Sound Localization and Interaural Time Sensitivity with Bilateral Cochlear Implants

by

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Abstract

Bilateral cochlear implantation is becoming more common as clinicians attempt to provide better sound-source localization and speech reception in noise for cochlear implant (CI) users. While some improvement over the abilities of monolateral implantees has been documented, bilateral performance for CI users is far from that achieved with normal hearing. Identifying factors that limit bilateral performance has been difficult because little is understood about CI listeners' localization abilities, their sensitivity to interaural cues, and the relationships between them. To better understand bilateral electric hearing, five bilateral CI users' abilities to locate sound sources and their sensitivities to interaural time difference (ITD) were studied in this thesis.

Unlike past studies, monolateral and bilateral performance was recorded before and after exposure to daily, bilateral-CI listening using constant- and roving-level stimuli. For constant-level stimuli, increasing bilateral-listening experience improved all subjects' bilateral performance but degraded two subjects' monolateral performance. Using roving-level stimuli, increasing bilateral-listening experience also improved bilateral performance but did not alter monolateral performance. Our results show that depending on the method of evaluation, the benefit of bilateral CIs over monolateral CI could be overstated for some subjects.

A simple decision model was used to predict subjects' localization performance based on their sensitivity to interaural time and level differences (ITD and ILD) measured through their sound processors. The predicted performance indicated that the measured performance could be accounted for by subjects' ILD sensitivity but not by their ITD sensitivity alone. Poor ITD sensitivity may be one reason that bilateral CI users' localization performance is poor compared to that of normal-hearing (NH) listeners.

To improve ITD sensitivity, a first step is to characterize ITD sensitivity on single, interaural electrode pairs because data in the literature is incomplete. In particular, the dependence of ITD sensitivity on the repetition rate and the number of pulses in the unmodulated pulse trains was studied. Just noticeable difference (JND) of ITD was measured with four subjects on their most ITD-sensitive, interaural electrode pair. At low rate (50 pps), ITD JND improved with increasing number of pulses, indicating integration of ongoing ITD cues. The best ITD JNDs were 85 – 354 μs. Using 800-pps trains, two subjects' ITD JND degraded with increasing number of pulses. Two subjects were insensitive to ITD up to 2 ms for 800-pps trains.

To begin studying the impact of CI processing on ITD sensitivity, ITD JND was also measured using low-rate (50 pps) pulse trains delivered to the external input of the subjects' sound processors. ITD JND improved with increasing number of pulses. While subjects were insensitive to ongoing ITD in unmodulated, high-rate pulse trains delivered to single, interaural electrode pairs, they were sensitive to ongoing ITDs in the low-frequency modulator of high-rate pulse trains in the through-processor case. A next step toward greater understanding of bilateral electric hearing is to fully investigate the degree to which subjects are sensitive to ITD using modulated pulse trains.

The results of this thesis show that there is significant localization benefit with bilateral CIs even though performance is not at the level of NL listeners. Further studies to improve ITD sensitivity may improve localization ability, which will further justify the risks and cost associated with bilateral implantation.

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Finally, above all, I thank God for being my Lord and Savior. Apart from Him, I can do nothing to accomplish this work.

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Chapter 1

Introduction

The discovery of sound sensation elicited by electric stimulation of the ear can be traced back to research done in the 1800s (Volta, 1800). Yet, attempts to restore hearing sensation to the deaf with electric stimulation of the auditory nerve was not published until the late 1950s (Djourno and Eyries, 1957). Today's hearing prosthesis is built on the successes of the research conducted in the 1970s (House and Urban, 1973; Clark et al., 1975; Eddington et al., 1978).

Over the last twenty years, a hearing prosthesis, called a cochlear implant, has emerged as a viable treatment for people with profound hearing loss, who do not benefit from amplification with conventional hearing aids. A cochlear implant is designed to bypass the damaged biological sound transducers in the inner ear. An external sound processor analyzes the acoustic signal from the microphone and encodes stimulation instructions on a RF signal transmitted to an implanted receiver stimulator that produces the electric stimuli. The electric stimuli are sent to the designated electrodes in the implanted electrode array to stimulate different regions of the cochlea.

More than 60,000 individuals worldwide have received a cochlear implant (CI) in one ear (NIH, 2002). Significant levels of speech understanding can be achieved without visual cues by many with a monolateral cochlear implant (Eddington et al., 1997). Improvement in quality of life has also been reported (Mo et al., 2005). However, speech reception in noisy environments and sound localization are poor with one cochlear implant (Eddington et al., 1997; Poon et al., 2001). Common practice in the US is to implant one ear and preserve the other for future advancements in the treatment of hearing loss. In recent years, bilateral implantation has become common in European countries and is increasing in North America. With a cochlear implant in each ear, hearing impaired listeners may benefit from the binaural inputs that may restore some of the information known to be essential for normal-hearing listeners to improve both speech reception in noise and localization of sound sources (Bronkhorst and Plomp, 1988; Zurek, 1992; Bronkhorst, 2000).

While studies on speech reception in noise and sound localization generally suggest that the use of two cochlear implants is better than one, the results are not at the level of normal-hearing listeners for the same tasks (Poon et al., 2001; van Hoesel et al., 2002; van Hoesel and Tyler, 2003; Nopp et al., 2004; Schleich et al., 2004). Information currently provided by two independent implants does not seem to be sufficient to restore all normal-hearing abilities. More effective deliverance of binaural information is needed to maximize the benefit of bilateral implantation. To meet this need, two approaches are taken in this thesis to gain a better understanding of bilateral electric stimulation. The first part of this thesis focuses on sound localization performance with bilateral cochlear implants and the potential use of interaural cues after extended bilateral listening. The second part focuses on how implant listeners' sensitivity to interaural time difference (ITD) imparted in the basic stimulation waveform can be influenced by stimulation parameters, such as repetition rate and the number of pulses in the electric pulse trains. We are interested in ITD because it is an important binaural cue to which bilateral cochlear implant listeners have shown poor sensitivity compared to normal-hearing listeners (van Hoesel et al., 1993; van Hoesel and Clark, 1997). The results of this thesis form an important basis for future development of bilateral cochlear implants to restore binaural advantages to hearing impaired listeners.

The reminder of this introduction will review the important cues for binaural hearing, the binaural auditory pathway, and the cochlear implant device. Considerations for the use of two independent sound processors are discussed. The objectives of this thesis will also be stated.

I. Interaural Cues

The primary cues that normal-hearing listeners experience with two ears are the spectral content, the interaural time difference (ITD), and the interaural level difference (ILD) of the sound. They are determined by the frequency content of the sound and the location of the external sound source relative the listener's head. Studies have shown that spectral information, such as spectral notches at high frequencies, are mainly used for identifying source elevation (Middlebrooks and Green, 1991). For sound sources on the horizontal plane with zero degree elevation, ITD and ILD are the primary cues used by normal-hearing listeners. A detailed review of binaural phenomena and spatial hearing can be found in Durlach and Colburn (1978) and Blauert (1997). Given that this thesis focuses on sound localization on the horizontal plane with bilateral cochlear implant listeners, whose devices only encode frequencies between 250 Hz to 6000 Hz, our focus will mainly be on ITD and ILD cues for sound localization.

The ITD is the difference in the arrival time of a sound reaching the two ears. For a sound source directly in front of the listener, the ITD is zero because the sound arrives at the two ears at the same time. For a source on one side of the listener, the ITD between the ears can be as much as 700 μs depending on the size of the listener's head. The ILD is the difference in the intensity or the sound pressure level of the sound between the ears. For a sound source directly in front of the listener, the ILD is zero, assuming a symmetrical head and pinnae. Due to the different amount of diffraction of low- and high-frequency sounds, the ILD for a source on the one side of the listener can range from a negligible amount to as much as 20 dB for low- and high-frequency signals, respectively (Shaw, 1974). The ability to use ITD and ILD cues is the basis for a normal-hearing listeners' ability to localize sound sources and to detect and discriminate sounds in noisy environments (Bronkhorst and Plomp, 1988; Middlebrooks and Green, 1991; Wightman and Kistler, 1992; Zurek, 1992; Bronkhorst, 2000; Macpherson and Middlebrooks, 2002).

Normal-hearing listeners' abilities to sense small changes in ITD and ILD are typically measured with headphones. Without reflections from the environment and the pinna, stimuli presented over headphones are usually not externalized, meaning that the sound is heard inside the head. Without externalization, manipulation of ITD and ILD cues can still move the perceived location of the sound inside the head. This is called lateralization. The use of headphone stimulation allows the experimenter to control the ITD and ILD cues in the stimuli separately and to measure the smallest change in these binaural cues that can be detected by the listeners. The smallest change in ILD that normal-hearing listeners can reliably detect is about 1 dB for various stimuli (Durlach and Colburn, 1978). Different listeners' thresholds range from about 0.5 dB to 2 dB, and there are only small differences between different kinds of signals. On the other hand, ITD sensitivity is greatly dependent upon the stimuli used. The smallest change in ITD that normal-hearing listeners can reliably detect can be as small as 10 μs using broadband stimuli (Klumpp and Eady, 1956). With tones, the just noticeable difference (JND) of ITD can range from 11 μs to 75 μs for tones below 1300 Hz (Klumpp and Eady, 1956; Wright and Fitzgerald, 2001). Above 1300 Hz, listeners are not able to discriminate ITDs in the cycle-to-cycle disparities present in the fine-structure of the high frequency tones (Klumpp and Eady, 1956; Zwislocki and Feldman, 1956). However, ITDs in the time-varying amplitude modulation or envelope of a high-frequency tone can be detected for relatively low modulation frequencies. For modulation frequency below 500 Hz, normal-hearing listeners' ITD JNDs with amplitude-modulated high frequency stimuli, such as sinusoidal amplitude modulation (SAM) and transposed stimuli, are in the range of 80 μs to 300 μs (Bernstein and Trahiotis, 1994; Bernstein, 2001; Bernstein and Trahiotis, 2002). ITDs in the modulation of high-frequency stimuli cannot be detected for modulation above 500 Hz.

In this thesis, we will focus on the sensitivity of ITD with bilateral cochlear implants. We are interested in ITD because there are great disparities between ITD sensitivity of bilateral cochlear implant listeners using simple, unmodulated pulse trains and ITD sensitivity of normal-hearing listeners using pure tones (van Hoesel et al., 1993; van Hoesel and Clark, 1997). Typical ITD JNDs for bilateral cochlear implant listeners using unmodulated pulse trains are similar to those of normal-hearing listeners using amplitude-modulated, high-frequency stimuli.

II. Binaural Auditory Pathway

When a sound wave reaches the ear of a normal-hearing listener, it vibrates the eardrum. The middle ear ossicles conduct this mechanical energy to the fluid-filled inner ear (cochlea) resulting in traveling waves traveling from the base to the apex of the cochlea. Since the cochlea is tonotopically organized, the high-frequency components of the incoming wave excite the basilar membrane near the base of the cochlea while the low-frequency components excite the basilar membrane near the apex. Hair cells on the basilar membrane convert the mechanical vibration into auditory nerve electrical discharges. The electrical signals are then processed by the auditory brainstem and the auditory cortex.

Major nuclei in the auditory brainstem for processing of binaural inputs from each cochlea are shown in a simplified schematic illustration in Figure 1. The ascending auditory pathway begins with the auditory nerve innervating the cochlear nucleus (CN). The outputs of the ipsilateral and contralateral CN converge on the cells in the ipsilateral medial superior olive (MSO). Studies in animal models have shown that the cells in MSO are highly sensitive to changes in ITD (Goldberg and Brown, 1969; Yin and Chan, 1990) suggesting that this structure probably plays an important role in the processing of ITD. Another nucleus in the brainstem that receives binaural inputs is the lateral superior olive (LSO). Each LSO receives inputs from the ipsilateral CN and the contralateral CN through the ipsilateral medial nuclei of the trapezoid body (MNTB). Recordings from cells in cat LSO have shown sensitivity to changes in ILD (Boudreau and Tsuchitani, 1968; Caird and Klinke, 1983). The LSO is commonly thought to be involved in ILD processing although some cells are sensitive to the ITD in low-frequency envelopes of high-frequency stimuli. MSO and LSO project to the inferior colliculus (IC). Studies in cats have shown that many cells in the IC are sensitive to changes in both ITD and ILD

(Kuwada and Yin, 1983; Yin et al., 1987), indicating additional processing of the binaural signals before arriving at the auditory cortex.

From the cochlea to the auditory cortex, frequency tuning is preserved at all levels of the ascending auditory pathway. This frequency tuning is based on the frequency-to-place or tonotopic organization in the cochlea. High frequency components of the incoming sound excite the more basal end of the cochlea while the low frequency components excite the more apical end. Subsequently, a subset of auditory nerve fibers (ANFs) innervating hair cells on the excited portion of the basilar membrane are excited. These ANFs relay the frequency-specific information from the cochlea to the CN that results in information flowing to the MSO, LSO, IC, and eventually the auditory cortex by activating frequency-specific regions in those nuclei along the pathway. Hence, there is a connection between the "place" of excitation in the cochlea and the "places" of activation in the brainstem and the cortex.

For binaural processing, data in the literature suggest that the place of stimulation in the two ears should be matched for maximal binaural sensitivity. For example, the MSO cells in an animal model respond best to ipsilateral and contralateral stimuli with similar frequencies (Guinan et al., 1972). In terms of human psychophysical performance, studies using SAM tones showed that normal-hearing subjects' ITD sensitivity degraded as the difference in carrier frequency between the two ears increased (Henning, 1974; Nuetzel and Hafter, 1981). These data suggest that cells in the brainstem are less likely to process signals from frequency-mismatched places in the two cochleae. For bilateral cochlear implants, pairing of electrodes between the two ears will be crucial for providing frequency-matched information to the brainstem for best binaural sensitivity. We will discuss this in Section V.

