needed to elicit a centered image. The function had the form

$$y = A\left[1 + \mathrm{erf}\left(\frac{x - \mu_X}{\sqrt{2}\sigma}\right)\right] - \mu_Y, \quad (1)$$

where x are the adjustment values tested, and A, μ_X, μ_Y, σ were the fitted parameters related to the range, x-offset, y-offset, and slope of the curve, respectively. The CUs in each ear (rounded to the nearest whole number) corresponding to where the fitted function crossed the x axis (that is, where a centered image should be perceived) replaced the *C* levels in the loudness map for the "matched" pair in the following experiments. The amount of adjustment applied for each subject is shown in Table II. Of the nine subjects, four subjects did not require any level adjustment and only IBW required an adjustment >6 CU in one ear.

TABLE II. Electrode pairs for "matched" and "mismatched" conditions. Negative Δ values imply the left ear electrode was closer to the base of the cochlea and positive Δ imply the left ear was more apical. The magnitude of adjustment (in CUs) applied to each Δ = 0 electrode is shown in italics.

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

D. Experiments

Experiments were conducted on the "matched" pair found using the procedure described in Sec. II C and using artificial "mismatched" pairs created by holding one of the electrodes in the "matched" pair fixed and varying the electrode used on the contralateral side. Table II shows the electrode pairs used in the experiments for each subject. It should be noted that no attempt was made to ensure a centered sound image for the mismatched pairs. In the following, Δ is used to denote the mismatch in terms of number of electrodes away from the matched pair. $\Delta = 0$ 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 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, $\Delta = \pm 2$, ± 4, and ± 8 were tested, along with $\Delta = 0$, yielding a total of seven Δ conditions.

III. EXPERIMENT 1: BINAURAL IMAGE FUSION

A. Methods

In this experiment, the effect of interaural frequency mismatch on the number of auditory images and their perceived location(s) was investigated with zero ITD and ILDs. The paradigm in Goupell *et al.* (2013b) was used, whereby subjects were asked to categorize the perceived auditory image by choosing from a list that described combinations of three parameters: (1) number of sounds perceived; (2) the intracranial locations of the sounds; and (3) degrees of binaural image fusion. The list had 10 options (shown at the bottom of Fig. 1) and was categorized as follows: *Single* auditory image (located either on the left, in the center, or on the right); *Multiple* auditory image (left strong, right weak; equally strong; left weak, right strong; three auditory images); *Diffuse* auditory images (no concentration; one concentration; two concentrations). On each trial, subjects were asked to choose from one of the 10 options, and were able to listen to a stimulus as many times as they needed (typically one to three times) before making a decision. Each of the seven Δs was presented 20 times in random order.

B. Results

The results of the binaural image fusion task are shown in Fig. 1(a). In each plot, dashed lines divide the responses into the single, multiple, and diffuse categories. Since loudness differences between the ears may affect the interpretation of these results, the data has been divided according to whether the subject required additional adjustment at $\Delta = 0$ in order to center the auditory image. The first and second rows of Fig. 1(a) show the data from subjects who required and did not require further adjustments, respectively. Subjects that required no level adjustment perceived a single auditory image in a majority of the trials when $\Delta = 0$ [Fig. 1(a), second row]. However, in some subjects the location of the auditory image changed with Δ. For example, subject IAJ typically perceived a single, centered auditory image when $\Delta = 0$, but for $\Delta \neq 0$, the auditory image was perceived off-center, even though ITDs and ILDs were still set to 0. For negative values of Δ, where the stimulated electrode on the left was more basal than that of the right, the auditory image was lateralized toward the left, and for positive values of Δ (stimulated electrode on right was more basal than left), the auditory image lateralized toward the right. Subject IBQ demonstrated similar trends, but multiple auditory images were perceived when $\Delta = +8$ and $\Delta = -8$. For subject IBX, a single centered auditory image was perceived for a large

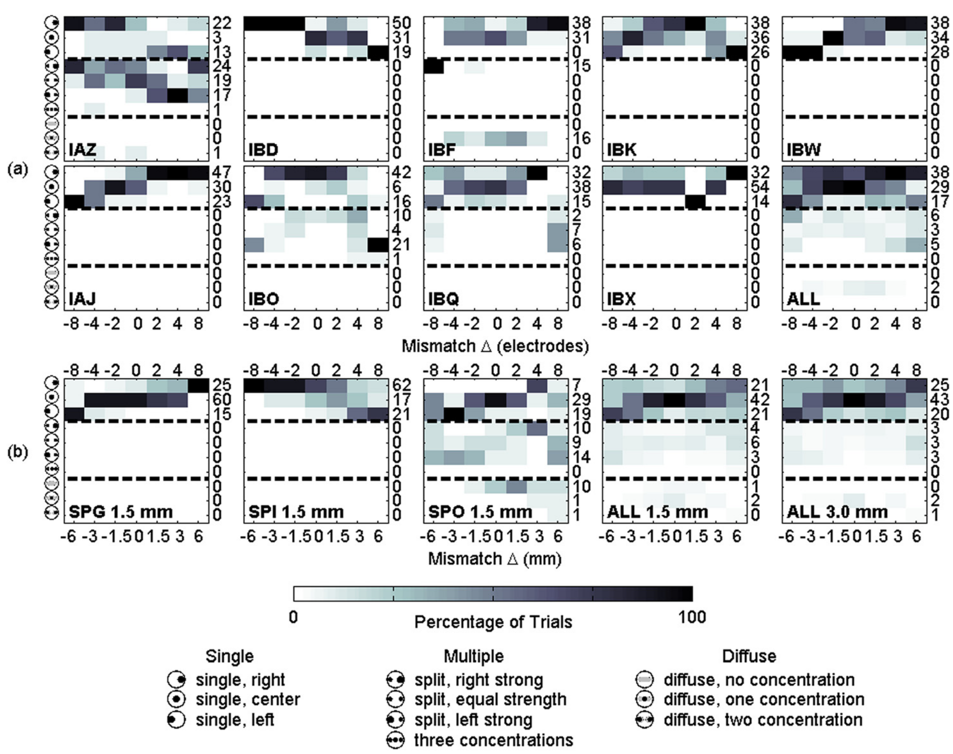

FIG. 1. (Color online) Data for the subjective fusion task is shown for CI and NH listeners in (a) and (b), respectively. Each panel shows the data for each subject. Grayscale shading is used to represent the percentage of trials. The lines through the plot group the categories of the fusion scale into "single," "multiple," and "diffuse" responses. The numbers on the right hand side of each panel show the percentage of responses for each fusion scale category with respect to the total number of responses. The panel labeled ALL shows the pooled data for all CI subjects. In (b), data from three NH listeners is shown as examples of the range of responses collected from listeners. The numbers above each panel show the mismatch in terms of number of electrode spacing. The two panels labeled ALL are the pooled data for the two Gaussian enveloped tone bandwidth conditions from Goupell *et al.* (2013b).

