The Relationship Between Intensity Coding and Binaural Sensitivity in Adults With Cochlear Implants

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Objectives: Many bilateral cochlear implant users show sensitivity to binaural information when stimulation is provided using a pair of synchronized electrodes. However, there is large variability in binaural sensitivity between and within participants across stimulation sites in the cochlea. It was hypothesized that within-participant variability in binaural sensitivity is in part affected by limitations and characteristics of the auditory periphery which may be reflected by monaural hearing performance. The objective of this study was to examine the relationship between monaural and binaural hearing performance within participants with bilateral cochlear implants.

Design: Binaural measures included dichotic signal detection and interaural time difference discrimination thresholds. Diotic signal detection thresholds were also measured. Monaural measures included dynamic range and amplitude modulation detection. In addition, loudness growth was compared between ears. Measures were made at three stimulation sites per listener.

Results: Greater binaural sensitivity was found with larger dynamic ranges. Poorer interaural time difference discrimination was found with larger difference between comfortable levels of the two ears. In addition, poorer diotic signal detection thresholds were found with larger differences between the dynamic ranges of the two ears. No relationship was found between amplitude modulation detection thresholds or symmetry of loudness growth and the binaural measures.

Conclusions: The results suggest that some of the variability in binaural hearing performance within listeners across stimulation sites can be explained by factors nonspecific to binaural processing. The results are consistent with the idea that dynamic range and comfortable levels relate to peripheral neural survival and the width of the excitation pattern which could affect the fidelity with which central binaural nuclei process bilateral inputs.

Key words: Binaural, Cochlear implants, Dynamic range, Monaural.

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INTRODUCTION

Bilateral cochlear implantation has benefits over unilateral implantation for speech reception in noise and sound localization, but bilateral cochlear implants (CIs) do not provide all of the benefits that listeners with normal hearing derive from having two ears. Localization of sound sources is limited in listeners with bilateral CIs (Nopp et al. 2004; Verschuur et al. 2005; Litovsky et al. 2009; Jones et al. 2014), and bilateral benefits for speech reception in noise depend mostly on "head shadow" with little to no benefit from binaural interaction (Schleich et al. 2004; Litovsky et al. 2006; Loizou et al. 2009; Bernstein et al. 2016).

Psychophysical studies examining binaural sensitivity of listeners with bilateral CIs have shown that many listeners are sensitive to interaural time and level differences (van Hoesel & Tyler 2003; Litovsky et al. 2010; Laback et al. 2015). In addition, they are sensitive to changes in interaural correlation (Long et al. 2006; Goupell 2015; Goupell & Litovsky 2015). Many of these studies have been performed with single pairs of electrodes (one active electrode in each ear), to examine binaural sensitivity in the absence of interference from neighboring electrodes. However, even with single-electrode pair stimulation, there is wide variability in the binaural sensitivity of listeners with CIs. There is also variability in binaural sensitivity across stimulation sites (i.e., neural population stimulated by each electrode) within listeners, and to date there has been little evidence for a systematic effect of place of stimulation along the cochlea in CI users (van Hoesel et al. 2009; Litovsky et al. 2010; Kan et al. 2015a). Some of this variability may be due to central binaural processing deficits caused by auditory deprivation (Litovsky et al. 2010). In addition, the extent to which there are differences in insertion depths between the left and right electrode arrays has been proposed as a source of variability in binaural sensitivity of listeners with bilateral CIs (van Hoesel & Clark 1997; Long et al. 2003; Poon et al. 2009; Kan et al. 2013; Goupell 2015). However, there is evidence that interaural mismatches need to be relatively large, (i.e., approximately >3 mm) to cause a significant decrement in binaural sensitivity (Poon et al. 2009; Goupell 2015; Kan et al. 2015b, 2013). We propose that even with matched places of stimulation across the two ears, limitations in binaural sensitivity may arise due to limitations at the auditory periphery.

The contributions of peripheral processing to binaural sensitivity are considered here because limitations in transmission of information in each ear alone may interfere with sensitivity to combined input from the two ears, and thus, binaural sensitivity (van Hoesel 2007; Ihlefeld et al. 2015). Mammalian physiology is such that the auditory nerves deliver inputs to the cochlear nuclei on each side. Inputs from the cochlear nuclei are then combined at the superior olivary complex, where binaural comparisons are performed (Yin 2002). Therefore, deficits in the peripheral representation of signals at either ear could produce poor binaural sensitivity. For CI users, monaural psychophysical studies have shown variability across stimulation sites in the stimulation levels that produce just-audible sensations and maximum acceptable loudness (MAL), as well as rates of loudness growth (Pfingst & Xu 2004; Bierer & Nye 2014). Listeners also show variability in performance across stimulation sites on tasks such as phase-duration modulation detection, rate discrimination, and temporal gap detection (Pfingst et al. 2007; Garadat & Pfingst 2011; Garadat et al. 2012; Ihlefeld et al. 2015). These differences may in part reflect the shape and extent of electrical current spread as well as the auditory neural survival and tissue growth at different stimulation sites. Anatomical studies have shown that there is variability in the distance of electrodes from the auditory nerve fibers, the extent of damage and tissue

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growth within the cochlea, and the auditory nerve survival in listeners with CIs (Nadol 1997; Finley et al. 2008; Fayad et al. 2009; Bierer 2010).

There is some evidence that characteristics of the electrode–neural interface relate to hearing performance. Kawano et al. (1998) found that greater spiral ganglion cell survival is associated with larger dynamic ranges (DRs) within some individuals with CIs. These limitations at the auditory periphery may also affect binaural sensitivity, because binaural processing requires peripheral processing. Furthermore, research in listeners with normal hearing suggests that binaural sensitivity is best when the inputs arise from frequency-matched peripheral locations (Henning 1974; Nuetzel & Hafter 1981; Goupell et al. 2013b). However, even with pitch-matched inputs, there is a significant gap in binaural sensitivity between many bilateral CI and normal-hearing listeners. It may be the case that peripheral deficits such as poor neural survival limit the extent to which there can be peripherally matched stimulation, thus limiting the number of central neurons receiving bilateral input (Goupell 2015).

The goal of the present study was to assess whether there is a relationship between binaural sensitivity and monaural hearing performance, which we take in part to reflect the status of peripheral coding of the incoming signal. A relationship between binaural sensitivity and monaural measures would suggest that limitations nonspecific to binaural processing, such as auditory peripheral processing, indeed affect binaural processing (Hall et al. 1984; van Hoesel 2007). The present study focused on the relationship between monaural intensity coding and binaural sensitivity, which has been examined in listeners with mild to moderate hearing loss but not CI users.

Effect of Monaural Intensity Coding on Binaural Signal Detection

For listeners with normal hearing, the introduction of an interaural time or phase delay in a speech signal improves speech reception thresholds in diotic noise (Licklider 1948; Schubert 1956). Similarly, the introduction of an interaural time or phase delay in a tonal signal improves signal detection in diotic noise (Green 1966). In these dichotic conditions, interaural decorrelation is created in the temporal envelope and temporal fine structure of the combination of noise and signal, which results in information that can be used by the listener to aid in signal detection (Bernstein 1991; van de Par & Kohlrausch 1995). The difference in signal detection ability between the diotic condition in which the signal and noise have the same interaural configuration (e.g., noise in phase, signal in phase = NoSo) and a dichotic condition in which the signal and noise have different interaural configurations is known as the binaural masking level difference (BMLD). Listeners with normal hearing demonstrate BMLDs as large as 25 dB, depending on the target frequency and bandwidth of the masking noise (van de Par & Kohlrausch 1997). Listeners with CIs have shown BMLDs when signal detection is measured using a limited number of electrodes in each ear (Long et al. 2006; Lu et al. 2010, 2011; Goupell & Litovsky 2015). However, there is variability across listeners in the magnitude of binaural unmasking demonstrated. For example, Lu et al. (2010) found BMLDs in 5 listeners with CIs to range from approximately 1 to 10 dB.

For listeners with CIs, acoustic information is conveyed in the amplitude modulations of high-rate electrical pulse trains (Loizou 2006). With this type of information, binaural release from masking relies on the ability of the listener to detect interaural decorrelation in temporal envelope. The ability to use interaural information in temporal envelope depends at least in part on the ability of the peripheral auditory system to encode changes in intensity in both ears. Therefore limitations in DR or resolution for changes in intensity at the periphery in either ear could limit listeners' ability for binaural release with temporal envelope information. Furthermore, small DRs and poor-intensity resolution could represent poor peripheral neural survival (Bierer & Nye 2014), which may limit the extent to which stimuli can be presented to interaurally matched peripheral neural fibers.