III. The Cochlear Implant

When sound reaches the ear of a normal-hearing listener, it undergoes a series of transformations through the outer ear, the middle ear, the inner ear, and the brainstem before the signal ultimately reaches the auditory cortex. Most hearing impaired listeners suffer from a sensory deficit, such as the loss of hair cells. The amplification provided by conventional hearing aids can partially compensate for this loss in many cases of mild or severe impairment. In the case of profound impairment, residual function is not sufficient for hearing aids to provide much help. A cochlear implant is designed to bypass these hair cells that translate the mechanical energy on the basilar membrane into spike activity on the auditory nerve by stimulating the auditory nerve electrically.

Figure 2 illustrates the general scheme of a multi-channel cochlear implant. The cochlear implant (CI) system consists of a microphone, a sound processor, a headpiece (radio frequency transmitter), an implanted cochlear stimulator (radio-frequency receiver), and an array of electrodes that is surgically implanted into the inner ear of a deaf person. The external sound processor processes the signal from the microphone to produce stimulation. Stimulation commands are encoded in the modulation of a radio frequency (RF) signal sent to the headpiece (HP) and inductively transmitted to the implanted cochlear stimulator (ICS) underneath the skin. The ICS controls the stimulation at each electrode. Nearby auditory nerve fibers are excited by current from these electrodes, and the resulting patterns of spike activity are transmitted up the auditory pathway (Figure 1).

Figure 3 illustrates the continuous-interleaved-sampling (CIS) processing strategy that is commonly used in a sound processor. The acoustic signal from the microphone is pre-emphasized before band-pass filters are used to split it into a number of analysis channels (16 in the systems used by our subjects). The signal in each analysis channel is rectified and low-pass filtered to extract the envelope. The amplitude of each channel's signal is then compressed by a nonlinear mapping function before amplitude modulating a high-frequency (~ 2 kpps) pulse train. The output of each channel drives a different electrode.

Because the carrier pulse trains are interleaved across channels, at any moment in time, only one electrode is being stimulated. Performance with interleaved stimulation is reported to be significantly better than performance with simultaneous stimulation (Wilson et al., 1991) because the amount of interaction of current fields produced by adjacent electrodes is greatly reduced (Favre and Pelizzone, 1993).

Each subject in our study has an array of 16 electrodes implanted in both cochleae. The sound processor takes advantage of the cochlear's tonotopic organization by mapping the connection of analysis channels to electrodes according to the center frequency of each channel's band-pass filter. Thus, higher frequency analysis channels are mapped to more basal cochlear positions and lower frequency channels more apically. This organization is designed to activate similar subjects of auditory nerve fibers and the corresponding brainstem neurons as would have been activated in normal hearing.

IV. ITD and ILD Cues with Two Asynchronous Cochlear Implants

With the CIS processing strategy, information about the incoming sound is represented in the modulation of the amplitude of the high-frequency pulse trains. With one cochlear implant in each ear, binaural cues like ITD and ILD associated with an external sound source will only be represented in the amplitude modulation of high-frequency pulse trains. Also, because the two implants operate independently, the stimulation in one cochlea is not synchronized with the stimulation in the other cochlea on a pulse-by-pulse basis.

Within an analysis channel, the amplitude of the current pulses represents the instantaneous intensity or level of the signal. For a matched pair of analysis channels (one left-ear, one right-ear, with identical bandpass filter characteristics), ILD is conveyed by differences in the effective stimulus amplitude delivered to their respective electrodes. Studies have shown that bilateral CI listeners are sensitive to differences in the level of the unmodulated pulse trains when a single interaural electrode pair is stimulated (van Hoesel et al., 1993; Lawson et al., 1998a; Lawson et al., 1998b; Lawson et al., 2001; van Hoesel and Tyler, 2003). Bilateral CI listeners are also sensitive to ILD imparted in the modulation of high-frequency pulse trains with stimulation through the processors (Laback et al., 2004). The ILD JNDs measured in all of these studies were about 1 dB, which is similar to normal-hearing listeners' ILD sensitivity.

Temporal information within an analysis channel is limited by the cutoff of the low-pass filter used in the envelope detection stage. Depending on the device manufacturers' specification, the cutoff of the low-pass filter may range from 250 Hz to 1500 Hz, and some devices may have different low-pass filter cutoffs for different analysis channels. For any matched pair of analysis channels, only the ITD information in the envelopes of the bandlimited signals remains after CIS processing. Limited available data indicate that bilateral CI listeners' sensitivity to ITD in the modulation of high-frequency pulse trains is poor when a single pair of interaural electrodes is stimulated (Lawson et al., 1998a; Lawson et al., 2001; Nam and Eddington, 2003; van Hoesel and Tyler, 2003). For stimulation through bilateral CI processors, subjects' ITD sensitivity is also poor compared to that of normal-hearing listeners using noise stimuli (Laback et al., 2004). If ITD sensitivity is not at the level of normal-hearing listeners' ITD sensitivity with ITD imparted in the modulation waveforms of high-frequency pulse trains, other means of delivering ITD information with bilateral cochlear implants need to be investigated. For example, ITD can be encoded in both the modulator and the carrier or only in the carrier of the pulse trains. Characterization of bilateral CI users' sensitivity to ITD in the carrier of unmodulated pulse trains is reported in this thesis.

V. Mapping of Analysis Channels to Electrodes with Bilateral Cochlear Implants

Physiological and psychophysical data suggest that binaural sensitivity decreases as the difference in interaural spectral content increases (Guinan et al., 1972; Henning, 1974; Nuetzel and Hafter, 1981; Bonham and Lewis, 1999). This means it is important for the outputs of corresponding left and right analysis channels to drive electrodes that are at similar cochleotopic positions.

One way to assess the location of an electrode in the cochlea is by the pitch sensation it elicits when stimulated. If the separation between electrodes is sufficient (0.75 mm in some patients), different pitch sensations are elicited when an identical signal is used to stimulate them (Eddington et al., 1978). For example, an unmodulated pulse train with 850 pulses per second (pps) repetition rate will evoke a higher pitch sensation when stimulating a basal electrode than when stimulating a more apical electrode. Hence, in order to select an interaural electrode pair to be driven by a matched interaural pair of analysis channels, it is important that the two electrodes (left and right) elicit similar pitch sensations in response to electric stimulation.

Many studies with bilateral cochlear implants have used the results of pitch-matching tests to assign analysis channels to electrodes (van Hoesel et al., 1993; Lawson et al., 1996; Lawson et al., 1998b; Long et al., 1998; Lawson et al., 2001; van Hoesel et al., 2002; Long et al., 2003; van Hoesel and Tyler, 2003). However, Long et al. (2003) found that pitch-matched interaural electrode pairs are not guaranteed to be optimal for ITD sensitivity. In Long et al. (2003), three sets of ITD sensitivity measurements were made in one subject with three electrodes in the right ear. For each set of measurements, one electrode in the right ear was paired with each of the eight electrodes in the left ear. One set of ITD sensitivity measurement showed that two of the pitch-indiscriminable pairs were not as sensitive to ITD as a pitch-discriminable pair. Long et al. (2003) also re-examined two bilateral CI subjects' ITD sensitivity in van Hoesel and Clark (1997) and found similar disagreements between the pitch-matched and the most binaurally sensitive electrode pairs.

While pitch comparisons may help find interaural electrode pairs that provide a degree of binaural sensitivity, Long et al (2003) suggests that they are not adequate for finding interaural electrode pairs with maximum binaural sensitivity. In an effort to provide maximum binaural sensitivity to our bilateral cochlear implant subjects, three measures of binaural sensation were used for the pairing of interaural electrodes (Eddington et al., 2003). The three measures are interaural pitch matching, fusion, and ITD sensitivity. The degree to which a single or fused auditory image can be created inside the head using simultaneous stimulation of an interaural electrode pair is an indication for integration of binaural stimulation. The subjects of this study were presented with interaural electrode pairs and asked to describe and draw the size(s) and location(s) of the auditory image(s) on paper. The responses were then categorized by the degree to which a sensation was fused. Finally, the ability to lateralize with ITD in the simultaneous stimulation of an interaural electrode pair was a third measure used in this study's subjects to assess binaural integration of two stimuli across the ears. Using the interaural electrode pairs producing fused sensations, the just noticeable difference in ITD was measured.

The pairing of interaural electrodes for all five subjects in our study were determined based on their results from the pitch, fusion and ITD measure. A detailed description of the procedures and the results for three of the five subjects are reported in Eddington et al. (2003). Given that all of our subjects were monolateral CI users prior to receiving the second implant, the analysis-channel to electrode assignment was not changed in the first-implanted ear. Hence, the results for the three measures were used to constrain which of the newly implanted electrodes should be paired with the first-implanted electrodes for use with bilateral sound processors. Table I shows the final mapping of analysis channel to electrode that was used by each subject in every-day life and in the studies described here. An 'x' indicates that a channel was not connected to an electrode in that ear.

Table I: Mapping of Analysis Channels to Electrode

	C092		C105		C109		C120		C128	
Analysis	Electrode		Electrode		Electrode		Electrode		Electrode	
Channel	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
1	1	X	1	X	1	1	X	X	1	1
2	2	1	2	1	2	2	2	1	1	2
3	3	2	3	2	3	3	3	2	1	3
4	4	3	4	3	4	4	4	3	2	4
5	5	4	5	4	5	5	5	4	3	5
6	6	5	6	5	6	6	6	5	4	6
7	7	6	7	6	7	7	7	6	5	7
8	8	7	8	7	8	8	8	7	6	8
9	9	8	9	8	9	9	9	8	7,8	9
10	10	9	10	9	10	10	10	9	9	10
11	11	10	11	10	11	11	11	10	10	11
12	12	11	12	11	12	12	12	11	11	12
13	13	12	13	12	13	13	13	12	12	13
14	14	13	14	13	14	14	14	13	13	14
15	15	14	15	14	15	15	15	14	14,15	15
16	16	15	16	15,16	16	16	16	15	X	X

VI. The Main Goals of the Thesis

The work in this thesis is directed toward a better understanding of binaural hearing with electric stimulation and future development of bilateral cochlear implants to restore binaural advantages to hearing-impaired listeners.

The first part of this thesis is a longitudinal study of sound-localization performance with monolateral and bilateral cochlear implants. The goals are:

1. To evaluate performance of one vs. two implants in a reverberant space with constant- and roving-level stimuli,
2. To examine the impact of bilateral listening experience on localization performance, and
3. To relate the subjects' ITD and ILD sensitivity to their bilateral localization performance.

Localization performance was measured using the sound processors worn by the subjects in daily life.

The second part of this thesis is a characterization of ITD sensitivity with bilateral cochlear implants. The goal is to evaluate how ITD sensitivity can be influenced by stimulation parameters. We chose to examine the effects of number of pulses and repetition rate of unmodulated pulse trains with whole-waveform delay on ITD sensitivity. Establishing the relationships between ITD sensitivity and stimulation parameters of the basic electric stimulus waveform used by cochlear implants is a first step towards identifying effective means for delivering ITD information and factors that limit bilateral CI users' performance.

VII. Overview of the Thesis Document

In this thesis, we characterized the ITD sensitivity and sound localization ability of listeners using bilateral cochlear implants. Chapter 2 reports the longitudinal study of sound localization performance with monolateral and bilateral cochlear implants. Localization performance after extended use of monolateral and bilateral cochlear implants are compared. ITD sensitivity to the stimulus from the center (0°) speaker in the localization task was also measured to examine the potential use of the ITD cue for localization with two independent implants.

Chapter 3 presents a set of experiments, results, and analyses from our study of ITD sensitivity as a function of two stimulation parameters (number of pulses and repetition rate) for stimulation of single, interaural electrode pairs. We also examined the effects of the number of pulses and repetition rate on ITD sensitivity using stimuli through the sound processors as a first step for studying the impact of cochlear implant processing and multichannel stimulation.

The last chapter of this thesis summarizes the results from the two studies and discusses the implications of the results for binaural hearing and the design of sound processing strategies for bilateral cochlear implants.

LIST OF FIGURES

Figure 1: Schematic organization of major nuclei in the ascending auditory pathway from the cochleae through the auditory nerve (AN), cochlear nuclei (CN), medial superior olives (MSO), lateral superior olives (LSO), and medial nuclei of the trapezoid body (MNTB) to the inferior colliculi (IC). SOC = superior olivary complex. [Adapted from Colburn, 1996 and Long, 2000.]