range of Δ values. In contrast, subject IBO perceived multiple auditory images in 36% of trials, especially when Δ was large. Similar trends were observed in the group that required a level adjustment at $\Delta = 0$ [Fig. 1(a), top row]. Subjects IBD, IBF, IBK, and IBW mostly perceived a single auditory image at $\Delta = 0$ and a lateralized auditory image with changes in Δ. It is interesting to note that, despite needing a 15 CU level adjustment at $\Delta = 0$ to obtain a centered image, subject IBW's response pattern is almost identical to that of subject IAJ who required no level adjustment. Since the patterns of responses were quite similar, Fisher's exact tests were conducted at each Δ, to test whether there were significant differences in the pattern of responses between the two groups of subjects. Since no significant differences were found ($p > 0.05$), the data for both groups was pooled together for the remaining analysis. The panel labeled ALL shows the pooled data.

The majority of subjects (78%) had a dominant lateralized auditory image toward the ear with more basal stimulation, with the remaining subjects having lateralized auditory images toward the ear with more apical stimulation. The pooled data show that a single auditory image was perceived most of the time (84% of all trials). Two auditory images were perceived in 14% of all trials, and diffuse auditory images were only perceived in 2% of all trials. Three auditory images were never perceived. Figure 2(a) shows that, as a function of increasing mismatch ($\Delta \neq 0$), the proportion of trials in which one auditory image was perceived decreased.

C. Discussion

The effects of mismatch on binaural image fusion showed that almost all subjects heard one auditory image when the pitch-matched pair was stimulated. With mismatch, five out of nine subjects (56%) still heard one auditory image, although the perceived location of the auditory image was typically toward one side of the head or the other. However, there was no consistent side to which the auditory image would be perceived among the subjects. In a few subjects, increasing mismatch led to a non-fused auditory image, with the majority reporting that one of the auditory images was located toward the side of the head with the more basal stimulation.

It is important here to address a possible concern in understanding these observations, which is that loudness differences across the ears may confound their interpretation. In particular, a loudness difference across the ears can potentially also be perceived as a lateralized auditory image. However, it is unlikely that loudness difference is the major factor driving the lateralization trends observed in this data. Extreme care was taken to ensure that perceived loudness across electrodes was balanced prior to the beginning of experiments by first comparing loudness across electrodes in groups of five electrodes, and then across all electrodes together. Although some subsequent adjustments were made to the matched electrode pair for some subjects, statistical analysis of subjects with and without adjustment showed no differences in the pattern of responses. Another argument for loudness not being a primary factor affecting results comes from a report by Fitzgerald *et al.* (2012); after careful sequential bilateral loudness balancing, a centered auditory image is not guaranteed when stimulating on an interaural pair of electrodes of the same number (that is, not pitch-matched). In addition, trends similar to those observed in the current experiment were observed in a companion study using a pulsed-sine vocoder in NH listeners with the same task (Goupell *et al.*, 2013b). For these reasons, we believe small loudness differences across different electrodes does not provide a reliable means to account for the perceived lateralization as a function of mismatch.

A comparison of the CI data with that of the NH data in Goupell *et al.* (2013b) can provide some understanding of the role of electrical current spread on binaural auditory image fusion and interaural frequency mismatch. In that study, Gaussian pulses modulated tonal carriers with a 100-Hz modulation rate. The bandwidths of the Gaussian pulses were 1.5 or 3 mm, which simulated different amounts of electrical current spread along the cochlea. Different center frequencies, offset in terms of mm along the cochlea, were

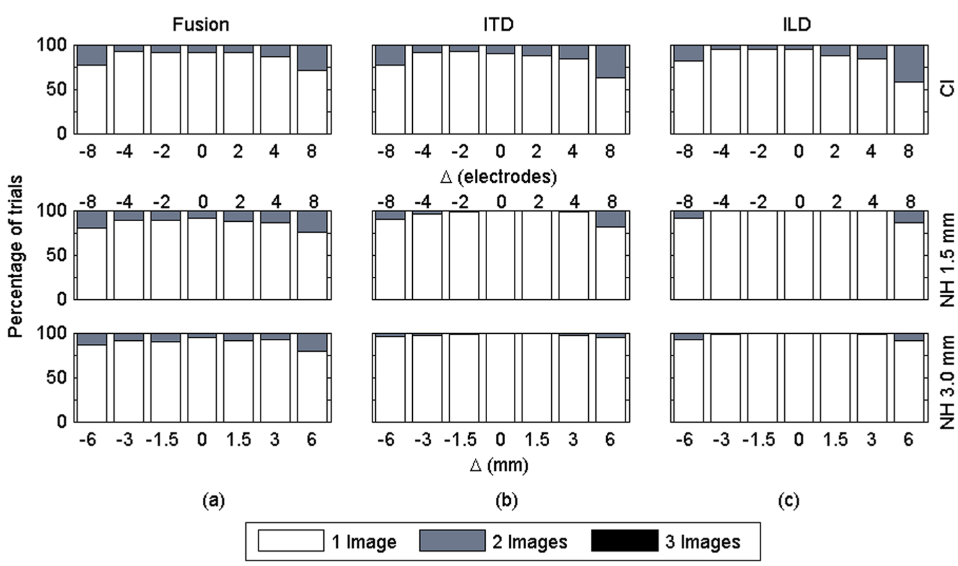

FIG. 2. (Color online) The proportion of trials where one, two or three auditory images were perceived is shown as a function of Δ for (a) the subjective fusion, (b) the ITD, and (c) ILD lateralization tasks. The normal hearing data (NH 1.5 mm and NH 3 mm) is reproduced from Goupell *et al.* (2013b). The numbers above the panels on the second row show the amount mismatch in terms of number of electrode spacing for the NH data.