In addition to the encoding of intensity within each ear, the symmetry between ears in loudness growth could affect listeners' dichotic signal detection. That is, the ability to detect interaural decorrelation in the temporal envelope of stimuli, which is useful for dichotic signal detection, could be limited by any internal interaural decorrelation introduced by asymmetries in loudness growth between the ears. Goupell et al. (2013a) reported that as the level of a diotic constant-amplitude stimulus was varied across percentages of the DR, deviations from the perception of a centered auditory image occurred, and suggested that this could result in unintended internal interaural decorrelation. Similarly, we would expect that asymmetries in loudness growth between the two ears would create internal decorrelation which would limit dichotic signal detection, because the decorrelation of the dichotic stimuli could only serve as a cue for signal detection when it is greater than the internal decorrelation present with the diotic reference stimuli.

Given the aforementioned variables that could potentially compromise binaural processing, in the present study, DR, amplitude modulation detection, and loudness growth were examined to evaluate whether these measures are related to dichotic signal detection. It was hypothesized that limitations in either ear for the DR and modulation detection measures could result in poor binaural sensitivity. Thus, we expected that listeners' performance in dichotic signal detection would show a relationship with the smaller DR or poorer amplitude modulation detection threshold of the two ears. For loudness growth, we were specifically interested in the difference between the ears to evaluate whether reduced symmetry results in poorer dichotic signal detection. Performance was measured at three stimulation sites per listener to examine the relationship between the monaural measures and dichotic signal detection within listeners across stimulation sites. We considered this approach advantageous over examining the relationship across listeners, as variability due to differences between listeners in attention, tolerance for loudness, or other factors was removed.

Performance on diotic signal detection was measured as a control condition, to evaluate whether listeners showed better performance when dichotic stimuli were used, that is, to determine whether subjects were able to use binaural processing in the dichotic condition. For listeners with CIs, diotic signal detection relies on the ability to detect the effect that the signal has on the temporal envelope of the noise. However, unlike dichotic signal detection, which relies on input from both ears, diotic signal detection only requires input from one ear to perform the task. Therefore, we expected that listeners' performance in diotic signal detection would show a relationship with the larger DR or better amplitude modulation detection threshold of the two ears.

Effect of Monaural Intensity Coding on Interaural Time Difference Discrimination

For listeners with normal hearing, low-frequency interaural timing information plays a major role in sound lateralization and spatial release from masking (Bernstein & Trahiotis 1985; Zurek 1993; Culling et al. 2004). With single tones, interaural time difference (ITD) just-noticeable differences (JNDs) can be as low as 11 µsec (Klumpp & Eady 1956; Brughera et al. 2013). For listeners with CIs, ITD JNDs, when measured with low-rate pulse trains to single electrode pairs can be as good as 25 to 50 µsec, but JNDs are generally higher and vary between participants, as well as within listeners across stimulation sites (Litovsky et al. 2010; Kan & Litovsky 2015; Laback et al. 2015).

A relationship between dichotic signal detection thresholds and ITD JNDs has been found across listeners with CIs (Goupell & Litovsky 2015). This relationship may be due to limitations at the auditory periphery that interfere with processing both types of stimuli. Therefore, we sought to determine whether a relationship between dichotic signal detection thresholds and ITD JNDs could be found within listeners, across different stimulation sites. In addition, we examined the relationship between DR and ITD JNDs, which allowed us to examine the relationship between DR and binaural sensitivity using stimuli with a constant-amplitude temporal envelope. A relationship between DR and ITD JNDs could suggest that DR represents limitations at the periphery, which affect temporal encoding or that small DRs represent poor neural survival, which could limit the extent to which there is stimulation to peripherally matched left and right neural fibers.

In this study, the primary focus was whether variability in dichotic signal detection and ITD discrimination was related to monaural hearing measures in either ear. We hypothesized that our monaural measures (i.e., DR and amplitude modulation detection) would predict dichotic signal detection (a task requiring encoding of temporal envelope), because these measures could reflect the integrity with which the temporal envelope is represented and coded. That is, larger DRs and better amplitude modulation detection may allow for better representation of amplitude modulations. However, the finding of a relationship between DR and ITD discrimination with stimuli consisting of pulses that have no amplitude modulations may be better explained by the concept that better auditory peripheral characteristics result in better binaural sensitivity because they allow for greater interaural matching of bilateral stimuli.

MATERIALS AND METHODS

Participants and Equipment

Participants included 11 adults with bilateral CIs, all with Nucleus device types manufactured by Cochlear Ltd. Table 1 shows participant characteristics and the electrode pairs used for the testing in the present study. Note that lower numbered electrodes are located in the basal region of the electrode arrays manufactured by Cochlear Ltd. Stimuli were delivered using the Nucleus Implant Communicator and L34 processors. The experimental procedures for this study were approved by the Institutional Review Board of the University of Wisconsin-Madison.

Stimuli

Electrical stimulation consisted of biphasic pulse trains in MP1 + 2 (monopolar) stimulation mode. Typically phase durations were 25 µsec per phase with an 8-µsec interpulse gap. For participant ICP, a 75-µsec phase duration was used to achieve levels that were loud enough. Stimuli were presented to individual electrodes or electrode pairs (one electrode in each ear) at basal, middle, or apical regions of the electrode arrays.

Pitch Matching

Stimuli for the evaluation of binaural hearing sensitivity were presented to pitch-matched pairs of electrodes in attempts to reduce the impact of interaural place of stimulation mismatch on binaural hearing sensitivity. The method of pitch matching followed that described in Kan et al. (2013). Stimuli for the pitch-matching task consisted of 300-msec constant amplitude pulse trains of 100 pulses per second (pps) presented at comfortable (COM) levels, defined for the participants as a level above the quiet range that the participants could listen to for an extended period of time (e.g., all day long). These stimuli matched those used for the ITD discrimination measure. For the pitch-matching task, participants rated the pitch of a stimulus presented from an electrode in one ear relative to the pitch of a stimulus presented from an electrode in the other ear. For each stimulus presentation, participants were asked to select one of the following responses: (1) much higher, (2) higher, (3) same, (4) lower, or (5) much lower. Typically, each of three electrodes on the left was compared with a set of 6 electrodes on the right (thus 18 combinations). ICS was the only participant who did not complete the pitch-matching task on the visit in which the other measures were made. For this participant, pitch-matched pairs from a previous visit were used. As can be seen in Table 1, pitch-matched pairs often did not deviate greatly from the number-matched pairs. IBQ stands out from the other participants in that this participant consistently required a large mismatch in electrode numbers to achieve interaural pitch matches.

Diotic and Dichotic Signal Detection

Diotic and dichotic signal detection thresholds were measured with 400-msec amplitude-modulated pulse trains presented at 1000 pps. Stimuli were created at a sampling rate of 44,100 Hz. Thirty-five samples of Gaussian noise were created in the frequency domain with a center frequency of 500 Hz, bandwidth of 50 Hz, and a duration of 400 msec. The target signal was a 300-msec 500-Hz sinusoid, which was temporally centered in the noise when presented. Both the signal and noise were ramped on and off with 50-msec Hann windows. The signal to noise ratio (SNR) of the tone and noise varied between 20 and −32 dB SNR in 2-dB steps. The tone was either presented with no interaural phase delay (So) or a 180° phase delay (Sπ). The noise was always diotic (i.e., the same in both ears, No). The diotic stimulus containing the target signal is referred to as NoSo and the dichotic stimulus as NoSπ. The Hilbert envelopes of the waveform stimuli were calculated, and normalized such that the average amplitude was 0.4 which corresponded to 87% DR after compression. The envelope was resampled at 1000 Hz and was compressed between the listener's threshold (THR) and a maximum stimulation level (M) using the compression function used by Long et al. (2006): $y = \text{round}[(1 - e\hat{}(-5.09 \cdot x)) \cdot (M - \text{THR}) + \text{THR}]$,

TABLE 1. Participant characteristics, device types, and tested electrodes

Participant	Age (yrs)	Duration with First CI (yrs)	Duration Bilateral (yrs)	Internal Device (L)	Internal Device (R)	Apex Pair (L,R)	Mid Pair (L,R)	Base Pair (L,R)
IBF	63	8.6	7.1	CI24RE(CA)	CI24RE(CA)	4,5	12,12	21,21
IBK	74	11.5	5.6	CI24R(CS)	CI24RE(CA)	4,5	12,12	18,18
IBP	64	10.3	9.7	CI24M	CI24M	4,8	12,14	20,17
IBQ	83	12.1	9.2	CI24RE(CA)	CI24R(CS)	8,2	12,5	20,15
IBR	59	9.9	6.3	CI512	CI24R(CS)	4,6	12,12	18,16
ICA	54	12.0	5.2	CI24RE(CA)	CI24R(CS)	3,3	12,13	20,20
ICI	56	5.7	5.0	CI24RE(CA)	CI24RE(CA)	4,8	12,14	20,20
ICJ	65	4.8	4.8	CI512	CI512	4,6	12,10	20,16
ICP	51	5.2	2.2	CI24RE(CA)	CI24RE(CA)	4,8	12,14	20,20
ICS	87	12.0	4.0	CI513	CI24R(CS)	4,5	12,12	18,19
ICT	21	2.6	2.6	CI512	CI512	4,3	12,12	20,19

L, left; R, right.

where x is the acoustic amplitude and y is the electrical amplitude in current units.* Similar to what was done by Long et al., values 30 dB below a maximum acoustic amplitude of 1 were dropped to provide an input DR of 30 dB. The envelopes were presented with a 400-msec electrical pulse train of 1000 pps.