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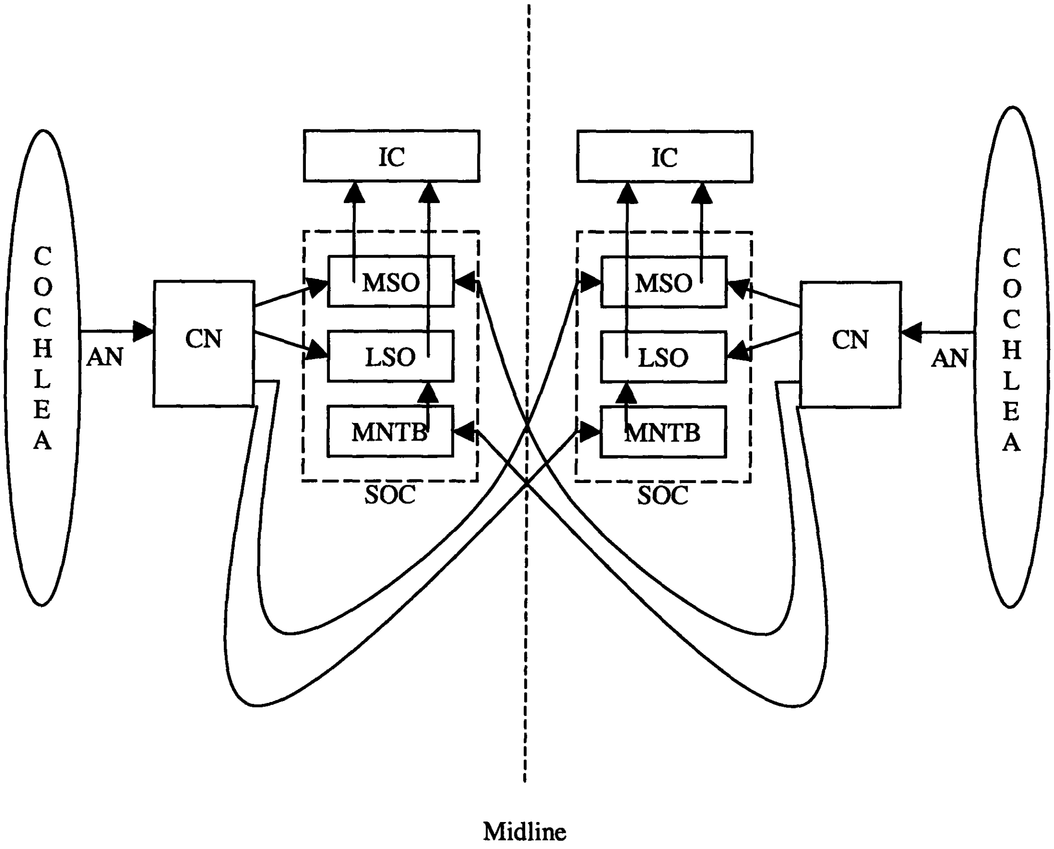

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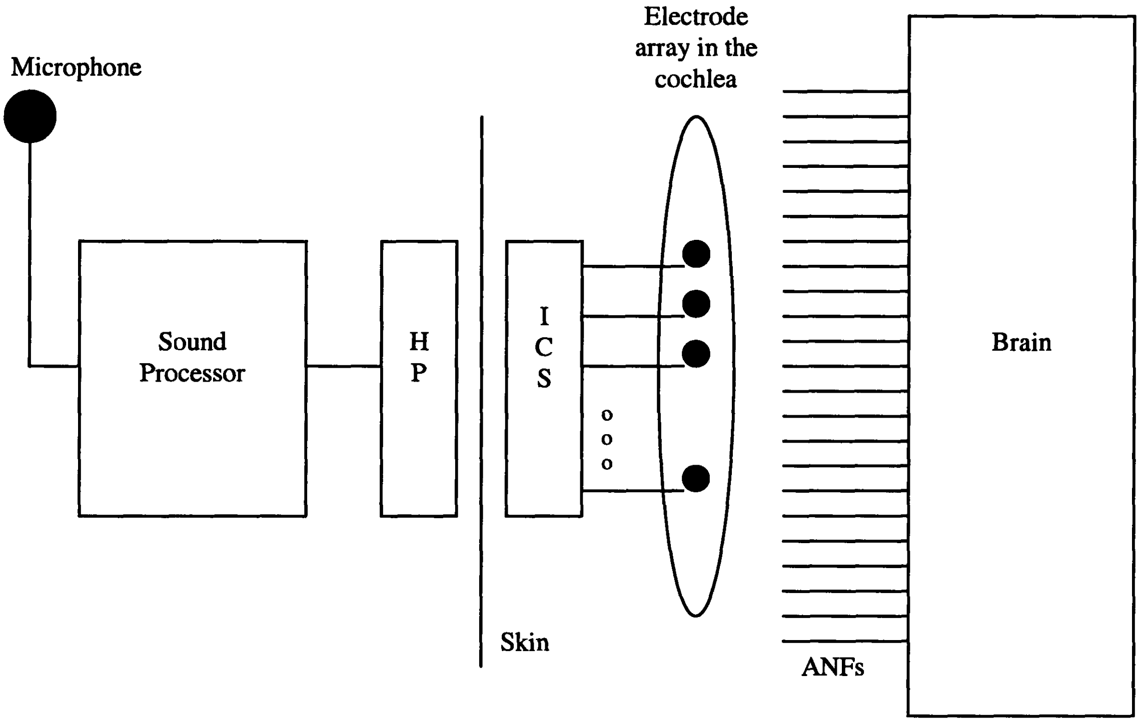

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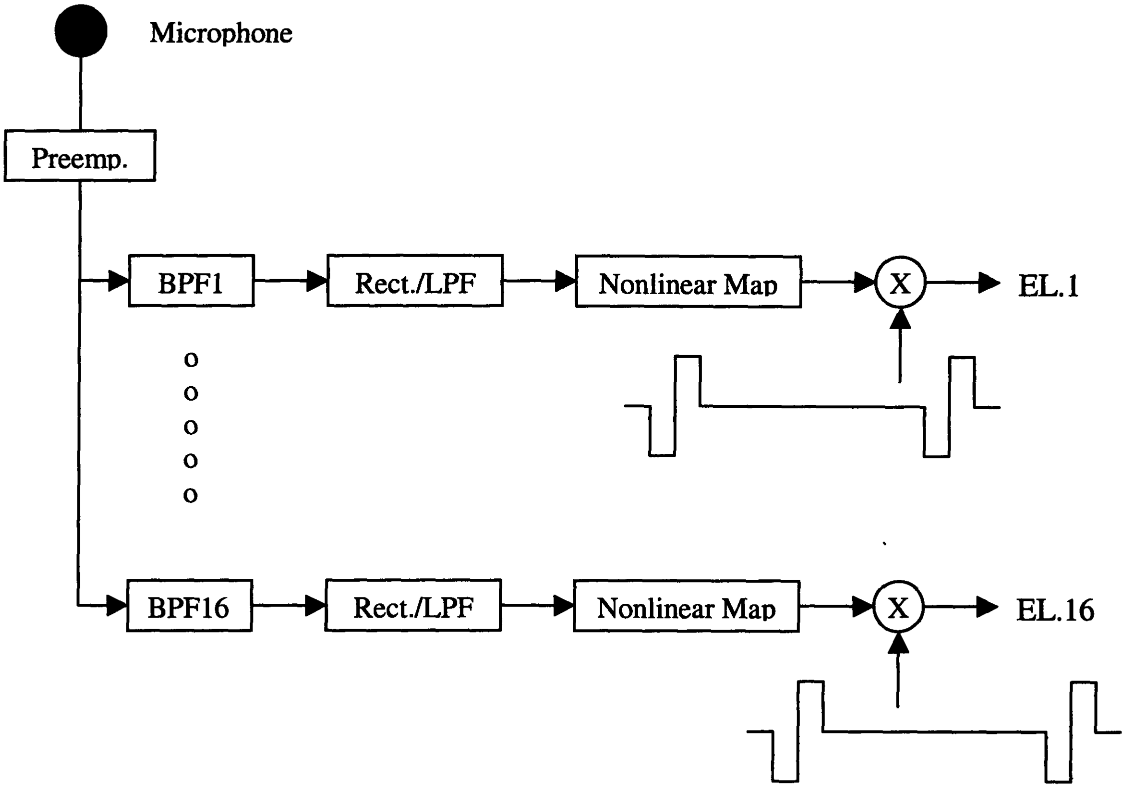

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Chapter 2

Sound Localization and ITD Sensitivity Using Noise Bursts with Monolateral and Bilateral Cochlear Implants

ABSTRACT

Sound localization abilities of five cochlear implant (CI) listeners were tested in a single-wall IAC room with white noise at constant- and roving-stimulus levels. Each subject's head-related impulse responses (HRIRs) were measured in the room for analysis of the interaural cues and to simulate the room environment in a test-booth setting. Sensitivity to interaural time difference (ITD) for four of the five subjects was measured using the simulated 0°-source noise through the external input of the sound processors.

All subjects were monolateral CI users for at least 14 months before receiving the second CI. A uniqueness of this study is that monolateral and bilateral performance was recorded before and after exposure to daily, bilateral-CI listening. Our data show that common methods of bilateral-benefit evaluation in past studies (using only data collected after months of bilateral experience) exaggerated the bilateral benefit for two subjects tested with constant-level stimuli. The exaggerated benefit was caused by degradation in the two subjects' monolateral performance after significant bilateral listening. Bilateral benefit for all subjects was not overstated using roving-level data.

In order to relate subjects' bilateral localization performance and their sensitivity to interaural time and level differences (ITD, ILD), localization performance for the 0°-source was predicted using a simple decision model based on their ITD and ILD sensitivities. The ITD-predicted performance was worse than the measured performance while the ILD-predicted performance was better than the measured and the ITD-predicted

performance. The modeled results suggest that the use of ILD alone can account for subjects' localization performance. However, the subjects were using ILD sub-optimally.

I. INTRODUCTION

Monolateral cochlear implant (CI) listeners have poor sound-localization ability compared to that of normal-hearing listeners with two ears (Gray and Baguley, 1993; Luntz et al., 2002; Poon et al., 2001). With one CI, listeners cannot take advantage of the primary cues, such as interaural time and level differences, used for sound localization by normal-hearing listeners (Durlach and Colburn, 1978; Middlebrooks and Green, 1991; Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002). It is possible that having two CIs, one in each ear, could provide these interaural cues to CI listeners and could lead to an improvement in sound-localization ability. The magnitude of such an improvement will not only determine whether the increased cost and the risks of receiving two CIs are justified, it will also influence the decision of whether or not to preserve an un-implanted ear for potential advancement in cochlear-implant technology, hair-cell regeneration, and other treatments for hearing loss.

A number of studies have measured CI listeners' abilities to localize sound sources with one and two independent CIs (Gantz et al., 2002; Tyler et al., 2002; van Hoesel et al., 2002; van Hoesel and Tyler, 2003; Litovsky et al., 2004; Nopp et al., 2004). All these studies show that on average, the subjects' bilateral performance is significantly better than monolateral performance. However, bilateral-CI performance is far from that achieved with normal hearing. Identifying factors that limit bilateral performance has been difficult. Little is know about the relationship between CI listeners' localization performance and their sensitivity to the interaural cues.

The monolateral and bilateral performance reported in the literature were typically measured after at least one month (and usually months) of bilateral-CI experience. The reported bilateral performance reflects the subjects' sound-localization ability after extended bilateral-CI use. However, the reported monolateral performance may not reflect the subjects' best monolateral-localization ability since it is typically measured by acutely turning off one CI. For those subjects who have used one CI prior to receiving the second CI, they may have developed a monolateral-localization strategy. After extended bilateral experience, these subjects may not be able to switch back from their bilateral-localization strategy to the monolateral-localization strategy on demand. Comparison of monolateral and bilateral performance after months of bilateral experience may not be an appropriate evaluation of the bilateral advantage with two CIs.

In the past studies, the degree to which interaural time and/or level difference cues are used for sound localization with bilateral CIs is unclear. Only van Hoesel et al. (2002) and van Hoesel and Tyler (2003) report measures of their subjects' ability to detect interaural time (ITD) and level difference (ILD) with their subjects' sound-localization results. Even in these studies, different stimulation conditions (e.g. stimulation on single, interaural electrode pair vs. stimulation of multiple, interaural electrode pairs through the CI processors) and different stimuli (pulse trains vs. noise bursts) between the psychophysical and the localization tests make it difficult to connect ITD and ILD results to sound localization results.

The study reported here addresses the issues mentioned above. Azimuthal sound-localization performance was measured with five bilateral-CI listeners, who were monolateral-CI users for at least 14 months prior to receiving a second CI. These subjects provided an opportunity to characterize localization strategies developed with extended monolateral-CI use before the subjects were introduced to bilateral listening: a more appropriate assessment of localization ability with one CI. Monolateral and bilateral performance measures made with increasing bilateral-CI experience under constant and roved stimulus-level conditions provide a basis for characterizing the localization strategies employed with one and two CIs. Unlike the other studies, our experiments were conducted in an echoic environment, which may better reflect subjects' performance in realistic situations than testing in anechoic chambers. Head-related impulse responses (HRIRs) were recorded with each subject to: (1) characterize the acoustic inputs to their CIs, (2) assess the impact of microphone position on the interaural cues, and (3) simulate the room environment in a test-booth setting analogous to headphone studies with normal-hearing listeners. In order to investigate the potential use of ITD cues provided by the two independent CIs for sound localization, the subjects' sensitivity to ITD using similar stimuli was also measured.

II. METHODS

A. Subjects

Five, bilateral, cochlear-implant users (C092, C105, C109, C120, and C128) participated in this study. The subjects were 40 to 78 years old with etiologies listed in Table I. The idiopathic loss (C105) was sudden, and the autoimmune loss (C120) was rapidly progressive. All subjects were post-lingually deafened and presumably developed normal-binaural hearing prior to the onset of their hearing loss. Table I gives the age of each subject at the onset of hearing loss, hearing aid use, and cochlear implant use. The subjects' most recent single-syllable word (NU-6 test) scores (measured monolaterally) using their implants are also given in Table I. Because Subject C092 did not finish the complete sequence of testing, some results, like the NU6 score for the right ear in Table I, are not available (NA).