used in each ear to simulate single-electrode interaural mismatch. The mismatches in mm corresponded to the mismatches in number of electrodes for the CI users. The main results of the study have been reproduced in Fig. 1(b) for direct comparison. The panels labeled SPG, SPI, and SPO are examples of responses obtained from three NH subjects listening to the 1.5 mm bandwidth stimuli. It can be seen that CI and NH subjects responded similarly, that is at $\Delta = 0$ a single, fused auditory image was perceived and with increasing mismatch a lateralized image was perceived. The percentage of NH subjects who perceived a lateralized image toward the ear with the more basal stimulation was quite similar to that of CI subjects [NH: 80% (both bandwidths); CI: 78%]. Similar trends can also be observed from Fig. 2(a), where the number of perceived auditory images increased with increasing mismatch. Fisher's exact tests conducted separately at each Δ found no significant differences ($p > 0.05$) in the pattern of responses between CI and NH subjects in either bandwidth conditions, suggesting that binaural image fusion as a function of mismatch might not be affected by differences in large spreads of excitation along the cochlea.

Although the exact mechanisms accounting for non-fused, non-centered auditory images with mismatch are unknown, we can speculate on some possible explanations. The non-fusion of auditory images can probably be explained physiologically. If auditory localization can be modeled by cross-correlation of matched frequency inputs (Jeffress, 1948; Stern *et al.*, 1988; Stern and Trahiotis, 1992), then when the same areas in the cochlea are stimulated in each ear, a single fused auditory image should be perceived. When nearby areas are stimulated in each ear, spread of current may stimulate a similar area across the ears but at slightly different times and intensities due to path length differences between the electrode array and auditory nerves in the two ears. These differences would lead to different delay lines being activated, resulting in a lateralized auditory image. If the difference in place of stimulation across the ears is sufficiently large, no coincidence occurs and two auditory images are perceived, as if monaural information is delivered separately to the two ears.

The lateralization of auditory images can be explained in at least two ways. One explanation is that in order to obtain an equal loudness percept, differing amounts of neurons may be recruited in each ear. This may inadvertently create an interaural level difference across the ears when integrating across all stimulated frequency, leading to the perception of an off-centered auditory image (Goupell *et al.*, 2013a). However, this probably cannot explain the systematic nature of the lateral shift with increasing interaural mismatch. A more likely explanation is that at a higher level, temporally coherent information, such as that provided by a 100 Hz electrical pulse train, might be an auditory grouping cue, leading to across frequency grouping of information that is pulled toward the side of the more dominant frequency region, which in the case of most listeners appears to be dominant at the ear receiving the higher frequency information. While the side where higher frequencies are located appears to be preferred, the reason for this is unknown but given the same proportion of subjects in both the CI and NH groups responded in the same way, it may be a result of individual preferences.

IV. EXPERIMENT 2: LATERALIZATION

Experiment 1 showed that interaural frequency mismatch led to subjects perceiving non-centered and/or split auditory images. In this experiment, the effect of interaural frequency mismatch on the perceived location(s) and number of auditory images was investigated with non-zero ITDs and ILDs imposed on the stimuli.

A. Methods

A lateralization task was used for this experiment and is the same as that described in the sound image centering task in Sec. II C. Subjects responded by marking the perceived lateral positions of sound sources on a set of colored bars imposed onto the picture of a face shown on the touchscreen. The number of colored bars available depended on the number of sources heard. If multiple sources were perceived, subjects were instructed to rank the perceived dominance of the sources and respond with the most dominant (primary) source on the topmost bar, followed by secondary and tertiary sources on the lower bars, respectively. Subjects were presented bilateral stimulation on the electrode pairs listed in Table II with either an ITD or ILD imposed on the stimuli. The reference for 0 CU ILD stimulation was nominally C level (either with or without centering) as defined by the subjects' loudness map. When a non-zero ILD was presented, the ITD was 0 μs; when a non-zero ITD was presented, the ILD was 0 CUs. Typical ITD values that were tested were 0, $\pm$100, $\pm$200, $\pm$400, and $\pm$800 μs and typical ILD values were 0, $\pm$2, $\pm$5, and $\pm$10 CUs, although these values varied depending on the subject's sensitivity to these cues. Positive and negative values indicate the intended right or left stimulus direction, respectively. Each combination of Δ and ITD/ILD was presented 20 times in random order, except for subject IBQ in the ITD lateralization task where only 10 trials were collected per ITD value due to time constraints.

B. Results

Lateralization data in which interaural frequency mismatch was varied from -8 to $+8$ are shown in Fig. 3(a) for subject IBD and Fig. 3(b) for subject IBQ. These subjects were chosen to demonstrate two different types of response patterns. In Fig. 3(a), the matched condition ($\Delta = 0$) resulted in centered auditory images when zero ILD was applied. An auditory image was perceived to be fully lateralized toward one ear with an ILD of $\pm$10 CUs. With increasing mismatch, the lateralization curves became increasingly distorted. Negative Δ resulted in lateralization curves that were biased toward locations on the right and a large ILD favoring the left side was required to re-center the auditory image. This rightward bias is consistent with the lateral shift seen in the binaural image fusion results in Fig. 1(a) for subject IBD. At $\Delta = 8$, a leftward bias can be observed and is also consistent with the leftward lateral shift observed in Fig. 1(a) for