Loudness mapping for the diotic and dichotic signal detection stimuli was conducted to obtain THRs and MAL levels. Stimuli consisted of constant-amplitude 400-msec, 1000-pps pulse trains. To measure THRs, the experimenter manually increased the current level until the participant detected the signal three times consecutively. Two measures of THRs were obtained for each of the six electrodes used in the study. If the first two measures were more than five current units apart, a third measure was obtained and the two closest values were averaged. MAL levels were defined for the participant as the loudest level that was still comfortable for short-duration listening or in other words the level just below too loud. To measure MAL levels, the experimenter manually increased the current level in small steps until the participant indicated that the level was high enough. Two measures of the MAL level were obtained. If the first two measures were more than 1 dB apart, a third measure was obtained. All measures of MAL were averaged.

Using the diotic noise of the diotic/dichotic signal detection task, loudness balancing was performed for each of the six electrodes by adjusting the *M* levels used for the compression function. The *M* levels were initially set to the participant's MAL levels. Two intervals of diotic noise were presented sequentially, one from each of two electrodes, and the participant indicated which of the two stimuli was perceived to be louder, or whether they were the same perceived loudness. The process began with the left-ear electrodes, whereby the *M* levels of the basal and apical electrodes were adjusted to match the loudness of the middle electrode. Subsequently, the level of the electrodes in the right ear was adjusted to match the loudness of their counterparts on the left.

Additional *M*-level adjustments were made to ensure that, before testing, participants perceived auditory images that were approximately intracranially centered. A single interval of diotic noise was presented. Participants indicated the intracranial perceived location of the stimulus. If the participant indicated that the stimulus was far off center, the experimenter stimulated each ear individually in order for the participant to hear the range of intracranial positions before reexamining the perceived position of the stimulus. Adjustments of up to a few current units were made to center the image, for instance, by reducing the level of the ear that dominated the off-center image. Table 2 shows the maximum levels (*M*s) that were used for No/NoSo/NoSπ stimulus presentation, as well as MAL levels. It can be seen that there are typically only minor differences between the *M*s and MALs.

The procedure for loudness mapping was changed after the first few participants (IBR, ICA, ICP, IBP), because the participants were showing only minimal improvement in the dichotic signal detection task relative to the diotic condition.† For participants IBR, ICA, and ICP, diotic and dichotic signal detection stimuli were compressed between THRs and approximately COM levels, instead of THRs and approximately MAL levels, which were subject to the same loudness balancing and centering. For participant IBP, diotic and dichotic signal detection stimuli were compressed both ways and signal detection thresholds were first measured with stimuli compressed using loudness-balanced and centered COM levels and then with stimuli compressed using loudness-balanced and centered MAL levels. Table 3 shows *M* levels that were used for No/NoSo/NoSπ stimulus presentation for participants IBR, ICA, and ICP, as well as IBP when tested at the lower-level *M*s.

Signal detection thresholds for NoSo and NoSπ were measured using a three-interval two-alternative forced-choice task in which the signal occurred in either the second or the third interval randomly determined on each trial. Nontarget intervals consisted of diotic noise. Each interval contained a different sample of noise, which was randomly selected without replacement for each trial. Correct answer feedback was provided. The SNR was varied using a two-down one-up adaptive procedure beginning at 20 dB SNR. Initially the step size was 8 dB and changed to 4 dB after 1 turnaround and 2 dB after 3 turnarounds. Tracks stopped after 10 turnarounds and the threshold of each track was estimated as the average of the values on the last 6 turnarounds of the track. Tracks were

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*One current unit is equal to .1759 dB for the cic3 internal devices (CI24M, CI24R, CI24R(CS)). One current unit is equal to 0.1569 dB for the cic4 internal devices (CI24RE, CI24RE(CA), CI512, CI513).

†Stimulus compression using a lower upper limit for these listeners may have limited dichotic signal detection performance due to smaller interaural differences.

TABLE 2. THRs, *M* levels used for the diotic/dichotic signal detection task, and MAL levels in current units at 1000 pps for each electrode on the L and R for each of the participants whose *M* levels were near MAL levels

Participant	Electrode (L)	THR (L)	MAL (L)	*M* (L)	Electrode (R)	THR (R)	MAL (R)	*M (R)*
IBF	4	121	175	173	5	114	169	169
	12	114	197	197	12	121	193	191
	21	128	185	185	21	130	194	194
IBK	4	143	236	234	5	143	238*	238
	12	156	244	244	12	145	238*	236
	18	161	244	242	18	147	235*	233
IBP	4	159	221	220	8	142	204	202
	12	143	210	210	14	129	201	201
	20	147	211	211	17	130	201	201
IBQ	8	130	225	225	2	122	216	216
	12	119	225	225	5	135	215	214
	20	130	222	222	15	128	215	215
ICI	4	133	173	172	8	124	168	168
	12	133	188	188	14	133	173	173
	20	124	159	159	20	119	165	163
ICJ	4	124	179	174	6	139	168	162
	12	107	173	173	10	134	173	170
	20	93	163	159	16	92	154	148
ICS	4	158	196	198	5	158	195	195
	12	123	193	193	12	157	210	210
	18	114	191	193	19	141	201	201
ICT	4	83	148	146	3	114	154	156
	12	94	154	154	12	103	162	156
	20	91	150	152	19	95	161	158

**Limited by twitching/physical sensation as opposed to loudness.*
L, left; M, maximum; MAL, maximum acceptable loudness; R, right; THRs, thresholds.

presented in blocks of NoSo and NoSπ to reduce the number of times the cues for the task switched. Blocks consisted of one adaptive track from each stimulation site (base, mid, or apex) presented in a newly randomized order for each block. At least four tracks were collected per stimulation site. Initially, participants were familiarized with the stimuli by doing 10 to 20 trials of the signal detection task for NoSo at 12 dB SNR (or 20 dB SNR) and for NoSπ at 0 dB SNR at each stimulation site. BMLDs were computed as the difference in dB between the threshold in the NoSo condition and the threshold in the NoSπ condition.

Amplitude Modulation Detection

Amplitude modulation detection was measured at each of the six electrodes individually. Stimuli consisted of 400-msec 1000-pps pulse trains. The standard stimulus had constant amplitude. The target was sinusoidally amplitude modulated on a linear milliampere (mA) scale using the formula $[f(t)][1 + m\cdot\sin(2\cdot\pi\cdot f_m\cdot t)]$, where $f(t)$ is the average current, f_m is the modulation rate of 30 Hz, and m is the modulation depth, which was a proportion of 1 and varied during the experiment. The $f(t)$ used for each electrode was loudness balanced near 40% of the DR (calculated using loudness-balanced MAL levels) in current

TABLE 3. THRs, *M* levels used for the diotic/dichotic signal detection task, and MAL levels in current units at 1000 pps for each electrode on the L and R for each of the participants whose *M* levels were near COM levels

Participant	Electrode (L)	THR (L)	MAL (L)	*M* (L)	Electrode (R)	THR (R)	MAL (R)	*M (R)*
IBR	4	115	173	162	6	119	188	167
	12	116	184	176	12	138	209	200
	18	114	186	172	16	130	203	192
ICP	4	105	189	179	8	145	215*	206
	12	90	161	146	14	117	192	177
	20	79	146	127	20	75	162	145
ICA	3	107	194	186	3	155	210	197
	12	163	233	218	13	175	219	206
	20	148	232	201	20	168	221	208
IBP	4	159	221	209	8	142	204	194
	12	143	210	198	14	129	201	187
	20	147	211	203	17	130	201	187

**Limited by twitching/physical sensation as opposed to loudness.*
COM, comfortable; L, left; M, maximum; MAL, maximum acceptable loudness; R, right; THRs, thresholds.

units. The loudness balancing used constant-amplitude 1000-pps pulse trains and followed the loudness-balancing procedure used for the diotic and dichotic signal detection stimuli.

The amplitude-modulation detection task consisted of a two-interval two-alternative forced-choice task. Participants were instructed to choose the interval that was fluctuating in loudness. Correct answer feedback was provided. The modulation depth was varied using a two-down one-up adaptive procedure. Initially the step size was 6 dB and changed to 3 dB after 2 turnarounds and 2 dB after 4 turnarounds. Tracks stopped after 10 turnarounds and the threshold of each track was estimated as the average of the values on the last 6 turnarounds of the track. One track for each of the six electrodes was collected in a randomized order before the next set of tracks in a newly randomized order. Three tracks were collected unless the SD of the thresholds was more than 3 dB for any condition, in which case a fourth track was collected, and the threshold was calculated as the average of all of the tracks.