Table I: Subject History

Subject	Etiology	Age (yr) at Onset of Hearing Loss		Age (yr) at First Hearing Aid Use		Age (yr) at Onset of CI Use		Most Recent NU-6 Scores (% Correct)	
		R	L	R	L	R	L	R	L
C092	Otosclerosis	18	18	18	28	41	39	NA	96%
C105	Idiopathic	62	70	N/A	N/A	76	74	28%	38%
C109	Genetic	30	30	37	34	48	50	94%	86%
C120	Autoimmune	34	34	36	36	40	43	84%	70%
C128	Genetic	11	11	17	17	36	39	84%	86%

All subjects were monolateral-CI users for at least 14 months before implantation of the second ear. Both ears of all subjects received the Clarion C2 HIFOCUS electrode array (16 electrodes in each cochlea). Their first-implanted cochlea also included an electrode "positioner" designed to push the array into a modiolar position. Only C092, C105, and C109 have a positioner in their second-implanted cochlea. Table II lists the speech processors, microphones, and the microphone position for each subject. C092 and C109 use two, behind-the-ear (BTE) processors with microphones that sit atop the pinnae. C105 and C120 use two, body-worn processors with microphones in the headpiece above the pinnae. C128 uses two, BTE processors with T-Mics at the entrance of the ear canals.

Table II: Subjects' Devices and Length of Use

Subject	CI Device R and L	Speech Processors	Microphone Type	CI Microphone Position	Months of CI Use at the *Bilateral-Period* testing R	L
C092	C2 HIFOCUS	BTE	BTE	Behind the ears	7mo	21mo
C105	C2 HIFOCUS	Body-worn	Headpiece	Above the ears	3mo	24mo
C109	C2 HIFOCUS	BTE	BTE	Behind the ears	20mo	3mo
C120	C2 HIFOCUS	Body-worn	Headpiece	Above the ears	41mo	6mo
C128	C2 HIFOCUS	BTE	T-Mic	Ear canal entrance	39mo	7mo

Without changing the assignment of analysis channels to electrodes of the first implant, the mapping of analysis channels to electrodes of the second implant was based on the results of three measures of binaural sensation (fusion, interaural pitch comparison, and interaural time sensitivity). These binaural assessments were done before the fitting of the second implant (Eddington et al., 2003).

B. Two Periods of Measurement

Localization performance was measured in two different time periods. Experiments done prior to the onset of daily bilateral CI use were conducted in the *pre-bilateral* time period.

Experiments done after the onset of daily bilateral CI use were conducted in the *bilateral* time period. *Pre-bilateral-period* measurements captured the subjects' monolateral and bilateral performance while the subjects continued using their original, monolateral-implant system after implantation of their second ear. The only bilateral stimulation during this period was when they visited the laboratory for acute (mainly psychophysical) testing. On the other hand, *bilateral-period* measurements captured the subjects' performance once they began using both CIs in daily life. During this period, monolateral use was restricted to acute laboratory testing. This longitudinal-testing approach allows one to examine the impact of bilateral stimulation on monolateral and bilateral CI performance. The last column in Table II lists the months of CI used at the *bilateral-period* testing reported here.

C. Sound Localization Experiment

Sound localization was measured in a carpeted 12' by 13' single-wall IAC room in the Sound Field Laboratory at Boston University. The walls and ceiling were not treated for reverberation. Seven loudspeakers (Bose® Acousticmass, ~2" diameter) were placed at 30° intervals on a 180° arc 5 feet from the subject's head (Figure 1). MATLAB (running on a PC outside the booth) was used to generate the input signal to a digital-to-analog converter (DA3, Tucker-Davis Technology, TDT, System II), a low-pass filter (FT6, TDT, System II) with 20kHz cutoff, an attenuator (PA4, TDT, System II), and a speaker amplifier (Tascam PA-20MKII) that was switched to one of the seven loudspeakers inside the booth.

The basic trial structure was a one-interval, seven-alternative, forced-choice (1I-7AFC) task. In each interval, the stimulus is presented from one of the seven loudspeakers chosen randomly. The stimulus is a group of three, 500-ms white noise bursts with a 300-ms inter-burst interval. The onset and offset of each noise burst was smoothed by a 5-ms hanning window. In each block of trials, the stimulus level was either constant or roved. In the constant-level condition, the level was 64 dB SPL, and the stimulus was presented five times from each source position, resulting in a total of 35 trials/block (5 trials x 7 speakers) all in random order. In the roved-level condition, three levels (50 dB SPL, 60 dB SPL, and 70 dB SPL) were presented three times at each source position, resulting in a total of 63 trials/block (3 trials x 3 levels x 7 positions) all presented in random order. The range of levels measured at a subject's microphone across speaker position for the constant-level case was about 13 dB. Thus, the 20 dB rove was sufficient to prevent subjects using the absolute level at each ear as a reliable cue. The listening conditions (monolateral-first-implanted CI, monolateral-second-implanted CI, and bilateral CIs) were constant within each block. Blocks of different combinations of listening and level conditions were randomized in each test session. After each stimulus presentation, the subject was asked to identify the active speaker by entering the loudspeaker number on a keypad. All subjects used the speech processors that they wore on a daily basis to do the test. No feedback was given to assess the subjects' localization ability based on every-day use of their implants.

Subjects' responses in each block of trials were recorded in a stimulus-response matrix. In the matrix, the subject-response position was plotted against the speaker position. Each point marks a response for a given trial. The root-mean-square (RMS) error of the responses in a block of trials was computed using the following relationship:

$$\begin{aligned} &E_{RMS}(N) = \sqrt{\frac{1}{T}\sum_{k=1}^{N}\sum_{i=1}^{M_k}(R_{ik}-\theta_k)^2}, \\ &\textit{and} \\ &T = \sum_{k=1}^{N} M_k, \end{aligned} \tag{2.1}$$

where N is the total number of speakers included in the calculation; T is the total number of trials for N speakers; k is the speaker number; M_k is the total number of trials presented at speaker k; R_{ik} is the listener's response in degrees in the i^{th} trial for speaker k; θ_k is the azimuth of speaker k in degrees. The standard deviation of the RMS error for each test condition was estimated by the boot-strapping technique (Efron and Tibshirani, 1993).

Five hypothetical, stimulus-response matrices are shown in Figure 2. For a perfect score, all responses fall on the diagonal line (Figure 2a), and the RMS error (N=7) is 0°. For responses distributed uniformly across speaker position (Figure 2b), or chance performance, the RMS error is 85°. If there are no hemifield confusions but random responses for the center speaker (Figure 2c), the RMS error is 43°. Eliminating the center speaker error (Figure 2d) further reduces the RMS error to 35°. In the case of an extremely biased response pattern as shown in Figure 2e, the RMS error is 108°, which is worse than chance performance in Figure 2b. These RMS error values will help interpret the RMS error data that follows.

D. Measurement of Head-Related Impulse Responses (HRIRs)

With each subject seated as in Figure 1, the output of each CI microphone was recorded for each loudspeaker driven by a maximum-length sequence (MLS) input signal. The head-related impulse response (HRIR) for each microphone was computed by circular correlation of the input and output signals (Rife, 1989; Vanderkooy, 1994; Moller, 1995). Because left and right CI-microphone signals were recorded simultaneously, interaural phase and level differences could be assessed in the left and right HRIRs. In addition to analyzing the interaural cues in the signals to each subject and the impact of microphone position on these cues, HRIRs were used to virtually simulate the environment for psychophysical testing.

A complete set of seven-loudspeaker HRIR measurements takes about five minutes. The stimulus level measured at the position normally occupied by the center of the subject's head was 78 dB SPL. Since the subjects' microphones are unplugged from their sound processors, the subjects did not hear any sound during the recording sessions. Each subject was instructed to sit in the room facing the 0°-speaker during the measurement period. No head restraint was used. While informal monitoring of head position verified compliance, very small shifts in head position were possible.

E. Measurement of ITD Sensitivity

The just-noticeable-difference (JND) in ITD was measured using virtual stimulation of the stimulus from the center (0°) speaker in the localization task. The subjects' ITD sensitivity was measured through their bilateral-CI processors to relate to their localization performance with the same stimuli. The 0°-source position was chosen to minimize the spectral differences between the left and right inputs. To recreate the stimulus from the 0°-source position in the localization task, the three noise bursts (with 500-ms duration, 300-ms inter-burst interval, and 5 ms on- and off-ramp) were filtered in MATLAB by each subject's Fourier transforms of the HRIRs, called head-related transfer functions (HRTFs), for the source at 0°.

Measurement of ITD JND for C105, C109, C120, and C128 were made in a single-wall sound booth in the Cochlear Implant Research Laboratory at the Massachusetts Eye and Ear Infirmary. C092 was not available for ITD JND testing. The computed right and left electric signals were delivered from a PC's sound card directly to the auxiliary port of the subject's sound processors. The stimulus level of the HRTF-filtered noise bursts was adjusted to be equivalent to a 64 dB SPL sound received by the CI microphones. Each ITD was generated by a whole-waveform delay of the stimulus to one implant relative to the other. The delayed side (left or right) was chosen at random in each trial. Note that externalization was reported by the subjects with the virtual stimulation.

The ITD JND was measured using a two-interval, two-alternative, forced-choice (2I-2AFC) adaptive test. A two-down, one-up adaptive procedure was used to target the 70.7% level on the psychometric function (Levitt, 1970; Leek, 2001). With a 2I-2AFC procedure, the first interval contained the reference condition (ITD = 0 μs). The second interval contained the test condition with an ITD determined by the adaptive procedure. After each presentation, subjects were asked to answer the question, "Did the second group of noise bursts move to the left or the right of the first group of noise bursts?"

They responded by entering “1” for left and “2” for right on the keyboard. The correct response (1 or 2) was shown on the computer screen after each trial.

Each adaptive run started at an ITD of 700 μs and an initial step size of 100 μs. To save time and to improve the resolution of the test, the step size is reduced by a half after the first peak reversal and is reduced by a half again after the second peak reversal in the adaptive track. Hence, the step size at the end of the trial sequence was 25 μs. An adaptive run was terminated after 14 reversals. The ITD JND of each run was the mean of the ITDs for the last eight reversals (four peaks and four valleys). The standard deviation of the ITDs for the last eight reversals was also calculated. If an adaptive track had an upward or downward slope greater than 1, the result was discarded. If a subject showed poor sensitivity with a start ITD of 700 μs, the test was repeated with a start ITD of 1500 μs and an initial step size of 300 μs. If the test ITD as determined by the adaptive procedure went up to 2 ms, the run was terminated and no ITD sensitivity was declared.

III. RESULTS

A. Sound Localization Performance

The stimulus-response matrices for each subject’s sound-localization performance are presented in Figures 3 – 7. There are six matrices in each figure. The left panels (a – c) show *pre-bilateral-period* results and the right (d – f) *bilateral-period* results. The results for three different listening conditions (monolateral first-implanted CI, bilateral, and monolateral second-implanted CI) are arranged from top to bottom in each figure.

Constant-level data (o) and roving-level data (▲) are offset horizontally for clarity. In general, from left column to right, there is an improvement in bilateral performance and no improvement in monolateral performance for both stimulus-level conditions. In several cases there is a degradation of monolateral performance with constant-level stimuli after bilateral experience.

For monolateral listening with constant-level stimuli (o), three (C092, C120, and C128) of the five subjects show some monolateral-localization ability (minimal hemifield errors) using their first CI in the *pre-bilateral* testing (Figures 3a, 6a, and 7a). Table II shows that C092, C120, and C128 had 14, 35, and 32 months of monolateral-listening experience with their first CI, respectively, at the *pre-bilateral* test session. These data suggest that C092, C120 and C128 developed a localization strategy with extensive monolateral listening. To some degree, as shown in the constant-level data in Figures 3c and 7c for C092 and C128, this ability carried over to C092's and C128's second-implanted ear without chronic monolateral listening experience using the second CI. At the *bilateral-period* testing, C092's and C120's monolateral-first-CI performance with constant-level stimuli degraded, and only C128's monolateral localization performance showed substantial hemifield accuracy. In general, the monolateral-localization abilities observed with these three subjects using constant-level stimuli were degraded when the stimulus level was roved (▲).

Two of the five subjects (C105 and C109) demonstrated little localization ability with monolateral CI under both stimulus-level conditions before and after the onset of bilateral CI use. Figures 4a, 4c, 4d, and 4f show that C105's monolateral-CI responses were biased towards the active implant. Roving level had little impact on C105's response pattern. For C109, her *pre-bilateral*, monolateral responses in Figures 5a and 5c were mainly limited to the side of the active implant for both stimulus conditions. After bilateral listening, C109's responses became less biased (Figure 5d) and more affected by roving stimulus level (Figure 5f).

For performance with two CIs using constant- and roving-level stimuli, all subjects' localization performance improved from the *pre-bilateral* to *bilateral* test period (comparing panel b and panel e in Figures 3 – 7). After at least three to seven months of bilateral CI listening (Table II), all subjects correctly identified the source's hemifield. For all subjects except C105, there were substantially more correct responses on the diagonal line in the *bilateral-period* results than those in the *pre-bilateral-period* results.

Overall, all subjects' bilateral performance after months of bilateral CI listening shows more correct responses on the diagonal than their monolateral performance using both types of stimuli. The corresponding RMS errors for each set of data are plotted in Figures 8 – 10 and discussed in Section IV.

B. ITD Sensitivity Using the Stimulus from the 0°-Speaker

ITD sensitivity measured using the stimulus from the 0°-speaker is reported in Table III.

Table III: ITD JNDs Measured Using the 0°-Speaker Stimulus

Subject	ITD JND (μs)
C092	Not available
C105	> 2000 μs
C109	319 μs ± 98 μs
C120	428 μs ± 150 μs
C128	588 μs ± 136 μs

C105 was not able to distinguish ITDs up to 2 ms. The ITD JNDs measured for C109, C120, and C128 were between 319 μs and 588 μs, which are much poorer than the average ITD JNDs of 10 μs to 67 μs measured in normal-hearing listeners (Klumpp and Eady, 1956; Bernstein et al., 1998).