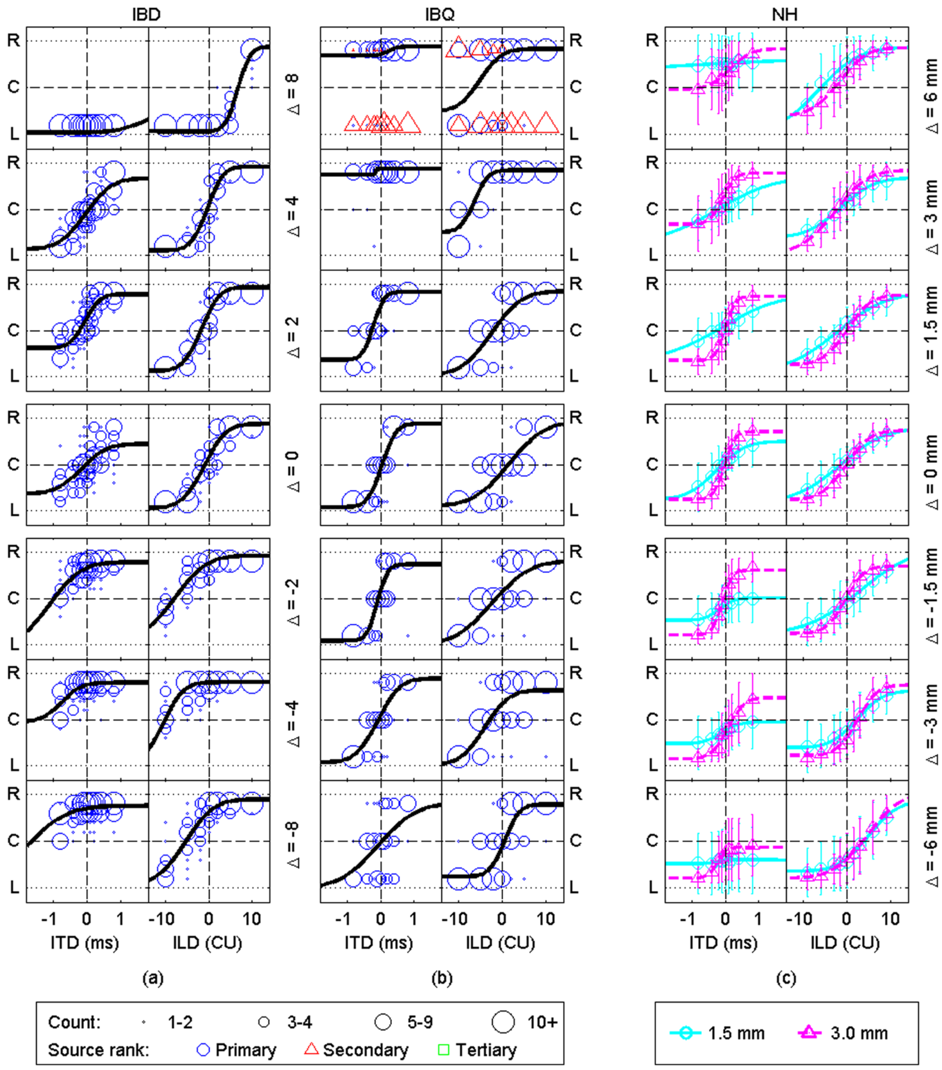

FIG. 3. (Color online) Lateralization responses for subjects IBD and IBQ, and NH listeners are shown in (a) and (b), respectively. Each column shows the lateralization result for either ITDs or ILDs and a different Δ is shown on each row. In (a), the lateralization responses between −7 and 7 were pooled into one of seven equally sized bins. The bin size on the far left (−10 to −7) and far right (7 to 10) were slightly larger than the other bins since there were typically fewer responses at the extreme left and right locations. The size of the circle indicates the number of sound sources perceived within a location bin. The lower row shows the mean location and standard deviation of the primary (most dominant) sound source. A cumulative Gaussian was used to fit the responses [see Sec. II C or Eq. (1)] and is shown as the solid line. IBD is chosen as an example of a subject that always perceived a single fused image and IBQ, is a subject who perceived multiple sound images at very large values of Δ. In (c), the grouped lateralization response for NH subjects presented with Gaussian enveloped tone stimuli of either 1.5 mm (solid line, circles) or 3 mm (dashed line, triangles) bandwidth is shown. The mean location is shown by markers and the error bars are the standard deviation of the mean. This data is reproduced from Goupell *et al.* (2013b).

subject IBD. The ITD condition shows a similar trend to that seen with ILDs; $\Delta < 0$ resulted in a rightward bias, with a perceived shift toward the left at $\Delta = 8$. However, at $\Delta = 8$ this bias remains for all values of ITD. Figure 3(b) shows the results for subject IBQ. It can be seen that she was able to lateralize the auditory image for a large range of Δ using ILDs, even when two auditory images were heard ($\Delta = 8$). It appears that there was a consistent perception of a dominant (primary) auditory image (circles), such that ILDs were able to influence the perceived lateral position. The distortion of the lateralization curve with increasing mismatch was less pronounced than that seen for subject IBD. For subject IBQ, ITDs were also more asymmetrical in their interaction with Δ values; applying non-zero ITDs to the stimulus at $\Delta = 4$ and $\Delta = 8$ did not influence the perceived lateral position and the auditory image remained on the right. However, for negative Δ, ITDs were successful at influencing the perceived lateral position of the stimulus. Subjects IBD and IBQ were similar in that ITDs produced a smaller change in laterality than ILDs for large mismatches. Figure 3(c) shows NH data reproduced from Goupell *et al.* (2013b). In that study, the bandwidth of Gaussian-pulsed tones was varied to simulate different amounts of current spread. It can be seen that at large mismatches ($\Delta = \pm 6$ mm; equivalent to ± 8 electrodes), ITD lateralization was severely affected; more so for 1.5 than 3 mm bandwidth. In comparison, ILD lateralization remained relatively robust.

The range of lateral positions for CI subjects are shown in Fig. 4, where lines are used to represent the leftmost to rightmost average lateralization perceived by each subject when non-zero ITDs and ILDs are applied to the stimuli. The symbols indicate the perceived location of the auditory images when the ITD and ILD were zero. A symbol at *C* would indicate a centered auditory image was perceived when the ITD and ILD were zero. Figure 4 shows that the range of lateral positions (i.e., the length of the lines) varied depending on the subject and Δ. Typically, the largest range is used at $\Delta = 0$ and decreases with increasing mismatch. In addition for some subjects, the range of lateral positions never crossed the midline (i.e., the lines never crossed the solid vertical line marked *C*). For instance, subject IAJ only heard sounds toward the left for $\Delta = -8$, even when ITDs or ILDs were varied. Subject IBK only heard sounds toward the left for $\Delta = 8$, again when ITDs or ILDs were varied; subject IBQ perceived split auditory images (sounds on both right and left) for $\Delta = 8$, when ITDs and ILDs were varied, but the perception of the dominant source never crossed the midline for ITDs.