Interaural Loudness Balancing

Interaural loudness balancing was conducted using 400-msec constant-amplitude 1000-pps pulse trains. The three sites of stimulation (base, mid, and apex) were examined separately. Stimuli were presented to the two ears sequentially. The level of the stimulus in one ear was held fixed and the level of the stimulus in the other ear was variable. The fixed stimulus was set to 40 to 90% of the DR in current units (%DR) in 10% steps. The DR used for testing was the same as that which was used for the diotic and dichotic signal detection task (the higher levels for IBP). The interaural loudness-balancing task consisted of a two-interval two-alternative forced-choice task in which the participant indicated which interval was louder. The variable stimulus was randomly assigned to one of the two intervals. If the participant indicated that the variable stimulus was louder, the level of the variable stimulus was decreased. If the participant indicated that the fixed stimulus was louder, the level of the variable stimulus was increased. A double-staircase adaptive track procedure was used in which for one track the variable stimulus started 25 current units above the %DR of the track, and for the other track the variable stimulus started 25 current units below the same %DR, with the restriction that the track did not start above the MAL level or below THR. For most participants, a one-down one-up adaptive procedure was used to track the level at which the participant indicated that the variable stimulus was louder 50% of the time. For participant IBP, a majority decisions rule (Levitt 1971; Zeng & Turner 1991) (i.e., 2 consecutive or 2 out of 3 responses that either the variable or the fixed stimulus was louder resulted in an adjustment to the level of the variable stimulus) was used, which also tracked the 50% level. The adaptive track changed the current amplitude in 10 current-unit steps initially, 5 current-unit steps after 1 turnaround, and 3 current-unit steps after 3 turnarounds. Tracks stopped after 10 turnarounds and the threshold of each track was estimated as the average of the values on the last 6 turnarounds. For the majority of participants, two double-staircase procedures (four tracks in total) were collected per %DR, one in which the stimulus in the left ear was fixed and one in which the stimulus in the right ear was fixed. All factor levels of stimulation site, fixed ear, and %DR were fully randomized, except in the case of ICJ whose mid pair was tested after the apical and base pair due to initial time limitations. For each stimulus that was presented at a fixed percentage of the DR in current units of a specific ear, the percentage of the DR of the stimulus in the other ear that provided a matched-loudness judgment was calculated. Current units were used because the envelopes were mapped to the electric DR in current units for the diotic and dichotic signal detection task.

ITD Discrimination

Stimuli used for measuring ITD discrimination consisted of 300-msec pulse trains with a rate of 100 pps, presented at *C* levels, which were loudness-balanced and perceptually centered COM levels. Loudness mapping was conducted to find COM levels. THRs and MAL levels were also measured using these stimuli to calculate the DR at this pulse rate. The method used for measuring THRs and MAL levels was the same as the method used for the diotic and dichotic signal detection stimuli, except that MAL levels were only measured once because the high level of current that participants can tolerate at lower pulse rates is more likely to provide uncomfortable sensations, such as facial twitching. Loudness balancing and centering were conducted using the loudness-balancing and centering method used for the diotic and dichotic signal detection stimuli to adjust the COM levels so that they were equal in loudness and approximately centered intracranially. Table 4 shows THRs, MAL levels, and *C* levels.

A method of constant stimuli was used to measure ITD discrimination. A two-interval two-alternative forced-choice task was used in which the participants indicated whether the second sound was perceived to the left or right of the first sound. Correct answer feedback was provided. Typically, ITD values of 50, 100, 200, 400, and 800 μsec were tested. These values were adjusted based on the sensitivity of the listener. Psychometric functions were calculated based on data from at least 4 ITDs and at least 40 trials per ITD (Wichmann et al. 2001a, b). JNDs were calculated from the psychometric function as the ITD which produced 70.7% accuracy.

RESULTS

Data Analysis

Diotic and dichotic signal detection thresholds and ITD JNDs were fit to linear mixed-effects models with random intercepts for participants. Random intercepts for stimulation sites were included for diotic and dichotic signal detection thresholds because multiple adaptive tracks were collected per stimulation site. *F* tests were used to examine within-participant effects across the three measured stimulation sites unless stated otherwise. When multiple effects were included in the mixed-effects model, *F* tests were conducted using type II sums of squares. Current units were converted to mA and then into dB for the DR measure, as well as the other measures resulting from loudness mapping. For each pulse rate, DR measures were made in two ways: (1) from THRs to *M*s (1000 pps) and THRs to Cs (100 pps) and (2) from THRs to MALs. The former is the DR with which the stimuli were presented (i.e., the stimulus DR). The stimulus DR is presented in figures and is always presented before the DR calculated with MALs in the "Results." ITDs in μsec were log-transformed (base 10) for hypothesis testing.

TABLE 4. THRs, MAL levels, and levels (*C*s) used for ITD discrimination task in current units at 100 pps for each electrode on the L and R

Participant	Electrode (L)	THR (L)	MAL (L)	*C* (L)	Electrode (R)	THR (R)	MAL (R)	*C* (R)
IBF	4	130	215	192	5	123	208	193
	12	140	225	204	12	139	222	213
	21	140	195	183	21	136	213	198
IBK*	4	155	NM	240	5	154	NM	243†
	12	189	NM	250	12	170	NM	243
	18	191	NM	246	18	172	NM	240
IBP	4	180	231	212	8	167	212	210
	12	172	227	212	14	160	216	204
	20	176	219	189	17	161	214	194
IBQ	8	151	245	242	2	174	239	239
	12	164	246	243	5	171	239	239
	20	170	231	228	15	170	230	227
IBR	4	158	197	189	6	160	195	187
	12	155	197	195	12	160	211	206
	18	153	193	190	16	147	210	205
ICA	3	117	206	199	3	164	227	216
	12	171	242	233	13	178	224	221
	20	186	247	239	20	189	223	219
ICI	4	163	192	183	8	157	181	175
	12	173	199	196	14	161	184	180
	20	153	174	171	20	132	177	174
ICJ	4	151	196	193	6	146	199	190
	12	155	195	186	10	148	198	190
	20	133	197	192	16	108	190	172
ICP	4	121	224†	218	8	161	220†	217
	12	132	197	180	14	144	216†	187
	20	119	170	148	20	113	219†	155
ICS	4	180	219	208	5	167	225	210
	12	160	244	205	12	186	232	215
	18	163	222	209	19	173	239	215
ICT	4	100	157	148	3	145	164	164
	12	126	162	159	12	138	170	158
	20	99	148	132	19	134	160	148

**MALs not measured because of twitching near comfortable levels.*
†Limited by facial twitching/physical sensation as opposed to loudness.
L, left; MAL, maximum acceptable loudness; R, right; THRs, thresholds.

When examining the relationship between the binaural and monaural measures, for each binaural measure, there were two associated monaural measures (i.e., left ear and right ear). Therefore, analyses were conducted using (1) the smaller monaural value (e.g., DR_{sml}), (2) the larger monaural value (DR_{lrg}), (3) the average of the two monaural values (DR_{avg}), and (4) and the difference between the two values (DR_{diff}). Each of these measures was calculated for each stimulation site (apex, mid, and base) independent of the other sites. Differences between the measures from the left and right ears were calculated by subtracting one measure from the other (in dB) and taking the absolute value of the difference.

For the NoSo/NoSπ measures, the results focus on the 8 participants for which NoSo/NoSπ stimuli were compressed using approximately MAL levels, but relevant results are shown for the 4 participants for which NoSo/NoSπ stimuli were compressed using approximately COM levels. Statistical tests apply to the eight datasets for which NoSo/NoSπ stimuli were compressed using approximately MAL levels. IBP's data with the second mapping procedure (using approximately MAL levels) is presented unless otherwise indicated.

Diotic and Dichotic Signal Detection Thresholds

As shown in Figure 1, all participants whose stimuli were compressed between THRs and approximately MAL levels (filled symbols) showed NoSπ thresholds that were lower on average than NoSo thresholds, and this occurred at each stimulation site. However, thresholds for both NoSo and NoSπ varied across sites, as did the BMLDs, which appear as numbers at the bottom of each plot. Average NoSo and NoSπ thresholds for these participants were 0.8 dB SNR (SD = 3.0) and −9.1 dB SNR (SD = 5.1), respectively, [$F_{1,168} = 198.61$, $p < 0.0001$]. The BMLD was 9.8 dB on average (SD = 4.9). The effect of place (apex, mid, and base) was not significant [$F_{2,14} = 2.45$, $p = 0.12$]. The Phase × Place interaction was also not significant [$F_{2,24} = 2.10$, $p = 0.14$]. Average NoSo and NoSπ thresholds for the participants whose stimuli were compressed between THRs and approximately COM levels (Fig. 1, unfilled symbols) were 5.2 dB SNR (SD = 4.7) and 2.2 dB SNR (SD = 5.1), respectively. The BMLD was 3.0 dB on average (SD = 3.3).