IV. DATA ANALYSIS

A. Monolateral Performance Using the First-Implanted CI

Figure 8 shows sound-localization performance of five subjects using their first CI. The first and second bars in each panel show the constant- and roving-level RMS errors for each subject measured without bilateral-CI listening experience (*pre-bilateral-period* measurement). The third and fourth bars show the constant- and roving-level RMS errors after months of bilateral-CI experience (*bilateral-period* measurement). The upper dashed line indicates the RMS error at 85° for chance performance. The middle one indicates the RMS error at 43° for identifying the correct hemifield with random center-speaker responses, and the lower one indicates the RMS error at 35° for correctly identifying source hemifield and the center speaker.

Looking at the first bar in each panel for each subject, three (C092, C120, and C128) of five subjects did better than chance (85°) using their first CI under constant-level condition without any bilateral experience ($p<0.05$). C092's and C120's RMS errors were near 43°, and C128's RMS error was near 35°. Their performance ("o" in Figures 3a, 6a, and 7a) shows that they can identify which side the sound was on with few left/right confusions. Figure 7a shows that C128 had few center-speaker error, resulting in the significantly ($p<0.05$) lower than 43° error performance. The other two subjects (C105 and C109) showed bias towards the side of the active implant ("o" in Figures 4a and 5a) with RMS errors greater than chance ($p<0.01$).

When the stimulus level was roved, comparison of the second bar to the first bar in each panel shows that roving level degraded ($p<0.01$) two subjects' (C120's and C128's) monolateral-first-CI performance to near chance. No measurement was made with C092. For C105 and C109, roving level eliminated bias ("▲" in Figures 4a and 5a), resulting in RMS errors near chance.

The impact of bilateral-listening experience on monolateral-first-CI performance under constant stimulus level can be seen by comparing the first and the third bars in each panel. Of the three subjects (C092, C120, and C128) who showed better-than-chance performance (first bar), bilateral experience significantly ($p<0.08$) degraded two subjects' (C092 and C120) monolateral-first-CI performance (third bar). Only one (C128) of the three subjects could switch back to the better-monolateral-localization strategy after months of bilateral experience. For C105 and C109, bilateral listening experience did not affect their monolateral-first-CI performance.

With roving-stimulus level, the impact of bilateral-listening experience can be seen by comparing the second and the fourth bars in each panel. All the roving data were poor but stable with bilateral experience. Monolateral-first-CI performance before and after bilateral-CI exposure was near chance under roving-level condition. Overall, monolateral-first-CI performance is near chance except for three subjects' performance using constant-level stimuli with zero-months of bilateral experience. The monolateral-localization strategies developed with extended monolateral experience were not useful for roving-level stimuli. Increasing bilateral experience degraded the better-than-chance monolateral performance with constant-level stimuli for two of the three subjects.

B. Monolateral Performance Using the Second-Implanted CI

Each subject's monolateral performance using the second CI is shown in Figure 9. The first and second bars in each panel show the constant- and roving-level RMS errors for each subject measured with no bilateral-CI experience and minimal listening experience with their second CI. The third and fourth bars show the constant- and roving-level RMS errors after months of bilateral experience.

Looking at the first bar in each panel in Figure 9, two (C092 and C128) of the five subjects performed better than chance and were able to identify source hemifield with constant-level stimuli. These two subjects had showed better-than-chance performance with their first CI (first bar in Figures 8a and 8e). Since the subjects had minimal listening experience with their second CI at the time of testing, C092's and C128's monolateral-second-CI performance indicate a transfer of monolateral-localization strategy under constant-level condition. For the other three subjects (C105, C109, and C120), monolateral-second-CI performance with constant-stimulus level was at chance. C105's and C109's monolateral-second-CI performance were biased like their monolateral-first-CI performance measured in the same test session (first bar in Figures 8b and 8c). On the other hand, C120's monolateral-second-CI performance was significantly worse ($p<0.05$) than his monolateral-first-CI performance with constant-level stimuli (first bar in Figure 8d).

Due to limited test time at the *pre-bilateral* test session, C092 and C120 were not tested with roving-level stimulus using their second CI. When the stimulus level was roved for C128, who showed better-than-chance performance using his second CI with constant-level stimuli (first bar in Figure 9e), his monolateral-second-CI performance (second bar in Figure 9e) was degraded to near chance. For C105 and C109, comparison of the first and second bars showed that their monolateral-second-CI performance was not affected by different stimulus-level conditions.

The impact of bilateral listening experience (comparison between the first and the third bars in each panel in Figure 9) on monolateral-second-CI performance using constant-level stimuli was only observed with C092 ($p<0.05$). C092 could not switch back to the better monolateral-localization strategy. For the other four subjects, their monolateral-second-CI performance did not change. C128 retained the ability to identify the source hemifield using his second CI alone with RMS error near 43°. C105, C109, and C120 still showed monolateral-second-CI performance near chance.

When the stimulus level was roved, comparing the second and the fourth bars in each panel in Figure 9 shows that subjects' monolateral-second-CI performance remained stable with bilateral CI experience. Performance was near chance.

C. Bilateral CI Performance

Sound-localization performance of five subjects using bilateral CIs is shown in Figure 10. The first bar in each panel shows that with no bilateral experience, every subject did better than chance with constant-level stimuli. C105's RMS error was between the two dashed lines, reflecting the left/right confusion errors seen in the scatter plot of his initial bilateral performance in Figure 4b. For the other four subjects, their initial bilateral RMS errors were near 43°. As illustrated in the scatter plots in Figures 3b, 5b, 6b, and 7b, these four subjects have the ability to identify which side the source was on with minimal left/right confusions.

The second bar in each panel in Figure 10 shows each subject's initial bilateral performance with roving-level stimuli. Measurement was not made with C092. For the four subjects, comparison of constant- and roving-level results in the initial bilateral testing (first and second bars in Figure 10) shows no significant difference ($p>0.05$) between the two stimulus conditions. Their scatter plots in panel b of Figures 4 – 7 also showed similar response patterns under the two conditions. Roving level did not have a large impact on subjects' initial bilateral performance as in monolateral listening.

As for the impact of bilateral experience, except for C092's performance, all subjects' bilateral performance improved with increasing bilateral experience. For C092 (Figure 10a), her bilateral performance before (first bar) and after (third bar) months of bilateral experience did not change with constant-level stimuli. For the other four subjects, there are significant differences ($p<0.03$) between the results of the two test sessions with both constant-level (first vs. third bar in Figure 10) and roving-level (second vs. fourth bar in Figure 10) stimuli.

After months of bilateral-CI experience (third and fourth bars in Figure 10), the RMS errors for four of the five subjects (all except C105) were significantly ($p<0.05$) less than 43°. As shown in the scatter plots ("▲" in panel e of Figures 3 – 7), all the subjects were able to identify the source hemifield correctly, but unlike the other four subjects, C105 was not able to locate the center speaker. Of those four subjects, C128's RMS error was near 35° while C092, C109, and C120 had RMS errors significantly ($p<0.05$) less than 35° using roving-level stimuli (fourth bar in Figures 10a, 10c, and 10d). These results show that C092, C109, and C120 demonstrated bilateral-CI-localization ability beyond left/right hemifield discrimination.

D. ITD and ILD Calculated from Head-Related Impulse Responses (HRIRs)

To analyze the ITD and ILD cues available to the subjects for localization, the ITD and ILD of the sound from each source position are calculated from the subjects' HRIRs recorded at their left- and right-CI microphones. Figures 11 and 12 are examples of the first 14 ms of the impulse responses measured at the left and right CI microphones for a source in the left and right hemifield, respectively. In Figure 11, the sound from the left hemifield reaches the left microphone before reaching the right microphone, and vice versa in Figure 12. Following the microphone's direct response, there are responses to reflections from the walls, floor, ceiling, and subject. The ITD for each source position can be estimated using the cross-correlation function of the left and right impulse responses; specifically, the estimated ITD is the delay for which the cross-correlation function is a maximum. The ILD cue can be calculated by the ratio of the average power of the left and right impulse responses.

Figures 13 and 14 show the cross-correlation results for the truncated impulse responses of Figures 11 and 12, respectively. The impulse responses were truncated to 7 ms to eliminate most reverberations of the echoic room. The upper panel shows the entire correlation function while the lower panel zooms in to the +/- 1 ms lag time. One can see the maximum of the cross-correlation result at a lag time of about –700 μs for the –90° speaker in Figure 13 and at about +250 μs for the +30° speaker in Figure 14. The computed ITDs for the speakers' direct responses are plotted in Figure 15. From the left-most (-90°) to the right-most (+90°) speaker positions, the ITD increases monotonically from approximately –800 μs to +800 μs.

Figures 16 and 17 show the cross-correlation results for the same cases in Figures 11 and 12 when the impulse responses are lengthened to 100 ms to include reverberation. For the –90° speaker, the result in Figure 16 shows the largest peak near 0 ms with smaller peaks around –4 ms and –11 ms lag time, corresponding to correlations of the direct response to the echoic portions of the microphone response. For the source at +30°, Figure 17 shows that the correlation value around 7 ms is slightly greater than that near 0 ms. The peak-picking technique assigns an ITD of 7 ms for the source at +30°. Figure 18 shows the computed ITDs using the maximum of the correlation results for the microphone responses with reverberation for all five subjects. While many of the calculated ITDs are the same as those in Figure 15, there are large values for the sources at -90° (for C105 and C109) and +30° (for C092, C105, C109, and C128). Looking at these subjects' impulse responses for those two source positions, there are responses to reflections that are larger than the direct responses of one of the microphones as shown in Figure 12. For the source at -90°, the impulse responses of C105 and C109 show large responses for a reflection around 16 ms. Looking at the illustration of the room in Figure 1, 16 ms is approximately the travel time from the source to the right wall and back to the subjects' right microphones. For the source at +30°, impulse responses of C092, C105, C109, and C128 show large responses for a reflection around 11 ms. This reflection is likely to be off the door behind the subject. Unlike the walls in the room, the door panel is not perforated, and there is a glass window on the door, making it even more reflective compared to the other walls in the room. This reflection is also seen in C120's impulse responses; however, since it is smaller than the direct response of the microphones, the direct ITD was chosen with the maximum-peak-picking method. These analyses suggest that if the subjects extract the ITD of a signal by performing a cross-correlation analysis and picking the maximum of the correlation result, the subjects might have seen large ITDs due to reverberations instead of the direct ITDs. Given that the subjects' responses to the speakers at -90° and +30° (in panel e of Figures 3 – 7) are not particularly worse than those of the other speakers, it is not likely that the subjects were affected by the large ITDs shown in Figure 18. Since the subjects seemed to ignore the large correlation with the delayed reflections, ITDs of the reverberant HRIRs can be determined by the maximum values of the cross-correlation functions within +/- 1 ms lag time, which encompasses the range of ITD measured in the less reverberant (7-ms duration) condition in Figure 15. The resulting ITDs for the reverberant case are the same as those in Figure 15. Hence, the calculated ITDs in Figure 15 will be used in the next section to calculate angle JNDs to relate to subjects' localization performance.

The ILD between the ears from each source position was calculated by the ratio of the average power, *AP*, of the left and right HRIRs:

$$ILD = 10\log\left(\frac{AP_{leftHRIR}}{AP_{rightHRIR}}\right) \tag{2.2}$$

The average power, *AP*, is the energy over the duration, *T*, of the response:

$$AP = \frac{\int_0^T x(t)^2\,dt}{T} \tag{2.3}$$

Figures 19 and 20 show the calculated ILD as a function of source position without reverberation (7-ms duration impulse responses) and with reverberation (100-ms duration impulse responses), respectively. Without reverberation (Figure 19), the calculated ILD increases from approximately –15 dB to +15 dB across source positions. With reverberation (Figure 20), the range of ILDs decreases to –12 dB to +12 dB. The differences in ILD between the extreme speakers -90°, -60° and +60°, +90° is small in the case without reverberation and is even smaller in the case with reverberation. From the -90° to the -60° position in Figure 20, there is less than 1 dB of increase in ILD for C092 and C109. A minimal change in ILD of 1 dB or less from the +60° to the +90° position is also observed for C092, C109, and C120. The calculated ILDs in Figure 20 will be used to calculate angle JNDs to relate to subjects' localization performance.

The subjects in the current study wear three different kinds of CI microphones at different positions on the head (BTE, for the microphone behind the ear at the pinna; Headpiece, for the microphone above the ear on the headpiece; and T-mic, for the microphone at the entrance of the ear canal). To examine whether microphone position accounts for a significant proportion of the variance in the calculated ITDs and ILDs in Figures 15, 18, 19, and 20, a two-way analysis of variance (ANOVA) was applied to these data assuming no physical difference between subjects' heads. The ANOVA results shown in Tables IV and V demonstrate that only speaker position accounts for a significant amount of the variance in ITD and ILD.

Table IV: Results of Two-Way ANOVA Tests for the Calculated ITDs of Five Subjects without and with Reverberation

	Factor 1 Mic Position (BTE, Paddle, or T-mic)	Factor 2 Speaker Position (Number 1 to 7)	Interaction of Factors 1 and 2
Calculated ITDs without reflections greater than 1 ms (Figure 15)	p = 0.63	**p < 0.01**	p = 0.25
Calculated ITDs with reflections greater than 1 ms (Figure 18)	p = 0.99	**p = 0.02**	p = 0.84

Table V: Results of Two-Way ANOVA Tests for the Calculated ILDs of Five Subjects without and with Reverberation

	Factor 1 Mic Position (BTE, Paddle, or T-mic)	Factor 2 Speaker Position (Number 1 to 7)	Interaction of Factors 1 and 2
Calculated ILDs without reverberation	p = 0.26	**p < 0.01**	p = 0.86
Calculated ILDs with reverberation	p = 0.07	**p < 0.01**	p = 0.30

E. Angle JNDs and Predicted-Localization Performance

Using the measured ITDs and ILDs from subjects' HRIRs in Figures 15 and 20, angle JNDs corresponding to subjects' ITD JNDs and ILD JNDs were estimated. To study the relationship between subjects' ITD and ILD sensitivity and their bilateral localization performance, the angle JNDs were then used in a simple decision model as given by Durlach and Braida (1969) to predict localization performance. In particular, the RMS error for the center (0°) speaker was predicted because ITD JNDs were measured using virtual stimulation of the center speaker. Subjects' ILD JNDs were obtained from the results of a battery of tests conducted in the Cochlear Implant Research Laboratory by Victor Noel using a single, non-HRIR-filtered noise burst in similar test procedures.