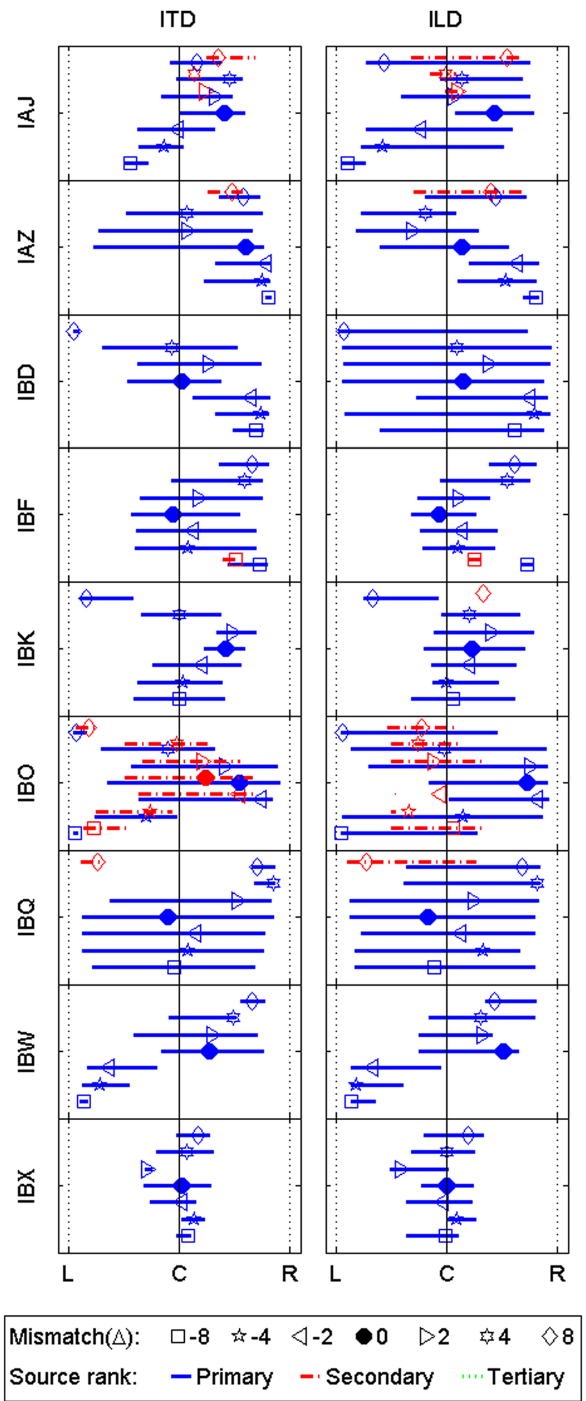

FIG. 4. (Color online) Range of perceived lateral positions for all CI subjects. Markers are used to indicate the perceived location of the primary, secondary and tertiary sound sources when ITD or ILD equals zero, as calculated by the cumulative Gaussian fit.

The variation in subject responses makes generalizing the lateralization results difficult. Hence, the lateralization data was analyzed using four metrics as a function of Δ. First, the *number* of perceived auditory images as a function of mismatch was analyzed and is shown in Fig. 2(b) for ITD conditions and Fig. 2(c) for ILD conditions. It can be seen that with increasing mismatch, subjects were more likely to report perceiving two auditory images. Although subjects were permitted to report three auditory images, no subject reported ever perceiving three images in the lateralization task. Similar trends can be seen in the NH data.

Second, the percentage of subjects whose range of lateral positions did not cross the center of the head despite an ITD or ILD being imposed on the stimuli was examined as a function of mismatch. This is shown in Fig. 5 and can be seen to increase with increasing mismatch, particularly for ITD lateralization. Similar trends are seen in the NH data for Gaussian-pulsed tones with 1.5 mm bandwidth but not for 3 mm.

Third, the utilized lateral range (ULR) as a percentage of the total available lateralization range was analyzed for individual subjects. The ULR was calculated by first finding the mean position for each ITD and ILD tested, and then the difference between the rightmost mean position and leftmost mean position was taken and divided by the total available range. Although this calculation may possibly underestimate the actual perceptual range, we have chosen this more conservative estimate of the ULR since CI users can have a large variability in the perceived lateral position corresponding to a particular ITD or ILD. The ULR is directly related to a subject's ability to perceive changes in the position of the auditory image with ITDs or ILDs, and their ability to perceive physiologically relevant lateralized images. One would assume that if a subject was able to take advantage of binaural cues at all Δ conditions, the ULR would be the same for all Δ. A smaller ULR would indicate that ITD or ILDs were only partially usable or totally unusable for auditory image lateralization. Figure 6 shows the ULR calculated for each subject as a function of mismatch. For some subjects the ULR was close to the full width of the head (for example, IBD and IBQ in the ILD case), while for others, the sound

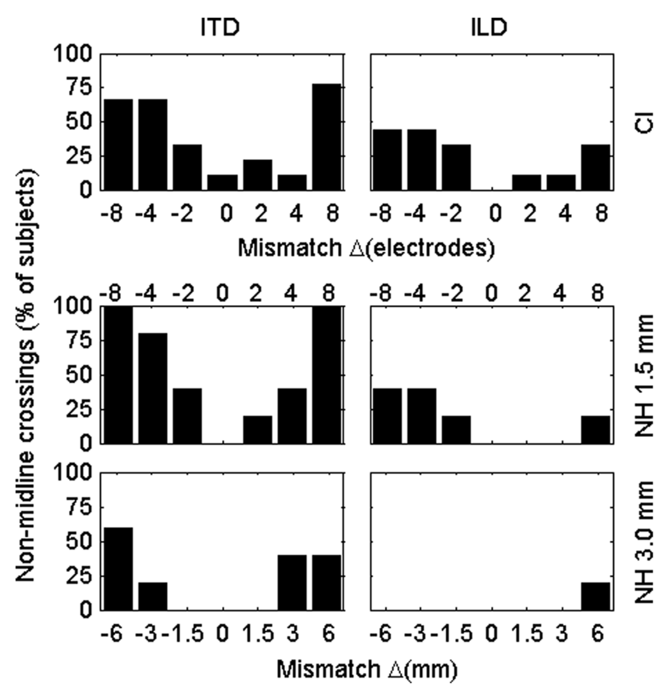

FIG. 5. A count of non-mid-line crossings for ITD and ILD lateralization is shown as a function of Δ for CI and NH listeners. The numbers above the panels on the second row show the amount mismatch in terms of number of electrode spacing for the NH data.