Effect of DR at 1000 pps • Contrary to the hypothesis for NoSo thresholds, DR_{lrg} was not significant in predicting NoSo thresholds [$F_{1,14} = 1.89$, $p = 0.19$]. However, DR_{diff} was significant

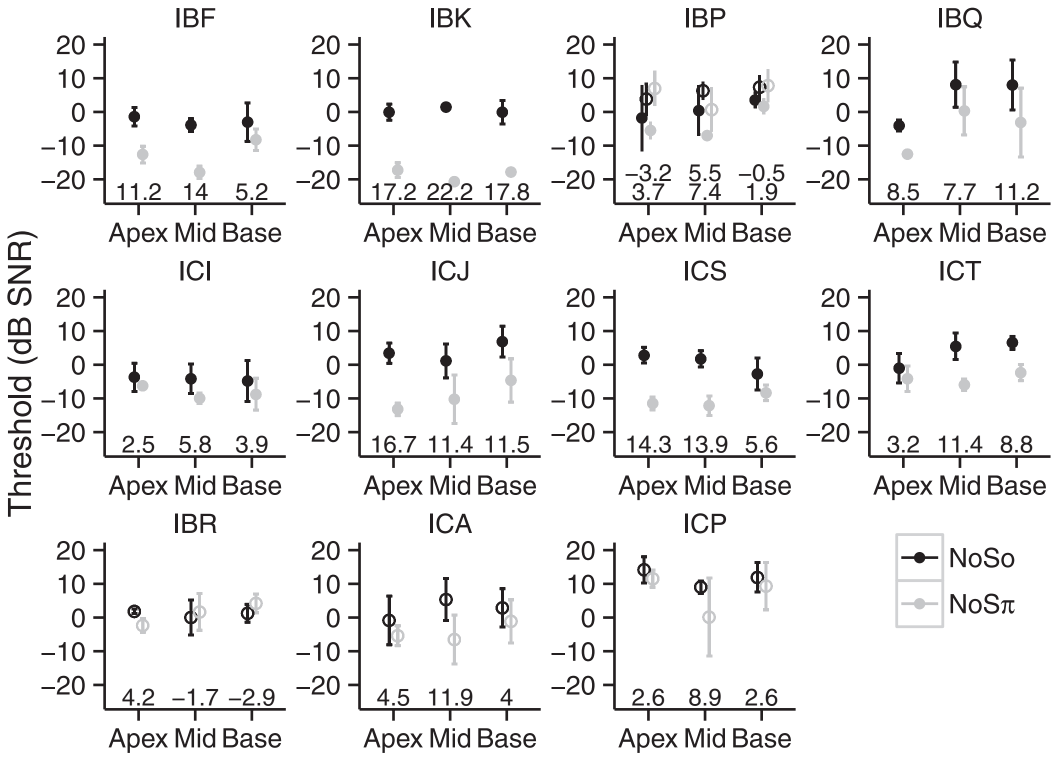

Fig. 1. Diotic (NoSo; black) and dichotic (NoSπ; gray) signal detection thresholds (dB SNR) as a function of place of stimulation. Each panel shows data from an individual participant. BMLDs for each place of stimulation are indicated by numbers on the plot. Filled symbols indicate stimuli compressed between THRs and approximately MALs. Unfilled symbols indicate stimuli compressed between THRs and approximately COMs. Error bars show SDs. BMLD indicates binaural masking level difference; COM, comfortable; MAL, maximum acceptable loudness; SNR, signal to noise ratio; THRs, thresholds.

in predicting NoSo thresholds [$F_{1,14} = 6.51$, $p = 0.023$].The left-hand panel of Figure 2 shows NoSo thresholds as a function of DR$_{\text{diff}}$ for the participants whose stimuli were compressed using approximately MAL levels. The three stimulation sites per participant are grouped by symbol and a conjoining line. There was a general increase in NoSo thresholds within participants across the three tested stimulation sites as the difference between the DRs of the left and right ears increased. IBF and ICJ were the only participants whose data notably differed from this pattern. For these 2 participants, the best NoSo thresholds were obtained when the difference between DRs was the largest. In addition, for a number of participants the effect of DR$_{\text{diff}}$ appeared to weaken at larger DR$_{\text{diff}}$ values. The right-hand panel of Figure 2 shows the relationship between NoSo thresholds and DR$_{\text{diff}}$ for the four datasets for which NoSo stimuli were compressed using approximately COM levels. The data resulting from the stimulus compression with approximately COM levels reasonably follow the same pattern as when stimuli were compressed with approximately MAL levels. The effect of DR$_{\text{diff}}$ on NoSo thresholds did not reach significance when DR was calculated using MAL levels at 1000 pps [$F_{1,14} = 4.316$, $p = 0.057$]. DR$_{\text{sml}}$ and DR$_{\text{avg}}$ were not significant in predicting NoSo thresholds [DR$_{\text{sml}}$: $F_{1,14} = 0.055$, $p = 0.82$; DR$_{\text{avg}}$: $F_{1,14} = 0.64$, $p = 0.43$].

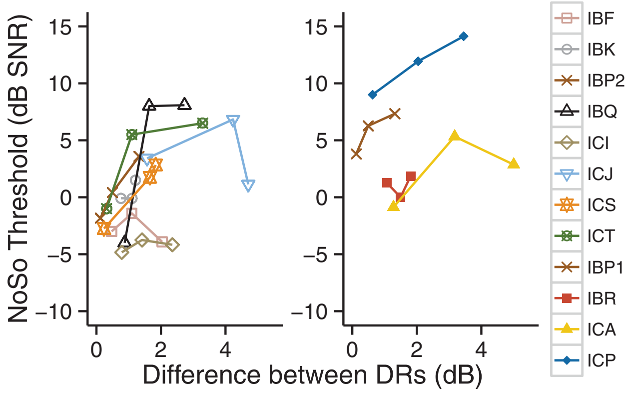

Fig. 2. Diotic signal detection thresholds (dB SNR) as a function of the absolute value of the difference between the DRs (dB) of the two ears. Thresholds of three places of stimulation per participant are grouped by a conjoining line, symbol, and color. Panels on the left and right show data from the participants whose stimuli were compressed using approximately MAL or COM levels, respectively. COM indicates comfortable; DR, dynamic range; MAL, maximum acceptable loudness; SNR, signal to noise ratio.

In accordance with the hypothesis for NoSπ thresholds, there was an improvement in NoSπ thresholds as DR$_{\text{sml}}$ increased for the participants whose stimuli were compressed using approximately MAL levels as shown in the left-hand panel of Figure 3 [$F_{1,14} = 8.12$, $p = 0.013$]. This pattern was less apparent for the 2 participants with the largest DR$_{\text{sml}}$, IBQ, and IBK. The right-hand panel of Figure 3 shows the relationship between NoSπ thresholds and DR$_{\text{sml}}$ for the four datasets for which NoSπ stimuli were compressed using approximately COM levels. NoSπ thresholds did not decrease with increasing DR$_{\text{sml}}$ for these participants. The effect of DR$_{\text{sml}}$ was significant on NoSπ thresholds when DR was calculated using MALs [DR$_{\text{sml}}$: $F_{1,14} = 7.74$, $p = 0.015$]. NoSπ thresholds also decreased with larger DR$_{\text{avg}}$ [$F_{1,14} = 5.81$, $p = 0.030$]. The effect of DR$_{\text{lrg}}$ and DR$_{\text{diff}}$ were not

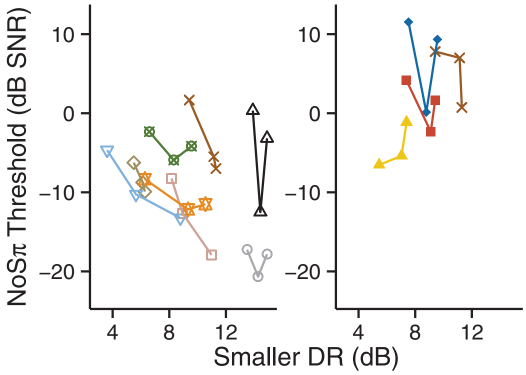

Fig. 3. Dichotic signal detection thresholds (dB SNR) as a function of the smaller DR (dB) of the two ears. Panels on the left and right show data from the participants whose stimuli were compressed using approximately MAL or COM levels, respectively. Thresholds of three places of stimulation per participant are grouped by a conjoining line, symbol, and color. COM indicates comfortable; DR, dynamic range; MAL, maximum acceptable loudness; SNR, signal to noise ratio.

significant in predicting NoSπ thresholds [DR$_{\text{lrg}}$: $F_{1,14} = 3.35$, $p = 0.088$; DR$_{\text{diff}}$: $F_{1,14} = 1.16$, $p = 0.30$].