The conversions from ITD JNDs and ILD JNDs to angle JNDs were estimated using the values for sources at -30° and +30° in Figures 15 and 20. Since we are focusing on the subjects' performance for the center speaker, values at +/-60° and +/-90° were not included in obtaining the conversion factors. ITD and ILD cues at 0° azimuth were assumed to be 0 μs and 0 dB, respectively. Table VI listed the ITD JNDs measured with virtual stimulation of the sound from the 0°-speaker position, the estimated source angle (in degree) per ITD (in μs) from Figure 15, and the corresponding angle JNDs computed by multiplying the second and the third columns. Table VII listed the subjects' ILD JNDs, the estimated source angle (in degree) per ILD (in dB) from Figure 20, and the corresponding angle JNDs.

Table VI: Angle JNDs Corresponding to Subjects' ITD JNDs

Subject	ITD JND (μs)	Source Angle (degree) Per ITD (μs) Estimated from Figure 15	ITD-Predicted Angle JND (degree)
C092	Not available	60°/520μs = 0.12°/μs	--
C105	> 2000 μs	60°/520μs = 0.12°/μs	> 231°
C109	319 μs ± 98 μs	60°/540μs = 0.11°/μs	35° ± 11°
C120	428 μs ± 150 μs	60°/460μs = 0.13°/μs	56° ± 20°
C128	588 μs ± 136 μs	60°/500μs = 0.12°/μs	71° ± 16°

Table VII: Angle JNDs Corresponding to Subjects' ILD JNDs

Subject	ILD JND (dB)	Source Angle (degree) Per ILD (dB) Estimated from Figure 20	ILD-Predicted Angle JND (degree)
C092	Not available	60°/11dB = 5.5°/dB	--
C105	3.4 dB ± 1.1 dB	60°/10dB = 6.0°/dB	20° ± 6.6°
C109	0.7 dB ± 0.2 dB	60°/15dB = 4.0°/dB	2.8° ± 0.8°
C120	1.7 dB ± 0.6 dB	60°/12dB = 5.0°/dB	8.5° ± 3.0°
C128	0.4 dB ± 0.2 dB	60°/9dB = 6.7°/dB	2.7° ±1.3°

Using the ITD- and ILD-predicted angle JNDs, RMS error for the 0° speaker was predicted with a simple decision model (Durlach and Braida, 1969). Figure 21 shows the model with the internal decision variable, X, for source identification and the conditional probability density function for X given the sound was presented from the source at 0°, $p(X|0°)$. Assuming that $p(X|0°)$ is Gaussian with mean at 0°, the standard deviation, σ, represents the observer's sensitivity to the source. ITD- and ILD-predicted angle JNDs were both used as σ in the model to predict subjects' localization performance for the center speaker.

According to the model, each stimulus presentation determines a value of X (a real random variable), and the observer's response is determined by the relation of X to a set of response criteria. For our source localization experiment with seven speakers from –90° to +90°, a set of response criteria was assumed to be halfway between two speaker positions ($C_0 = -\infty$, $C_1 = -75°$, $C_2 = -45°$, $C_3 = -15°$, $C_4 = +15°$, $C_5 = +45°$, $C_6 = +75°$, and $C_7 = \infty$). The observer responds R_k if and only if $C_{k-1} < X \leq C_k$. With $p(X|0°)$ being Gaussian with mean at 0°, the probability of responding speaker k given a sound was presented at 0°, $P(R_k|0°)$, is:

$$P(R_k\,|\,0°) = \int_{C_{k-1}}^{C_k} p(X\,|\,0°)dX = \frac{1}{\sqrt{2\pi}\sigma}\int_{C_{k-1}}^{C_k} e^{\frac{-(X-0)^2}{2\sigma}} dX \qquad (2.4)$$

RMS error for the 0°-speaker was calculated after obtaining the probability of each of the seven responses for the stimulus presented at 0°. The ITD- and ILD-predicted RMS errors are compared with the measured RMS error in Figure 22.

The first bar in each panel of Figure 22 shows each subject's RMS error for the center speaker measured in the localization test using bilateral CIs. These error values are calculated from the 0°-speaker data extracted from the set of roved-level data collected using seven speakers in the *bilateral* test period. The second and the third bars in each panel are the center RMS errors predicted by the decision model based on each subject's ITD- and ILD-predicted angle JNDs, respectively. The dashed line marks the chance performance at 60°.

For all four subjects, ITD-predicted performance (second bar in Figure 22) was worse than the measured performance (first bar) and the ILD-predicted performance (third bar). Of the four subjects, only C105's measured center RMS error was near chance performance. However, the ITD-predicted center RMS errors were near chance for C120 and C128 and worse than chance for C105.

Not only was the ILD-predicted performance better than the ITD-predicted performance, ILD-predicted performance (third bar) was better than the measured performance (first bar) for three of the four subjects. One subject's (C120's) center RMS error was zero. The ITD- and ILD-predicted results suggest that while the bilateral CI subjects' ITD sensitivity alone could not account for their measured localization performance, their ILD sensitivity could account for their performance in the localization test.

V. DISCUSSION

A. Comparison to Results in the Literature

Measures of sound localization performance of sixty bilateral cochlear implant subjects have been reported in the literature (Gantz et al., 2002; Tyler et al., 2002; van Hoesel et al., 2002; van Hoesel and Tyler, 2003; Litovsky et al., 2004; Nopp et al., 2004). Table VIII summarizes the methods used in these localization studies and their various experimental designs.

Table VIII: Summary of Localization Studies with Bilateral Cochlear Implants.

Study	# of Subj	CI Devices	Months of Bilateral CI use	# of Spk	Azimuth Range	Speaker Separation	Stimulus	Stimulus Level
Tyler et al (2002)	7	Nucleus CI-24M	3	2	±45°	90°	Speech-weighted noise	70dB SPL +/-5dB
Gantz et al (2002)	10	Nucleus CI-24M	12	2	±45°	90°	Speech-weighted noise	70dB SPL +/-5dB
van Hoesel et al (2002)	1	Nucleus CI-24M	?	11	±90°	18°	Pink noise	70dB SPL +/-3dB
van Hoesel and Tyler (2003)	5	Nucleus CI-24M	>=12	8	±54°	15.5°	Pink noise	65dB SPL +/-4dB
Litovsky et al (2004)	17	Nucleus CI-24R, CI-22, CI-24	3	8	±70°	20°	Pink noise 50ms off	65dB SPL +/-6dB
Nopp et al (2004)	20	Combi 40/40+	1 to 48	9	±90°	22.5°	Speech-shaped noise	3 random levels (60,70,80 dB SPL)
Current study	5	Clarion C2 HIFOCUS	3 to 7	7	±90°	30°	White noise	64 dB SPL or 3 random levels (60,70,80 dB SPL)

Using one speaker at 45° in the left and right hemifields, the seven subjects in Tyler et al. (2002) and Gantz et al. (2002) scored 100% correct after 12 months of bilateral listening. They were able to identify whether the sound was coming from the left or the right speaker. The analysis of our subjects' RMS errors in Figure 10 also demonstrates that all of our subjects are able to correctly identify the source hemifield with two CIs after extended bilateral listening. Four of our five subjects' RMS errors (third and fourth bars in each panel in Figure 10) were significantly ($p<0.05$) better than the hemifield-only performance with center-speaker error (Figure 2c). Since we tested more than one source position in each hemifield, we can also show that three of our five subjects are able to perform better than chance within the hemifields (Figure 2d). This shows that three of our subjects' bilateral-CI-localization ability is not limited to only left/right discrimination.

Studies of van Hoesel et al. (2002), van Hoesel and Tyler (2003), and Litovsky et al. (2004) show results for bilateral-CI listeners tested using arrays of eight to eleven speakers with level rove of +/-3 to 6 dB. Given the rove range is less than the range of levels from different source positions with constant-level stimuli in monolateral-CI listening (about 13 dB was estimated from our subjects' HRIRs), absolute-level listening at one ear may still be a reliable cue to some subjects. Hence, constant-level data from the current study are used to compare with results from these three studies. [Note that the rove in level has little impact in our bilateral data (Figure 10).] The stimulus-response matrices of our subjects after months of bilateral experience (panels d to f of Figures 3 – 7) show response patterns that resembled those in these three studies using monolateral and bilateral CIs. The average RMS errors (and the standard deviation) for all subjects' performance in the three studies and in the current study are re-plotted in Figure 23. Each panel in Figure 23 represents one listening condition (left CI, bilateral CIs, and right CI). For each of the listening conditions, the average performance of the subjects of this (first bar) and the Litovsky et al. (2004) (fourth bar) studies are statistically the same ($p\geq0.2$). Performance of the one subject in van Hoesel et al. (2002) is significantly different ($p<0.01$) from the subjects in Litovsky et al. (2004) but not different ($p=0.3$) from the subjects of this study. Average RMS error for the van Hoesel and Tyler (2003) (third bar) subjects is significantly smaller ($p<0.04$) than each of the other studies for all listening conditions.

It is uncertain why the subjects in van Hoesel and Tyler (2003) perform better than our subjects and others in the literature as shown in Figure 23. One possible reason is the difference in the range of azimuth positions covered by the array of speakers in each study. The speaker array in van Hoesel and Tyler (2003) only spanned ±54° compared to the ±90° span in van Hoesel et al (2002) and in the current study. The speaker array in Litovsky et al (2004) spanned ±70°. There are three issues associated with the difference in the range of source positions. First, for a given stimulus-response pattern, the RMS error depends on the range of source positions. For example, if any one of the N speakers in a N-speaker array is equally likely to be a response for a given source position (as in Figure 2a), then the RMS errors are 50° for 8 speakers spanning ±54°, 65° for 8 speakers spanning ±70°, 81° for 11 speakers spanning ±90°, and 85° for 7 speakers spanning ±90°. The smaller the stimulus range, the smaller the RMS errors for the same stimulus-response pattern. Secondly, the stimulus range can have an impact on source-identification performance. Koehnke and Durlach (1989) show that increasing the total range of interaural differences (time and level) can decrease subjects' ability to distinguish between two fixed interaural differences. Looking at Figures15 and 20, the total range of interaural time and level differences for sources spanning ±70° and ±90° is larger than that for sources spanning ±54°. Considering a subject's internal coordinate system for interaural discrimination, a decrease in a subject's ability to distinguish between two fixed interaural differences means that there is more overlap between the internal distributions for the two interaural differences. With more overlaps between the distributions, there would be more error for a given set of decision criteria. The third issue associated with the difference in stimulus range is that resolution of interaural difference cues is better in the front than near ±90° (Mills, 1958, 1972). Also, Figures 15 and 20 show that ITD and ILD differences are small beyond ±60° range. Thus, listeners' performance may improve if there are no sources beyond ±60°. All three issues associated with the difference in the range of source positions are consistent with the better source-identification performance by the subjects in van Hoesel and Tyler (2003) than all the subjects' performance in the current and in the other studies with bilateral CIs.

In Figure 24, the roved-level data in the current study are compared to the roved-level data reported in Nopp et al (2004). In both studies, the stimulus level was roved over a

20 dB range, and the speaker array spanned ±90°. Since Nopp et al. (2004) reported their data in terms of mean deviation between the judged azimuth and the azimuth from which a sound was presented, we also calculated the mean deviation for our subjects' data as defined by Nopp et al. (2004). According to Nopp et al. (2004), the mean deviation, *d*, is the mean value (over N source positions) of the unsigned difference between the average of the judged azimuth responses ($\bar{\varphi}_k$) for stimuli from a source at azimuth θ_k:

$$d = \frac{1}{N}\sum_{k=1}^{N}\left|\bar{\varphi}_k - \theta_k\right| \tag{2.5}$$

In all three listening conditions, mean performance across subjects in both studies is statistically equivalent ($p \geq 0.4$) in spite of the differences in the experimental protocols, such as anechoic vs. echoic test environment, the number of speakers tested, speaker separation, and the different types of noise stimuli used.

B. Evaluation of Monolateral vs. Bilateral Performance

The degree to which sound-source localization performance is better with two implants than one is one criterion used to justify the added cost and risk of bilateral implantation. It seems clear that (1) monolateral localization performance should be measured in subjects who have been listening monolaterally for many months and had a chance to develop a monolateral listening strategy and (2) bilateral localization performance should be measured in subjects who have been listening bilaterally and developed a bilateral listening strategy. Unfortunately, this is not the path taken by past studies (Gantz et al., 2002; Tyler et al., 2002; van Hoesel et al., 2002; van Hoesel and Tyler, 2003; Litovsky et al., 2004; Nopp et al., 2004).

The common evaluation method of bilateral benefit in past studies uses constant-level stimuli to measure monolateral and bilateral performance after months of bilateral experience. While this method captures bilateral performance with everyday bilateral listening, it captures monolateral performance with minimal monolateral listening. Figure 25a shows data from the current study evaluated with the method used in past studies. There are two bars for each subject. The first bar shows constant-level performance with his/her first CI, and the second bar shows constant-level performance with bilateral CI. These are the same data presented in Figures 8 and 10 (the third bar in each panel) measured after months of bilateral listening. Comparing the two bars for each subject, all subjects showed significantly ($p<0.05$) better performance with bilateral CIs.