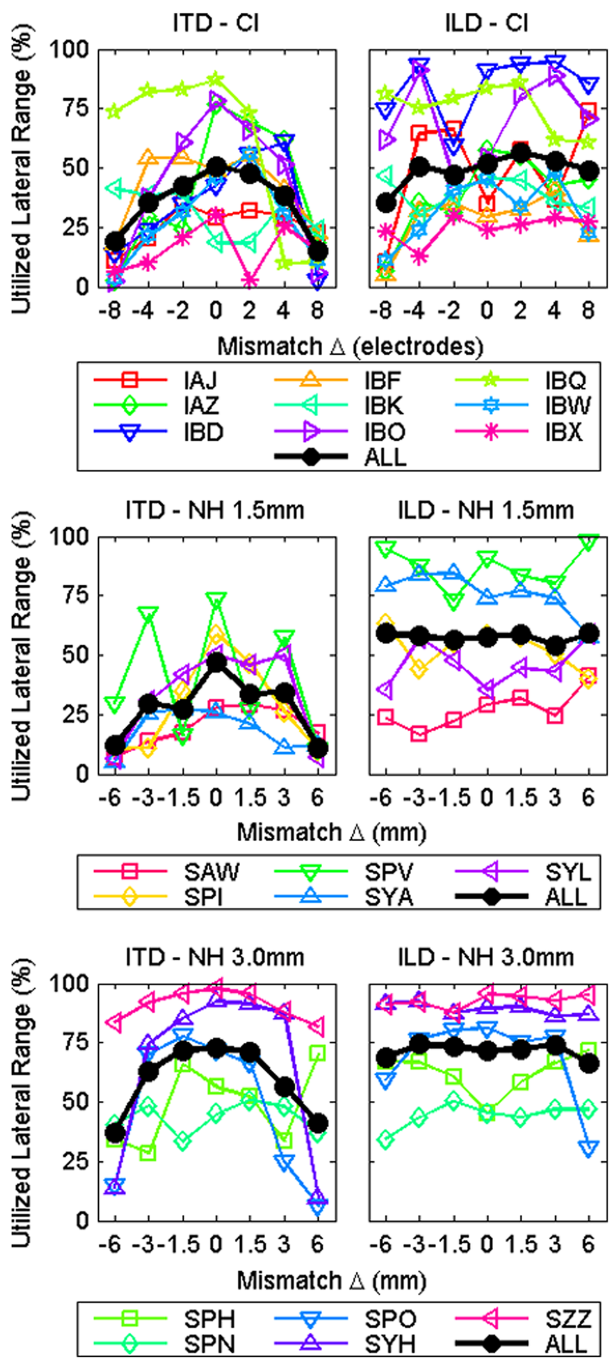

FIG. 6. (Color online) Utilized lateralization range for ITD and ILD lateralization tasks are shown for CI and NH listeners as a function of Δ. The group mean is shown as ALL.

image stayed within a small range of locations within the head (for example, IBX only used 25% of the available range for both ITD and ILD lateralization). On average, the ULR for ILD lateralization appears to be relatively constant regardless of Δ, but for ITD lateralization, there is a noticeable decrease with increasing mismatch. A Friedman's test was conducted to investigate the significance of the decrease in the ULR as a function of Δ, where $\alpha = 0.05$. No significant difference in the ULR as a function of Δ was found for ILD lateralization [$\chi^2(6) = 9.52$, $p = 0.146$], but a significant difference was found for ITD lateralization [$\chi^2(6) = 19.95$, $p < 0.005$]. *Post hoc* analysis with Bonferroni correction revealed significant differences between $\Delta = 0$ and $\Delta = \pm 8$ for ITDs. Similar trends are seen in the NH data for Gaussian-pulsed tones, especially for 1.5 mm bandwidth. The ULR for 3 mm bandwidth was higher than that used by CI subjects.

Fourth, a statistical analysis was conducted in which the JND between two lateral locations were estimated from the lateralization data using the method described in Litovsky *et al.* (2010). The lateralization responses were first linearized by applying an arcsin transformation; then d′ was calculated for each left/right ITD or ILD pair of the same value (e.g., +400 μs and −400 μs), which is defined as the distance between the two distributions of responses and calculated as the difference between the two distribution means divided by the pooled estimate of their standard deviations. A line, constrained to pass through zero, was then fitted to the d′ values and the JND was estimated as the point where the best-fit line intersected the value $d' = 1$. Estimated JNDs are shown in the top row of Fig. 7 as a function of Δ. Large inter-subject variability can be seen in ITD JNDs. Subject IBF had ITD JNDs that were consistently less than 200 μs for all Δ. In comparison, subject IAJ had ITD JNDs that were always greater than 800 μs. Similarly, large inter-subject variability can be seen in ILD JNDs. Subject IBD had ILD JNDs as small as 1–2 CU for all Δ. In comparison, subject IBW showed much larger ILD JNDs (almost 6 CU) at $\Delta = 0$ and greater variability for different values of Δ. When JNDs are normalized to $\Delta = 0$ for each subject individually, the pattern of ILD JNDs can be seen to be quite similar for all values of Δ in most subjects, staying within a range of two times the normalized JND. On the other hand, normalized ITD JNDs are lowest around $\Delta = 0$ and increase quite substantially for values of Δ beyond ±4 electrodes. Friedman's test was conducted to analyze the significance of these effects. ITD and ILD JNDs that could not be estimated were set to 2000 μs and 15 CU, respectively. No significant difference in JNDs were found as a function of Δ in ILD lateralization [$\chi^2(6) = 9.24$, $p = 0.161$], while a significant difference was found for ITD lateralization [$\chi^2(6) = 23.45$, $p < 0.005$]. *Post hoc* analysis with Bonferroni correction on the ITD lateralization data revealed significant differences between $\Delta = 0$ and $\Delta = \pm 8$. Similar trends are seen in the NH data for Gaussian-pulsed tones, especially for 1.5 mm bandwidth. However, JNDs obtained with 3 mm bandwidth were much lower than that achieved by CI subjects.