Effect of THR and *M* Levels at 1000 pps • NoSo and NoSπ thresholds were analyzed as a function of THRs and *M*s at 1000 pps, which allowed for the examination of whether the effect of DR was largely an effect of THRs or *M*s as shown in Table 5. There were no significant relationships between THRs and NoSo or NoSπ thresholds. There were also no significant relationships between *M*s and NoSo or NoSπ thresholds.

Effect of Amplitude Modulation Detection Thresholds • NoSo thresholds were not significantly related to MDT$_{\text{sml}}$ [$F_{1,14} = 0.84$, $p = 0.37$], contrary to the hypothesis. Furthermore, no relationship between NoSo thresholds and MDTs was significant (MDT$_{\text{lrg}}$: [$F_{1,14} = 1.00$, $p = 0.33$]; MDT$_{\text{avg}}$: [$F_{1,14} = 0.97$, $p = 0.34$]; MDT$_{\text{diff}}$: [$F_{1,14} = 0.015$, $p = 0.90$]). Similarly, NoSπ thresholds were not significantly related to MDT$_{\text{lrg}}$ [$F_{1,14} = 1.15$, $p = 0.30$], and no other relationship between NoSπ thresholds and MDTs was significant (MDT$_{\text{sml}}$: [$F_{1,14} = 2.85$, $p = 0.11$]; MDT$_{\text{avg}}$: [$F_{1,14} = 2.79$, $p = 0.12$]; MDT$_{\text{diff}}$: [$F_{1,14} = 0.066$, $p = 0.80$]).

Effect of Symmetry of Loudness Growth • Each panel of Figure 4 shows the interaural loudness-balancing data of a listener at a particular place of stimulation (apex, mid, and base). Each data point of each panel shows the percentage of the DRs of left and right ears that were matched in loudness through the adaptive procedure. Thresholds calculated from the upper and lower track of the double-staircase procedure have been averaged. Black symbols indicate that the stimulus in the left ear was fixed and the stimulus in the right ear was variable, and vice versa for the white symbols. The diagonal line shows the line of equality. Points falling below the line of equality can

TABLE 5. *F* values ($F_{1,14}$) and *p* values of the relationships between THRs/*M* levels and diotic (NoSo)/dichotic (NoSπ) signal detection thresholds

	NoSo Thresholds	NoSπ Thresholds
THR$_{\text{sml}}$	$F = 1.40$, $p = 0.26$	$F = 0.23$, $p = 0.64$
THR$_{\text{lrg}}$	$F = 0.21$, $p = 0.65$	$F = 0.53$, $p = 0.48$
THR$_{\text{avg}}$	$F = 0.62$, $p = 0.44$	$F = 0.49$, $p = 0.49$
THR$_{\text{diff}}$	$F = 1.37$, $p = 0.26$	$F = 0.15$, $p = 0.70$
M_{sml}	$F = 0.0052$, $p = 0.94$	$F = 2.65$, $p = 0.13$
M_{lrg}	$F = 0.062$, $p = 0.81$	$F = 1.27$, $p = 0.28$
M_{avg}	$F = 0.012$, $p = 0.91$	$F = 2.97$, $p = 0.11$
M_{diff}	$F = 2.32$, $p = 0.15$	$F = 1.85$, $p = 0.20$

M, maximum; THRs, thresholds.

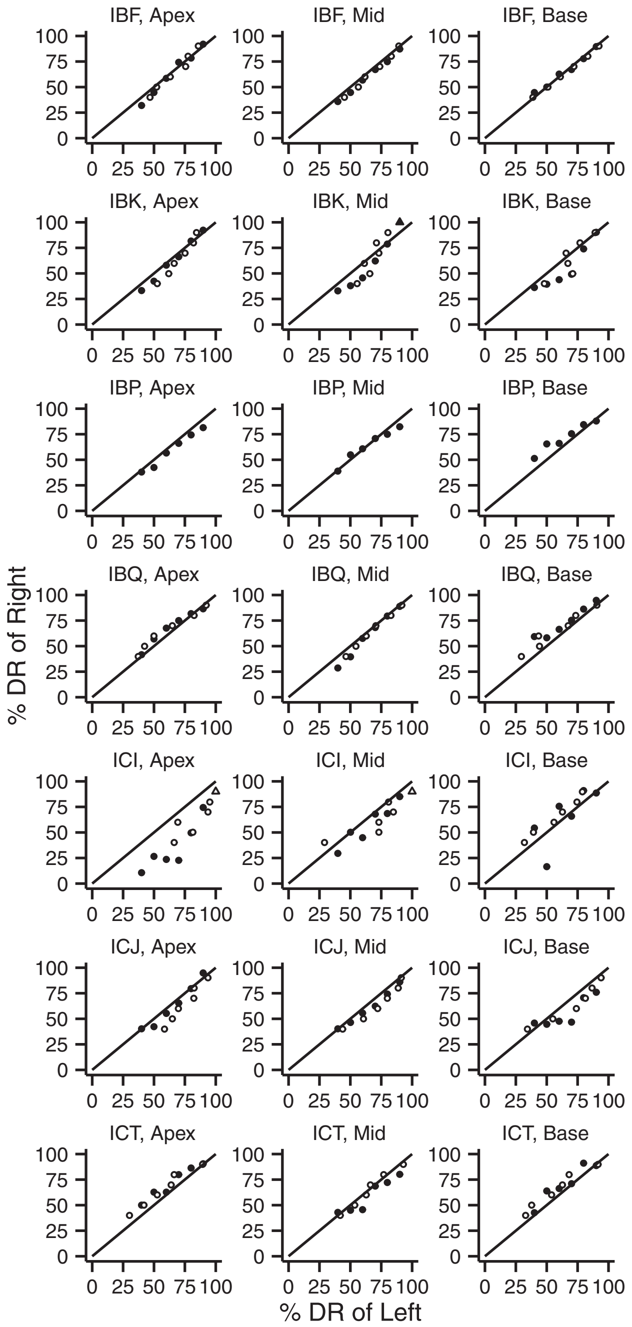

Fig. 4. Interaural loudness-balancing data. Percentage of the DR on the right (ordinate) matching in loudness to a percentage of the DR on the left (abscissa) is shown. The diagonal line shows the line of equality. Each row shows data from an individual participant. Each column shows data from a specific place of stimulation. White points represent the data for which the right-ear stimulus was fixed and the left-ear variable. The black points represent the data for which the left-ear stimulus was fixed and the right ear was variable. DR indicates dynamic range.

be interpreted as indicating that the right ear was louder, and points falling above as indicating that the left ear was louder. A triangle was plotted when a value could not be estimated due to the necessity for the variable stimulus to exceed MAL levels. This occurred on one pair for IBK and two pairs for ICI.

Three values were calculated from the interaural loudness-balancing task. The first two measures were intended to be representative of asymmetries in loudness growth between the ears. The first measure was the root-mean-square (RMS) error of each data point (in %DR) from the line of equality (intercept = 0, slope = 1). In addition, multiple RMS measures were made by calculating the RMS of lines of different intercepts (in 1% steps; slope = 1). The minimum RMS value of this process was the second measure. The third measure was the intercept of the line (slope = 1) that provided the minimum RMS value, which was intended to be representative of whether one ear was generally louder than the other. Contrary to the hypothesis, there was no relationship between NoSπ thresholds and the RMS error from the line of equality [$F_{1,12} = 0.81$, $p = 0.39$] or NoSπ thresholds and the minimum RMS error [$F_{1,12} = 0.024$, $p = 0.88$]. There was also no relationship between NoSπ thresholds and the absolute value of the intercept at which the minimum RMS error occurred [$F_{1,12} = 1.19$, $p = 0.30$].

In light of the finding of a relationship between NoSo thresholds and DR_{diff}, the relationship between symmetry of loudness growth between ears and NoSo thresholds was of interest. However, there was no significant relationship between NoSo thresholds and the RMS error from the line of equality [$F_{1,12} = 0.0$, $p = 0.98$] or NoSo thresholds and the minimum RMS error [$F_{1,12} = 0.14$, $p = 0.71$]. There was also no relationship between NoSo thresholds and the absolute value of the intercept at which the minimum RMS error occurred [$F_{1,12} = 0.029$, $p = 0.87$]. Furthermore, no relationship was found between DR_{diff} and the RMS error from the line of equality [$F_{1,12} = 0.043$, $p = 0.84$], the minimum RMS [$F_{1,12} = 0.095$, $p = 0.76$], or the absolute value of the intercept at which the minimum RMS error occurred [$F_{1,12} = 0.48$, $p = 0.50$].

Effect of ITD JNDs • NoSπ thresholds were examined as a function of ITD JNDs. The within-participant relationship between ITD JNDs and NoSπ thresholds was not significant [$F_{1,14} = 4.26$, $p = 0.058$]. Furthermore, when IBP was removed from the dataset, the relationship between ITD JNDs and NoSπ thresholds was no longer near significant [$F_{1,12} = 1.00$, $p = 0.34$].