However, for three (C092, C120, and C128) of our subjects, who demonstrated some monolateral-localization abilities using constant-level stimuli in the *pre-bilateral* testing, the monolateral performance measured using the common evaluation method does not reflect these three subjects' monolateral-localization abilities with extended monolateral listening prior to the onset of bilateral listening. Data in Figure 8 illustrated that these three subjects' monolateral performance using constant-level stimuli was degraded with increasing bilateral listening experience. A more appropriate comparison of monolateral and bilateral performance is shown in Figure 25b. The difference between Figure 25a and 25b is that the first bar for each subject in Figure 25b shows his/her monolateral-first-CI performance measured with at least 14 months of monolateral CI use and no bilateral CI experience. In Figure 25b, only three (C105, C109, and C120) of the five subjects showed significantly ($p<0.05$) better performance with bilateral CIs. Comparing the two evaluation methods of bilateral benefit (Figures 25a and 25b), the difference between monolateral and bilateral performance was exaggerated for the three subjects (C092, C120, and C128) whose monolateral performance with constant-level stimuli degraded after bilateral CI exposure.

Given the large impact of roving-stimulus level on C092's, C120's, and C128's monolateral performance shown in Figures 8 and 9 (first bar vs. second bar in each panel), they appeared to have developed a monolateral-localization strategy mainly based on the absolute-loudness level at the CI microphone with extended monolateral listening. [Note that the subjects may also use spectral cues to locate sound sources even though spectral cues were not manipulated in the current study to investigate the use of spectral information.] Since all subjects' monolateral performance with roving-level stimuli were stable with increasing bilateral experience as shown in Figures 8 and 9 (second and four bars in each panel), all subjects' roving-level data show significantly ($p<0.05$) better results with bilateral CIs using both methods of evaluation as illustrated in Figures 26a and 26b. The exaggerated differences between monolateral and bilateral performance for C092, C120, and C128 observed in Figure 25 with constant-level stimuli was not observed in Figure 26 with roving-level stimuli.

A number of past studies (Gantz et al., 2002; Tyler et al., 2002; van Hoesel et al., 2002; van Hoesel and Tyler, 2003; Litovsky et al., 2004; Nopp et al., 2004) showed substantial localization benefit with bilateral CI over monolateral CI. The subjects in all except one (Nopp et al., 2004) of those past studies received two implants in one surgery and then listened chronically to two asynchronous processors for at least three months before their monolateral and bilateral CI performance were measured. It is not surprising that the reported monolateral performance is significantly poorer than the reported bilateral performance when tested in this manner. The subjects had no opportunity to develop a monolateral listening strategy. In the current study, constant-level-monolateral-CI results measured before and after extended bilateral listening suggest that the monolateral performance reported in those past studies using stimuli with relatively constant level (or insufficient amount of level rove to eliminate absolute-loudness listening with one CI) do not reflect what the subjects' monolateral localization ability would have been after months of monolateral CI experience. The benefit of bilateral listening was probably overestimated in those past studies also. As shown with our roving-level data in Figure 26, of the past studies listed, only measurements from Nopp et al. (2004) probably did not exaggerate the difference between monolateral and bilateral performance since a sufficient amount of level rove (20 dB) was used even though monolateral and bilateral performance were measured after months of bilateral listening.

C. Bilateral Localization Performance and Sensitivity to ITD and ILD Cues

After months of bilateral CI listening, all subjects' sound localization performance with bilateral CIs shows significantly better-than-chance performance. Four of the five subjects were also able to do better than identifying the source hemifield. Comparison of constant- and roving-level data shows that unlike monolateral performance, level rove did not have a large impact on subjects' bilateral performance. To see whether subjects' sensitivity to ITD and ILD cues through their asynchronous CI processors may account for their bilateral localization performance, measurements of subjects' sensitivity to ITD and ILD were converted to source positions or angle JNDs corresponding to the subjects' ITD JND and ILD JND to predict localization performance for the center loudspeaker using a simple decision model (Durlach and Braida, 1969).

The model results in Figure 22 show that using ITD cue alone, subjects would perform worse than the measured performance. On the other hand, the model results show that using ILD cue alone, subjects could perform better than the measured performance. The ILD-JND-predicted localization performance suggests that subjects' ILD sensitivity could account for their localization performance, but the subjects did not use the ILD cue optimally.

One possible reason for the sub-optimal use of ILD cue is the different total range of ILD presented in the discrimination and the sound localization task. Koehnke and Durlach (1989) show that subjects' ability to distinguish between two fixed ILDs is worse for a task with a large ILD range compared to a task with a small ILD range. The 2I-2AFC-discrimination task is similar to testing with two loudspeakers. The discrimination task was also adaptive, which is analogous to having two loudspeakers getting closer together as it zooms into the subject's ILD JND decreasing the range of ILD presented. For the localization task, the seven loudspeakers were at fixed locations from –90° to +90°, which means that the total range of ILD presented was fixed and larger than the range of ILD in the discrimination task. Hence, the localization results reflected a poorer ILD sensitivity compared to the ILD-predicted localization results based on the better ILD sensitivity measured from the discrimination task with a smaller ILD range.

Another possible reason for the sub-optimal use of ILD cue is the interaction of ITD and ILD cues for binaural processing. All our subjects were post-lingually deafened and presumably had developed normal, binaural hearing prior to their hearing loss. It is possible that the normally developed binaural system forces the use of both ITD and ILD cues for sound localization. Based on the predicted localization performance from the subjects' ITD and ILD sensitivity in Figure 22, the use of both cues would lead to sub-optimal performance compared to using ILD cues alone.

D. Comparison to Normal-Hearing Listeners

With the current test setup, normal-hearing listeners can locate the seven sources perfectly using constant- and roving-level stimuli. Thus, bilateral-localization performance of our implantees is poor compared to normal. The primary cues used by normal-hearing listeners for localization on the horizontal plane are ITD and ILD cues (Durlach and Colburn, 1978; Middlebrooks and Green, 1991; Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002). Measurements of our subjects' sensitivity to ITD and ILD cues using noise bursts presented through their asynchronous processors are reported in Tables VI and VII. The subjects' ILD JNDs were between 0.4 – 3.4 dB, which are similar to those of normal-hearing listeners (1 – 2 dB, Durlach and Colburn, 1978). However, subjects' ITD JNDs were between 319 – 588 μs, which are much poorer than the average ITD JNDs of 10 μs to 67 μs measured in normal-hearing listeners using noise bursts (Klumpp and Eady, 1956; Bernstein et al., 1998). One of our subjects was not sensitive to ITDs up to 2 ms. Localization performance predicted by our subjects' ITD and ILD JNDs also demonstrated closer-to-normal localization performance based on the subjects' ILD sensitivity compared to performance based on the subjects' ITD sensitivity. Poorer-than-normal ITD sensitivity is likely to be one reason that bilateral CI users did not achieve normal localization performance in the current study.

Bursts of white noise were used in the current study for both localization and ITD sensitivity measurements. The ITD information in both the envelope and the fine structure of the white noise bursts were available to normal-hearing listeners. However, for CI listeners, only the ITD information in the envelopes of the analysis-channel-filter outputs was presented to them after CI processing. When normal-hearing listeners' sensitivity to envelope ITD was measured using high-frequency signals, such as SAM tones and transposed stimuli, the reported ITD JNDs were 100 – 300 μs (Bernstein, 2001). Hence, some of our CI subjects' ITD JNDs are more consistent with normal-hearing listeners' sensitivity to ITD presented only in the envelope of the stimuli.

From studies with normal-hearing listeners like Wightman and Kistler (1992), normal-hearing listeners' localization performance without fine structure ITD cues is poor compared to performance with proper ITD cues in both the envelope and the fine structure of the stimuli. Improvement in delivering the ITD information in the fine structure of the input signal to CI listeners may be essential for improvement in CI users' ability to locate sound sources.

VI. CONCLUSIONS

A longitudinal study of sound localization performance with monolateral and bilateral cochlear implants was conducted with five CI subjects. Each subject's monolateral CI performance was measured prior to the onset of bilateral CI listening to capture his/her monolateral-CI-localization ability with at least 14 months of monolateral listening. Three of five subjects demonstrated better-than-chance monolateral performance using constant-level stimuli. A significant change in the monolateral performance was observed in two of those three subjects after months of bilateral CI listening. The change in monolateral performance suggests that monolateral CI performance measured with constant-level stimuli (or stimuli with small level rove) reported in past studies do not necessarily reflect monolateral CI users' localization ability with extended monolateral CI experience. Meanwhile, bilateral performance for four of the five subjects also improved significantly with increasing bilateral CI use. These results suggest that current methods used to evaluate bilateral benefit after extended period of bilateral listening with constant-level stimuli probably over estimate the benefit of bilateral CI listening for some subjects.

The more appropriate comparison is made between monolateral localization performance measured in subjects with many months of monolateral listening and bilateral localization performance measured in subjects with many months of bilateral listening. Using the more appropriate comparison, three of our five subjects demonstrated significantly better localization ability with two CIs than one CI with constant-level stimuli. When the stimulus level was roved, all five subjects showed significantly better localization performance with two CIs than one CI. Roving level had large impact on monolateral listening and minimal impact on bilateral listening. Three of the five subjects also demonstrated the ability to identify sound sources beyond left/right source-hemifield discrimination.

In addition to measuring subjects' localization abilities, subjects' ITD sensitivity was measured using virtual stimulation of the 0°-speaker through the auxiliary ports of their asynchronous CI processors. Subjects' ILD sensitivity from other measurements in the laboratory was also reported in the current study. While subjects' ITD sensitivity was poor, their ILD sensitivity was similar to that of normal-hearing listeners. To better understand how subjects' ITD and ILD sensitivity relates to their localization performance, localization performance was predicted from each subject's ITD and ILD JNDs using a simple decision model. Comparison of the predicted and the measured results shows that subjects' localization performance was consistent with the use of ILD cues. Subjects' ITD-JND-predicted performance was worse than the measured and the ILD-JND-predicted performance.

Overall, the results presented show that there is significant localization benefit with bilateral CIs over monolateral CIs even though performance is not at the level of normal-hearing listeners. Further research should focus on improving bilateral CI users' sensitivity to ITD, which will improve bilateral CI performance and further justify the risks and cost associated with bilateral implantation.

LIST OF FIGURES

Figure 1: Schematic drawing of the set-up for the sound-source localization experiments.

Figure 2: Five Hypothetical stimulus-responses matrices. Panel a shows perfect performance (RMS error = 0°). Panel b shows chance performance for a subject unable to discriminate source hemifield (RMS error = 85°). For a subject able to discriminate source hemifield, panels c and d show the performance and the error difference without (RMS error = 43°) and with (RMS error = 35°) correct identification of the center speaker, respectively. Panel e shows biased performance, resulting in a RMS error (108°) greater than chance performance in panel b.

Figure 3: C092's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 7 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance. ["NA" indicates data not available.]

Figure 4: C105's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 3 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance.

Figure 5: C109's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 3 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance.

Figure 6: C120's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 6 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance. ["NA" indicates data not available.]

Figure 7: C128's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 7 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed

corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance.

Figure 8: Monolateral-First-CI performance with constant-level (unfilled bars) and roving-level (filled bars) stimuli as a function of bilateral experience. The top-dashed line marks chance performance (RMS error = 85°; see Figure 2b). The lower dashed lines show chance performance for being able to discriminate source hemifield with center speaker errors (RMS error = 43°; see Figure 2c) and without center speaker errors (RMS error = 35°; see Figure 2d). ["NA" indicates data not available.]

Figure 9: Monolateral-Second-CI performance with constant-level (unfilled bars) and roving-level (filled bars) stimuli as a function of bilateral experience. The dashed lines are the same as those described in Figure 8. ["NA" indicates data not available.]

Figure 10: Bilateral-CI performance with constant-level (unfilled bars) and roving-level (filled bars) stimuli as a function of bilateral experience. The dashed lines are the same as those described in Figure 8. ["NA" indicates data not available.]

Figure 11: An example pair of head-related impulse responses (HRIRs) for a source at –90°. The upper panel shows the response measured at the left microphone while the lower panel shows the response measured at the right microphone.

Figure 12: An example pair of head-related impulse responses (HRIRs) for a source at +30°. The upper panel shows the response measured at the left microphone while the lower panel shows the response measured at the right microphone.

Figure 13: Result of the cross correlation of the truncated (7-ms duration) left and right head-related impulse responses with minimal reverberation for the source at –90° shown in Figure 11. The upper panel shows the entire correlation function while the lower panel zooms in to the +/- 1 ms lag time.

Figure 14: Result of the cross correlation of the truncated (7-ms duration) left and right head-related impulse responses with minimal reverberation for the source at +30° shown in Figure 12. The upper panel shows the entire correlation function while the lower panel zooms in to the +/- 1 ms lag time.

Figure 15: ITDs corresponding to the maximum values of the cross-correlation functions of the truncated (7-ms duration) HRIRs for each speaker position. The ITDs are the same in the reverberant (10-ms duration) HRIRs when the maximum values of the cross-correlation functions are taken within +/- 1 ms lag time. Each symbol represents data for each subject with their microphones behind the ears (BTE), on the headpieces, or at the entrances of the ear canals (T-Mic).

Figure 16: Result of the cross correlation of the (100-ms duration) left and right head-related impulse responses with reverberation for the source at –90° shown in Figure 11.

The upper panel shows the entire correlation function while the lower panel zooms in to the +/- 14 ms lag time.

Figure 17: Result of the cross correlation of the (100-ms duration) left and right head-related impulse responses with reverberation for the source at +30° shown in Figure 12. The upper panel shows the entire correlation function while the lower panel zooms in to the +/- 14 ms lag time.