C. Discussion

The effects of interaural frequency mismatch on the lateralization of ITDs and ILDs showed that with small amounts of mismatch ($\Delta = \pm 2$ electrodes), all subjects were still able to perceive ITDs and ILDs as systematic changes in the position of an auditory image (Figs. 3 and 4). With increasing mismatch, lateralization curves became increasingly distorted and subjects were more likely to perceive multiple auditory images. However, it is notable that even when subjects heard more than a single auditory image, they were able to extract directional cues from ITDs and ILDs; reporting them as perceptually lateralized, intracranial

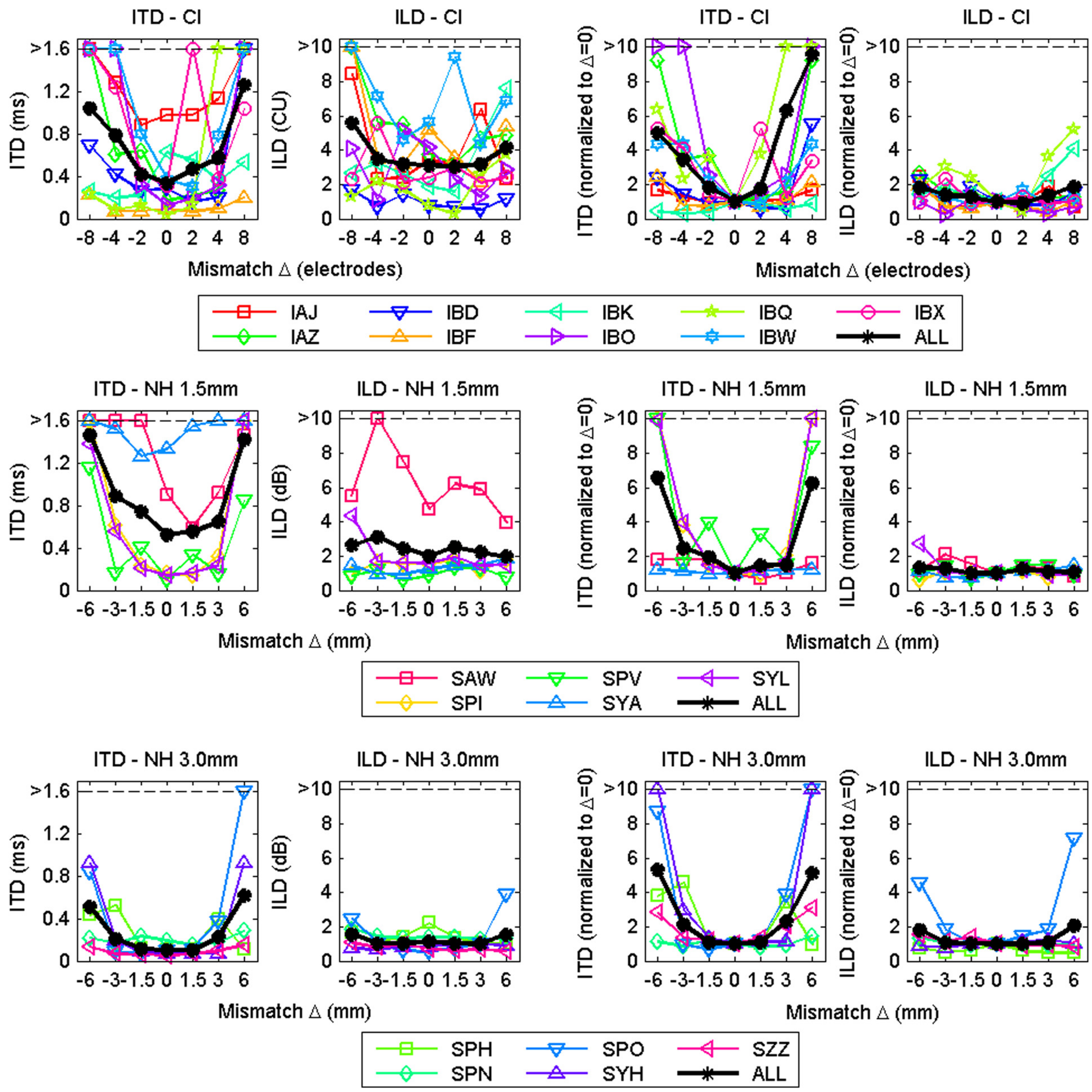

FIG. 7. (Color online) Estimated JNDs between two lateral locations for ITD and ILD lateralization are shown for CI and NH listeners in the first two columns. Where thresholds could not be estimated, they are shown as >10 CU and >1600 μs for ILD and ITD, respectively. The right two columns show the thresholds normalized by the threshold for $\Delta = 0$. The group mean is shown as ALL.

auditory images. At large mismatches ($\Delta = \pm 8$ electrodes), the ability to lateralize a sound source image across the midline was severely affected in up to 67% of subjects for ITDs and 44% of subjects for ILDs (Fig. 5), suggesting that lateralization produced by ITDs is more vulnerable to disruption from interaurally mismatched inputs. Similar results were obtained in Goupell *et al.* (2013b), where lateralization of ITDs was found to be significantly less robust than that of ILDs to interaural frequency mismatch. Statistical analysis in that study revealed that lateralization of Gaussian enveloped tones with 3 mm bandwidth was significantly better than that of 1.5 mm bandwidth, presumably because the greater bandwidth produced a greater overlapping area of excitation across the two ears. A comparison of the data from Goupell *et al.* (2013b) with our data from CI users show that, on average, results are much closer to the CI data for the 1.5 mm bandwidth than the 3 mm bandwidth on all measures. For the 3 mm bandwidth condition, results are better than that achieved by our CI subjects (as well as the 1.5 mm condition) which seems to suggest that a greater current spread may be beneficial for overcoming the effects of interaural frequency mismatch but this amount of spread of excitation is not as common among CI users.