The between-participant relationship between ITD JNDs and NoSπ was also not significant [$F_{1,6} = 4.59$, $p = 0.076$]. Figure 5 shows the between-participant relationship between ITD JNDs and NoSπ thresholds. Each data point represents the average NoSπ threshold for a participant as a function of the participant-average ITD JND.

Interaural Time Difference Just-Noticeable Differences

Figure 6 shows ITD JNDs for each place of stimulation for each participant individually. The mean ITD JND was 282 µsec (SD = 232). There was no effect of place on ITD JNDs [$F_{2,20} = 1.65$, $p = 0.22$].

Effect of DR at 100 pps • The left and middle panels of Figure 7 show the relationship between ITD JNDs and DR_{sml}, and ITD JNDs and DR_{lrg}, respectively. Similar to NoSπ thresholds, ITD JNDs were significantly lower at stimulation sites with larger DR_{sml} [$F_{1,20} = 10.14$, $p = 0.0047$]. In addition, stimulation sites with larger DR_{lrg} and DR_{avg} had significantly lower ITD JNDs [DR_{lrg}: $F_{1,20} = 8.89$, $p = 0.0074$; DR_{avg}: $F_{1,20} = 10.85$, $p = 0.0036$]. It can be seen in Figure 7 that the relationship between DR and ITD JNDs did not appear as consistent as the relationship between DR and NoSπ thresholds (Fig. 3). That is, there were a number of participants who did not show better ITD JNDs with larger DRs. DR_{sml} and DR_{lrg} were only significant when the other was not included in the model. The finding that both DR_{sml} and DR_{lrg} were significant in predicting ITD JNDs can be explained by the fact that the relationship between DR_{left} and DR_{right} was significant [$F_{1,20} = 20.06$, $p = 0.00023$]. The effect of DR_{avg} remained significant when IBP and ICA were removed from the analysis [DR_{avg}: $F_{1,16} = 6.39$, $p = 0.022$]. The effect of DR_{sml} on ITD JNDs was significant when DR was calculated using MALs at 100 pps [DR_{sml}: $F_{1,18} = 4.42$, $p = 0.0498$]. However, the effect of DR_{lrg} and DR_{avg} was no longer significant when DR was calculated using MALs at 100 pps [DR_{lrg}: $F_{1,18} = 2.49$, $p = 0.13$; DR_{avg}: $F_{1,18} = 4.15$, $p = 0.056$]. The effect of DR_{diff} on ITD JNDs was not significant [$F_{1,20} = 0.13$, $p = 0.72$].

Effect of THR and *C* Levels at 100 pps • ITD JNDs were analyzed as a function of THRs and Cs at 100 pps as shown in Table 6. Only the relationship between C_{diff} and ITD JNDs was significant [$F_{1,20} = 9.82$, $p = 0.0052$], a finding that had not been predicted. In the right-hand panel of Figure 7, it can be seen that ITD JNDs were poorer with larger C_{diff} in some of the participants. The relationship between ITD JNDs and C_{diff} remained significant when ICA was removed from the analysis [$F_{1,18} = 5.56$,

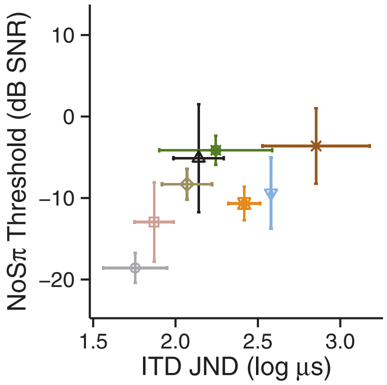

Fig. 5. Dichotic signal detection thresholds as a function of ITD JNDs (in $\log_{10}$ µsec). There is one point per participant. Error bars show SDs. ITD indicates interaural time difference; JNDs, just-noticeable differences.

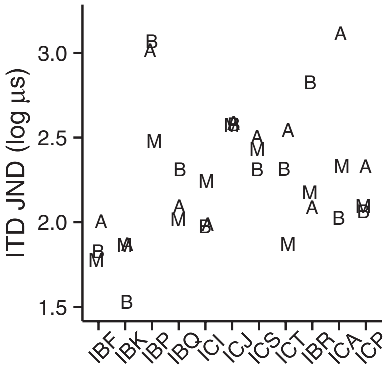

Fig. 6. ITD JNDs (in $\log_{10}$ µsec) for each participant at an A, M, and B stimulation site. A indicates apical; B, basal; ITD, interaural time difference; JNDs, just-noticeable differences; M, medial.

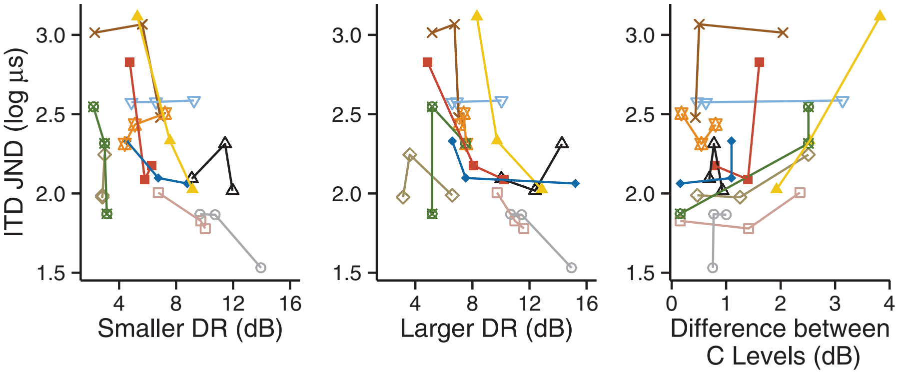

Fig. 7. ITD JNDs (in $\log_{10}$ µsec) as a function of the smaller DR (dB) of the two ears (left). ITD JNDs as a function of the larger DR (dB) of the two ears (middle). ITD JNDs as a function of the difference between *C* levels (dB) between the left and the right sides (right). JNDs of three places of stimulation per participant are grouped by a conjoining line, symbol, and color. DR indicates dynamic range; ITD, interaural time difference; JNDs, just-noticeable differences.

$p = 0.030$]. When both $\mathrm{DR}_{\mathrm{avg}}$ and C_{diff} were included as effects in the model predicting ITD JNDs, both effects were significant [$\mathrm{DR}_{\mathrm{avg}}$: $F_{1,19} = 8.92$, $p = 0.0076$; C_{diff}: $F_{1,19} = 7.93$, $p = 0.011$].

DISCUSSION

In this study, we examined whether monaural hearing measures could explain some of the variance in binaural sensitivity across different stimulation sites in bilateral CI users. A relationship between the monaural and binaural measures could suggest that limitations at the auditory periphery affect binaural hearing in listeners with CIs. Loudness balancing and centering were conducted under the assumption that differences in loudness and the perception of centered images could affect binaural sensitivity across stimulation sites (Domnitz & Colburn 1977; Dietz et al. 2013). In addition to DR and amplitude modulation detection, symmetry in loudness growth between the left and the right ears was examined. Binaural measures included dichotic signal detection (NoSπ) and ITD discrimination. The influence of monaural measures and symmetry in loudness growth on diotic signal detection (NoSo) was also examined.

Diotic Signal Detection

It was expected that monaural encoding of intensity could affect diotic signal detection because the diotic signal detection task required the listener to detect characteristics of the temporal envelope of the stimuli to detect the presence of the tone. It was hypothesized that diotic signal detection would be related to the larger DR or better amplitude modulation detection thresholds of the two ears, because the information necessary to do the task should be more accessible in that ear. No relationship was found between diotic signal detection and modulation detection thresholds (or the difference between modulation detection thresholds of each ear). Also, no relationship was found between diotic signal detection and the larger DR or smaller DR of the two ears. It was assumed that larger DRs would give rise to better diotic signal detection, but this did not necessarily have to be the case. In some cases, DRs may be large because listeners can hear sounds at very low current levels. In such cases, acoustic signals would be mapped to lower loudness levels, which could result in poorer diotic signal detection, as auditory discrimination performance of CI listeners tends to degrade at lower stimulation levels (Chatterjee & Yu 2010). However, diotic signal detection thresholds were not found to be predicted by either the larger or smaller DR or modulation detection threshold.

TABLE 6. ***F* values ($F_{1,20}$) and *p* values of the relationships between THRs/stimulation levels (*C*s) and ITD JNDs**

	ITD JNDs
$\mathrm{THR}_{\mathrm{sml}}$	$F = 2.95, p = 0.10$
$\mathrm{THR}_{\mathrm{lrg}}$	$F = 2.70, p = 0.12$
$\mathrm{THR}_{\mathrm{avg}}$	$F = 3.28, p = 0.084$
$\mathrm{THR}_{\mathrm{diff}}$	$F = 0.52, p = 0.48$
C_{sml}	$F = 0.24, p = 0.63$
C_{lrg}	$F = 1.64, p = 0.21$
C_{avg}	$F = 0.81, p = 0.38$
C_{diff}	$F = 9.82, p = 0.0052$

ITD, interaural time difference; JND, just-noticeable difference; THRs, thresholds.

The results showed that diotic signal detection thresholds were worse when there was a greater difference between the DRs of the two ears (Fig. 2). In other words, variability across stimulation sites was not related to the size of the DR but rather the difference between the DRs of the two ears. This suggests that when there were discrepancies between the DRs, this resulted in either masking between the two ears or a lack of a bilateral benefit (i.e., lack of better performance in a bilateral condition than with either ear alone). In this study, we did not test left and right monaural signal detection (i.e., NmSm). A comparison between monaural signal detection in each ear and diotic signal detection would provide evidence as to whether there was interference or a lack of a bilateral benefit when the DRs differed between the ears.

If the internal representations of the stimuli differ in each ear, this could potentially result in contralateral masking between the ears. While small differences were sometimes found in the loudness growth between the left and right ears of the participants (Fig. 4), no relationship was found between the discrepancies in loudness growth and the difference between the DRs of the left and right ears, or diotic signal detection thresholds. However, the loudness growth measures do not tell us how well subjects were able to follow the modulations of the stimuli when listening to each ear alone. The neural encoding of the stimulus envelope may have been distorted to varying degrees due to neural adaptation and refractoriness (Jeng et al. 2009). Therefore, the neural representations of the envelopes in each ear may have been different from each other, but it is not obvious why this would be associated with a difference between the DRs of the two ears.

Dichotic Signal Detection

All 8 participants whose stimuli were compressed between THR and approximately MALs showed lower dichotic thresholds than diotic thresholds at all places suggesting that they were using binaural processing to detect the signal in the dichotic condition (filled symbols of Fig. 1). The average BMLD of the 8 participants was 9.8 dB, which is comparable with the average BMLD of 9 dB found by Long et al. (2006) and the average BMLD of 8.5 dB (50-Hz bandwidth noise) found by Goupell and Litovsky (2015), but it is larger than the average of 4.9 dB (50-Hz bandwidth noise) found by Lu et al. (2010). The method of temporal envelope calculation in this study was the same as that used by Goupell and Litovsky but was different from the half-wave rectification used by the other studies. However, it appears that relatively large BMLDs can be achieved by CI users with either method. It is not clear why the average BMLD found by Lu et al. was smaller than the BMLDs of the other studies, but it may be due to the particular listeners in that study as the sample size was small.

It was expected that dichotic signal detection would be related to the smaller DR or poorer amplitude modulation detection thresholds of the two ears, because the ability to use interaural differences for signal detection relies on the listener making use of information from both ears. Similar to diotic signal detection, no relationship was found between dichotic signal detection and amplitude modulation detection. Amplitude modulation detection was examined at a low percentage of the DR, while the diotic and dichotic signal detection stimuli varied across the DR, which may have contributed to the lack of a relationship between modulation detection thresholds and signal detection thresholds because somewhat different neural populations were presumably involved with the two sets of stimuli. Furthermore, it is possible that a relationship exists between diotic or dichotic signal detection and amplitude modulation detection thresholds, but we were unable to detect this relationship due to limitations in our sample size.

Dichotic signal detection was worse when the smaller DR of the two ears was relatively small (Fig. 3). It has been suggested that smaller DRs are related to poor neural survival (Kawano et al. 1998; Bierer & Nye 2014). For CI users, there can be degeneration of peripheral processes of neurons and loss of spiral ganglion cells (Fayad & Linthicum 2006). It has been estimated through histological evaluations of human temporal bones with CIs that spiral ganglion neural survival is on average 25% of what it is in normal human temporal bones, with wide variability between individuals (Pfingst et al. 2011). Kawano et al. (1998) found spiral ganglion cell survival in human temporal bones to positively correlate with DR within some individuals. It would be expected that poor neural survival would make it such that a larger spread of current is needed to achieve sufficient loudness (Cohen et al. 2006). With poorer survival, the likelihood of stimulating peripheral neural fibers on the left and right, which provide input to the same central binaural processing units would be reduced. This would likely be the case regardless of whether there is poor neural survival on one or both sides. Therefore, this could explain why dichotic signal detection thresholds were predicted by the smaller of the two DR values. A similar explanation of the relationship between DR and dichotic signal detection thresholds could be provided by the existence of fibrous tissue and bone growth in the cochlea, which has been found in implanted cochleae and which may impede the electrical current from the neural elements (Fayad et al. 2009; Kawano et al. 1998).

The participants who were tested at lower levels of stimulation (stimuli compressed using approximately COM levels; unfilled symbols of Fig. 1) showed smaller BMLDs compared with the participants whose stimuli were presented using higher levels. Compared with single-electrode pair stimulation, multielectrode pair stimulation requires lower levels per electrode to maintain comfortable loudness due to across-channel loudness summation (Galvin et al. 2014). This suggests that part of the reason that listeners with CIs fail to show binaural release from masking with multielectrode stimulation may be that interaural information is less salient for each individual electrode. It would be informative to determine whether listeners with CIs can demonstrate BMLDs for single-electrode pair stimulation using the levels of stimulation needed for their clinical maps, which are intended for multielectrode stimulation.

No relationship was found between symmetry in loudness growth between the left and right ears and dichotic signal detection thresholds despite some participants showing small but reliable deviations in loudness growth between the ears (Fig. 4). It may be that differences in loudness growth between the ears affect binaural hearing but we were unable to show it by comparing the performance between the loudness growth and dichotic signal detection measures. The finding of a relationship between diotic signal detection thresholds and differences between the DRs of the two ears suggest asymmetries between the ears that one would expect could affect dichotic signal detection as well.

Interaural Time Difference Just-Noticeable Differences

A relationship was found between ITD JNDs and DR within participants similar to what was found for dichotic detection thresholds (left and middle panels of Fig. 7). DR may reflect neural survival and thus account for ITD JNDs. When there is a high level of neural survival, there would likely be stimulation to a greater number of interaurally matched neural fibers. However, the finding that both ITD JNDs and dichotic signal detection thresholds are related to DR does not necessarily mean that the same mechanism is responsible for each relationship. It should be noted that the relationship between ITD JNDs and DR appeared less consistent than the relationship between dichotic signal detection thresholds and DR in that a number of participants did not show a relationship between ITD JNDs and DR. A recent study by Ihlefeld et al. (2015) also found a relationship between ITD discrimination performance and a monaural measure, namely, rate discrimination in CI users. In that study a relationship was found between ITD discrimination and monaural rate discrimination on the poorer performing side supporting the authors’ hypothesis that a common mechanism, which they suggested might be centrally located, limited ITD and rate discrimination at higher pulse rates.

No relationship was found between ITD JNDs and dichotic signal detection thresholds across stimulation sites despite the previous finding of a relationship between the two measures across participants (Goupell & Litovsky 2015). Furthermore, a significant relationship between ITD JNDs and dichotic signal detection thresholds across participants was not replicated in this study (Fig. 5). That no relationship was found between the two binaural measures across participants may be related to the fact that Goupell and Litovsky (2015) found a correlation using the site out of two which produced the best ITD JNDs. In the present study, the measure of performance was the average of three sites such that the across-site variability may have made the relationship across participants more difficult to observe. It should be noted that ITD is not a cue that most listeners with CIs are able to use with their day-to-day clinical speech processing strategies (Grantham et al. 2007; Aronoff et al. 2010). ITD JNDs in this study may have been different had listeners had ongoing experience with this cue through their CIs.

In addition to a relationship between ITD JNDs and DR, a relationship was also found between the differences in stimulation levels (*C* levels) between ears and ITD JNDs (right panel of Fig. 7). This suggests that either low or high *C* levels can result in relatively good ITD sensitivity, but a problem occurs when the *C* levels differ. One explanation for this result is that differences in *C* levels between the ears reflect a difference in the shape or width of current spread between the ears. Cohen et al. (2006) found that higher comfortable levels were associated with larger widths of excitation. Furthermore, both higher comfortable levels and larger widths of excitation have been associated with electrodes that are farther from the neural elements (Parkinson et al. 2002; Saunders et al. 2002; Cohen et al. 2003). Therefore, differences between the ears in *C* levels could have resulted in differences in current spread between the ears, which could indicate reduced stimulation to interaurally matched neural fibers.

The reasons for limitations in binaural sensitivity at individual stimulation sites are likely multifaceted including peripheral limitations such as neural survival, as well as asymmetries between ears in the shape and spread of excitation. The finding of a relationship between binaural sensitivity and DR, as well as between ITD discrimination and the difference in *C* levels between the ears in this study provides some support for this idea. Psychophysical measures made in either ear are limited in their interpretation because the relationships between psychophysical measures and the characteristics at the auditory system of listeners with CIs is complex. However, knowledge of the relationship between monaural measures and binaural hearing sensitivity should provide some insight into why limitations exist in binaural sensitivity at individual stimulation sites. Ideally, these problems can be addressed to provide listeners with CIs better access to binaural hearing.

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