The reduced ability to perceive ITDs and ILDs as changes in the lateral position of a sound source may partially explain the increase in ITD and ILD discrimination thresholds observed in bilateral CI users when measured with a non-pitch-matched pair of electrodes (e.g., van Hoesel, 2004; Francart and Wouters, 2007; Blanks *et al.*, 2008; Poon *et al.*, 2009; Goupell *et al.*, 2013b). Specifically, if the JND is a measure of the smallest perceptible change in the lateral position of an auditory image, then the smallest

JND would be at the steepest part of the lateralization curve, which can be assumed to pass through an ITD or ILD of zero. Since the lateralization curves of our subjects become particularly shallow for large mismatches, a larger difference would be needed to perceive changes in lateral position of the auditory image. ITD and ILD JNDs estimated from the lateralization data showed that with increasing mismatch, there was a significant decrease in ITD JNDs for $\Delta = \pm 8$, but not for ILDs (Fig. 7). In order for ITD and ILD JNDs to be within twice the JND at $\Delta = 0$, the window of interaural frequency mismatch was about four electrodes (3 mm in cochlea distance) for ITDs, and up to 16 electrodes (12 mm in cochlea distance) for ILDs. This would imply that there is a 3 mm tolerance to interaural frequency mismatch in CI users, which is within the 3.4 mm range found by Poon *et al.* (2009). Although we have chosen to normalize ITD and ILD JNDs to $\Delta = 0$, it should be noted that JNDs at $\Delta = 0$ are not necessarily the lowest in some of our subjects. However, JNDs at $\Delta = 0$ are typically within two to four electrodes of the lowest JND obtained within the subject and is consistent with data shown in Poon *et al.* (2009), where the electrode pair with the lowest JND is not necessarily the one with the strongest pitch-match across the ears.

V. GENERAL DISCUSSION

A. Implication of mismatch and binaural processes

Interaural frequency mismatch is likely to occur for bilateral CI users but the effects of this type of mismatch on sound localization are not well understood. In this study, we examined the effect of interaural frequency mismatch on two perceptual phenomena that are informative about the gap in performance between bilateral CI users and listeners with normal acoustic hearing. The first measure was binaural image fusion and the second measure was lateralization. In the lateralization task, ITDs or ILDs were imposed on constant amplitude pulse trains of 300 ms duration, presented at a rate of 100 pps. These stimuli were presented to a pair of pitch-matched electrodes, as well as to deliberately "mismatched pairs," created by holding an electrode of the matched pair constant and varying the electrode stimulated on the contralateral side.

The results from this study offer some insights into explaining why CI users have difficulty locating the source of a sound accurately and the large variability in sound localization performance between users. First, small interaural mismatches (two electrodes or 1.5 mm) can cause a lateral shift in an auditory image. Although these experiments are unable to measure a direct correspondence between the perceived lateral shift and a physical offset in location of a sound source in the free-field, ITD, and ILD JNDs can increase quite dramatically even with small amounts of mismatch. This implies that, in the presence of mismatch, a larger change in spatial location is needed before a difference in sound source position is detected. Second, at larger mismatches, there is a lack of binaural image fusion in some CI users and thereby increase the difficulty in accurately locating a sound source. For other CI users, large lateral shifts in the auditory image are observed, which will add an inherent bias in the localization results. Although it is believed that CI users are currently unable to fully take advantage of ITD cues due to lack of synchronization of current clinical devices (Laback *et al.*, 2004; van Hoesel, 2004), one might imagine that if better ITD cues were made available to CI users via synchronized bilateral processors, then large interaural frequency mismatches may cause conflicting perceptions of ITDs and ILDs leading to a distorted auditory spatial map.

These results for sound localization may also have ramifications on a CI user's ability to obtain spatial release from masking (SRM). Briefly, SRM is the improvement in speech-in-noise understanding gained from a spatial separation between a target talker and maskers, and has been shown to be significantly lower and highly variable in CI users compared to NH subjects, for both adults (Loizou *et al.*, 2009) and children (Misurelli and Litovsky, 2012). Although better ear listening accounts for much of the deficit in the benefit from SRM in CI users (van Hoesel *et al.*, 2008; Loizou *et al.*, 2009; Aronoff *et al.*, 2011; Culling *et al.*, 2012), it is likely that interaural frequency mismatch, among other factors, may explain why performance in CI users is unable to surpass that of better ear listening. One might hypothesize that in the absence of ITDs and ILDs, a small amount of mismatch can cause a frontal sound source to be perceived lateralized to one side. If another sound source physically coincides with the lateralized frontal sound source, the two physically separate sound sources may end up being perceived as co-located, thus reducing the perceived signal-to-noise ratio in the better ear. In the case of a large amount of mismatch, there may be no binaural image fusion in the signals across the ears and this may cause confusion in understanding the speech of a target talker. However, this interpretation should be taken with caution since it is unclear if the results obtained here with single electrode mismatch will carry into multi-electrode stimulation, which is needed for speech understanding.

B. Implications of mismatch on clinical mapping procedures

From a practical viewpoint, these results would indicate that pitch-matching in clinical programming of bilateral CIs is somewhat important, so that a single fused auditory image will be perceived. However, precise pitch-matching does not seem to be necessary since binaural image fusion and lateralization using ITDs appears to be maintained up to 3 mm away from a pitch-matched pair. A caveat with this rule-of-thumb is that it may not be important to maintain salient ITD cues since ITD thresholds of CI users are typically much larger than would occur naturally on the head. Also, data presented in Litovsky *et al.* (2010) seems to indicate that not all CI users can take advantage of ITD cues, namely, prelingually deafened bilateral CI users. Hence, in practice, as long as clinical processors remain unsynchronized, it may only be important to pitch-match electrodes across the ears so that ILD cues are maximally effective in order for a CI user to have some reliable spatial cues for the lateral dimension. What is unclear at this point is how the interaction due to current spread, when multiple electrodes are stimulated, affects the salience of ITDs and ILDs.

VI. CONCLUSIONS

Interaural frequency mismatch affects binaural image fusion and lateralization of auditory images in CI users. With increasing mismatch, auditory images were often perceived off the mid-line. In a few subjects, large mismatches led to the perception of multiple auditory images, but this seemed to have little effect on lateralization with ITDs and ILDs. However, perceiving an off-centered auditory image due to mismatch was more disruptive for lateralization with ITDs. Comparison of CI and NH listeners showed that the CI data was best modeled by a vocoder using Gaussian-pulsed tones with 1.5 mm bandwidth. It would seem that in order for ITD and ILD lateralization to both be salient, one should stimulate within 3 mm of an interaurally pitch-matched pair of electrodes.

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