Figure 18: ITDs corresponding to the maximum values of the cross-correlation functions of the reverberant (100-ms duration) HRIRs for each speaker position when the entire cross-correlation functions were evaluated. Each symbol represents data for each subject with their microphones behind the ears (BTE), on the headpieces, or at the entrances of the ear canals (T-Mic).

Figure 19: ILDs corresponding to the ratio of the average power of the truncated (7-ms duration) impulse responses for each speaker position with minimal reverberation. Each symbol represents data for each subject with their microphones behind the ears (BTE), on the headpieces, or at the entrances of the ear canals (T-Mic).

Figure 20: ILDs corresponding to the ratio of the average power of the reverberant (100-ms duration) HRIRs for each speaker position. Each symbol represents data for each subject with their microphones behind the ears (BTE), on the headpieces, or at the entrances of the ear canals (T-Mic).

Figure 21: A simple decision model for source identification. $p(X|0°)$ is the conditional, probability density function for the internal decision variable, X, given a sound was presented from the source at 0°. For the current experiment with seven speakers from –90° to +90°, a set of response criteria was assumed to be halfway between two speaker positions ($C_0 = -\infty$, $C_1 = -75°$, $C_2 = -45°$, $C_3 = -15°$, $C_4 = +15°$, $C_5 = +45°$, $C_6 = +75°$, and $C_7 = \infty$). The observer responds R_k if and only if $C_{k-1} < X \leq C_k$.

Figure 22: Measured and modeled performance for the center (0°) speaker predicted from the subjects' ITD and ILD JNDs. The dashed line represents chance performance (RMS error = 60°; subject equally likely to choose any one of the seven responses when the center speaker is activated.

Figure 23: Mean RMS error (bars) and standard deviation (error bars) for all subjects in the current study and in three other studies. Moving from left to right in each panel, the first bar (N=5 subjects) represents the current study results measured during the *bilateral period* with constant-level stimuli; the second bar (N=1) represents data from van Hoesel et al. (2002); the third bar (N=5) data from van Hoesel and Tyler (2003); and the fourth bar (N=17) data from Litovsky et al. (2004). Individual data (if reported) are marked by 'x'. The left and right panels show performance using the left- or right-CI alone. Bilateral performance is shown in the middle panel.

Figure 24: Means (bars) and standard deviations (error bars) for deviation, *d*, [as defined in Nopp et al (2004)] of all subjects in the current study and in the study by Nopp et al. (2004). The first bar (N=5 subjects) represents the current study results measured during the *bilateral period* with roving-level stimuli. The second bar (N=20) represents the data from Nopp et al. (2004). Individual data are marked by 'x'. The left and right panels show performance using the left and right CI alone. Bilateral performance is shown in the middle panel.

Figure 25: Two methods of evaluation of bilateral benefit with constant-level data. The upper panel shows the prevailing method of evaluation comparing monolateral (left bar above each subject ID) and bilateral (right bar above each subject ID) performance measured after months of bilateral listening (white bars). The lower panel shows a more appropriate method of evaluation of bilateral benefit by comparing the experienced bilateral performance (white bars) with the experienced monolateral performance measured prior to the onset of bilateral CI use (gray bars). * indicates significant difference between the monolateral and bilateral measurements with $p<0.05$. The dashed lines are the same as those described in Figure 8.

Figure 26: Two methods of evaluation of bilateral benefit with roving-level data. The upper panel shows the prevailing method of evaluation comparing monolateral (left bar above each subject ID) and bilateral (right bar above each subject ID) performance measured after months of bilateral listening (black bars). The lower panel shows a more appropriate method of evaluation of bilateral benefit by comparing the experienced bilateral performance (black bars) with the experienced monolateral performance measured prior to the onset of bilateral CI use (gray bars). * indicates significant difference between the monolateral and bilateral measurements with $p<0.05$. The dashed lines are the same as those described in Figure 8. ["NA" indicates data not available.]

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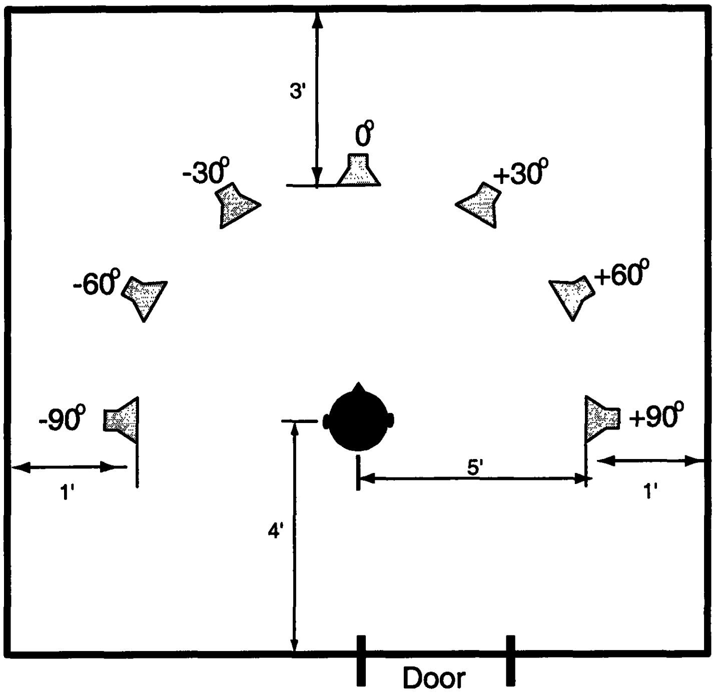


Figure 2: Five Hypothetical stimulus-responses matrices. Panel a shows perfect performance (RMS error = 0°). Panel b shows chance performance for a subject unable to discriminate source hemifield (RMS error = 85°). For a subject able to discriminate source hemifield, panels c and d show the performance and the error difference without (RMS error = 43°) and with (RMS error = 35°) correct identification of the center speaker, respectively. Panel e shows biased performance, resulting in a RMS error (108°) greater than chance performance in panel b.

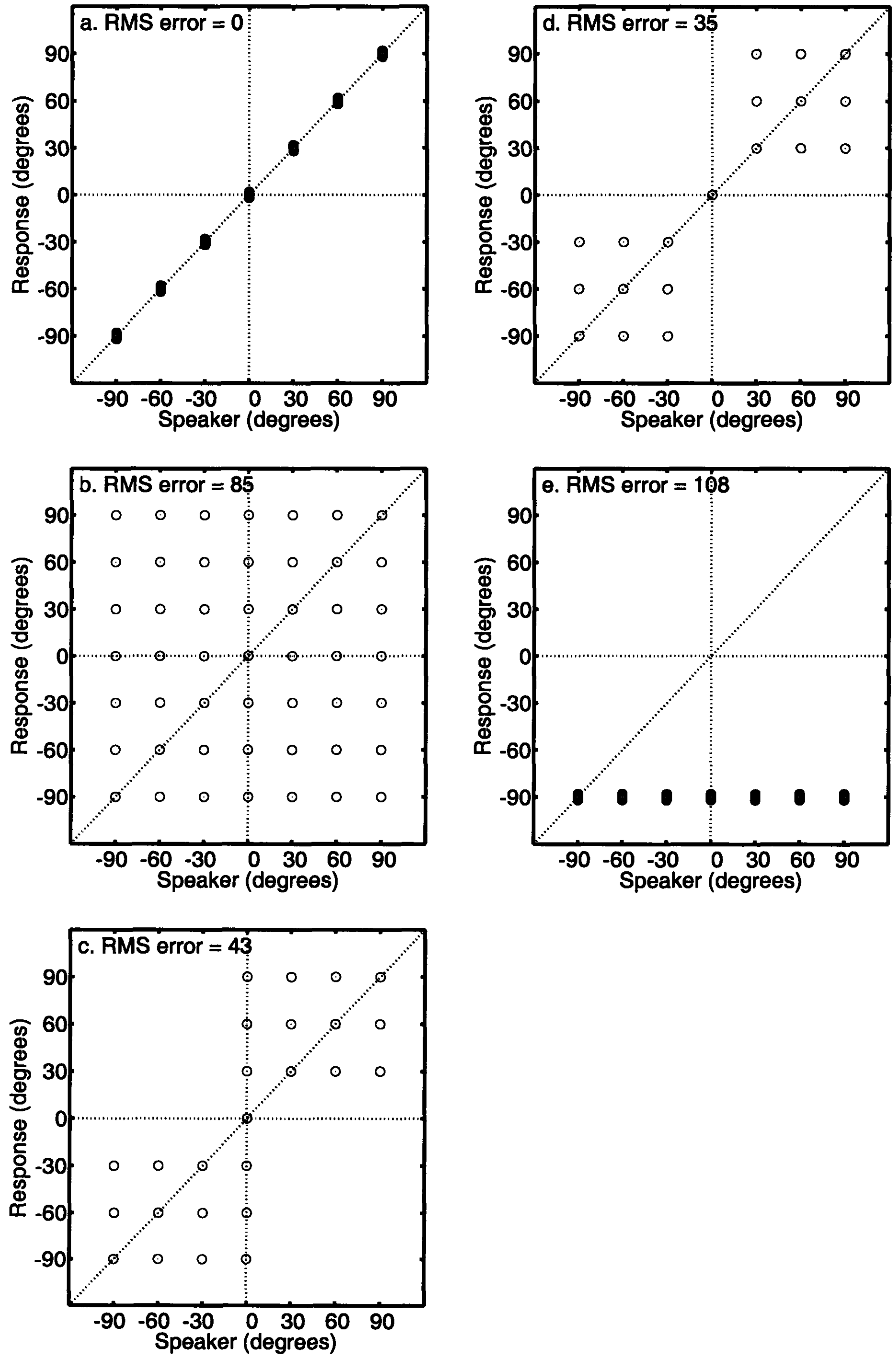


Figure 3: C092's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 7 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance. ["NA" indicates data not available.]

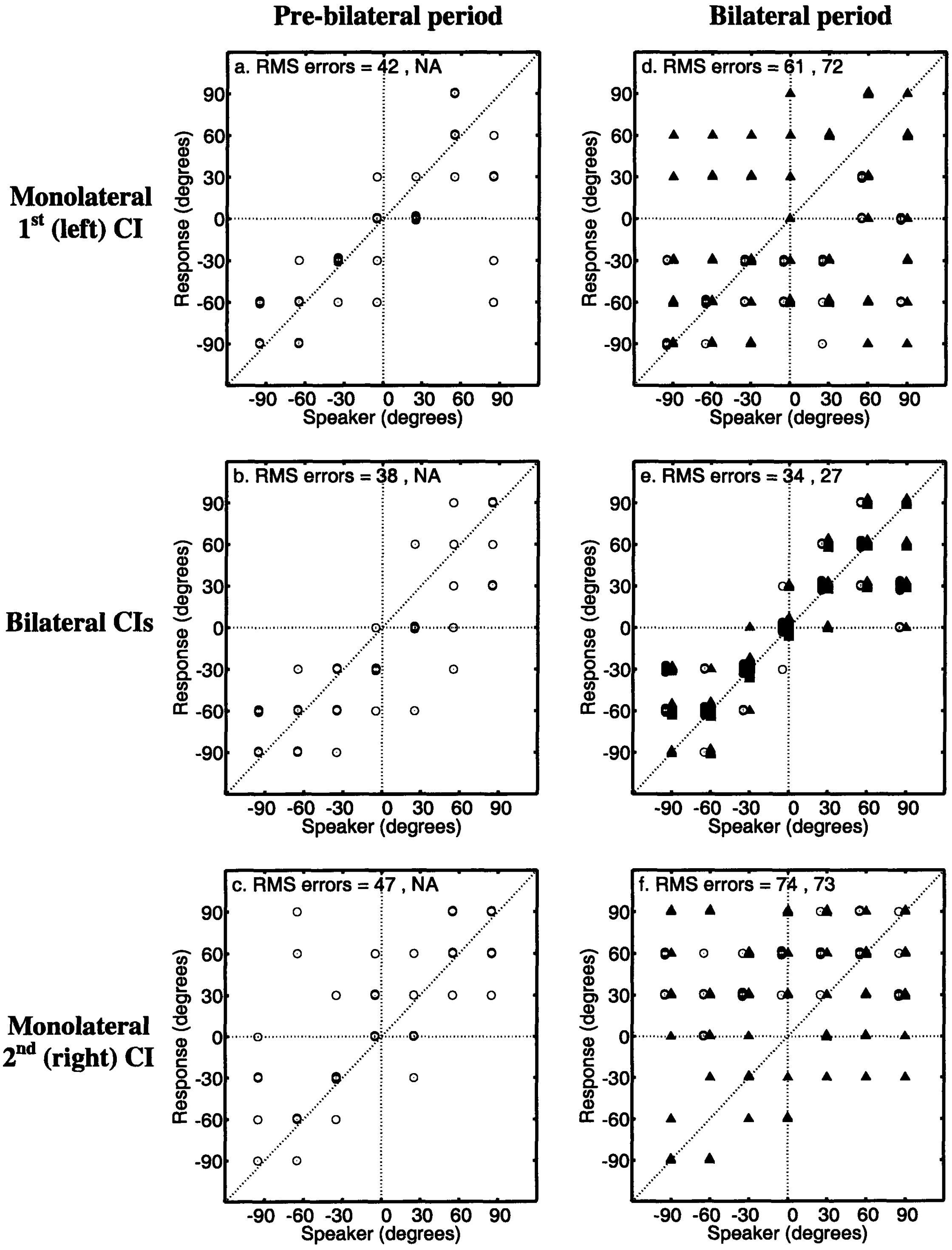


Figure 4: C105's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 3 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance.

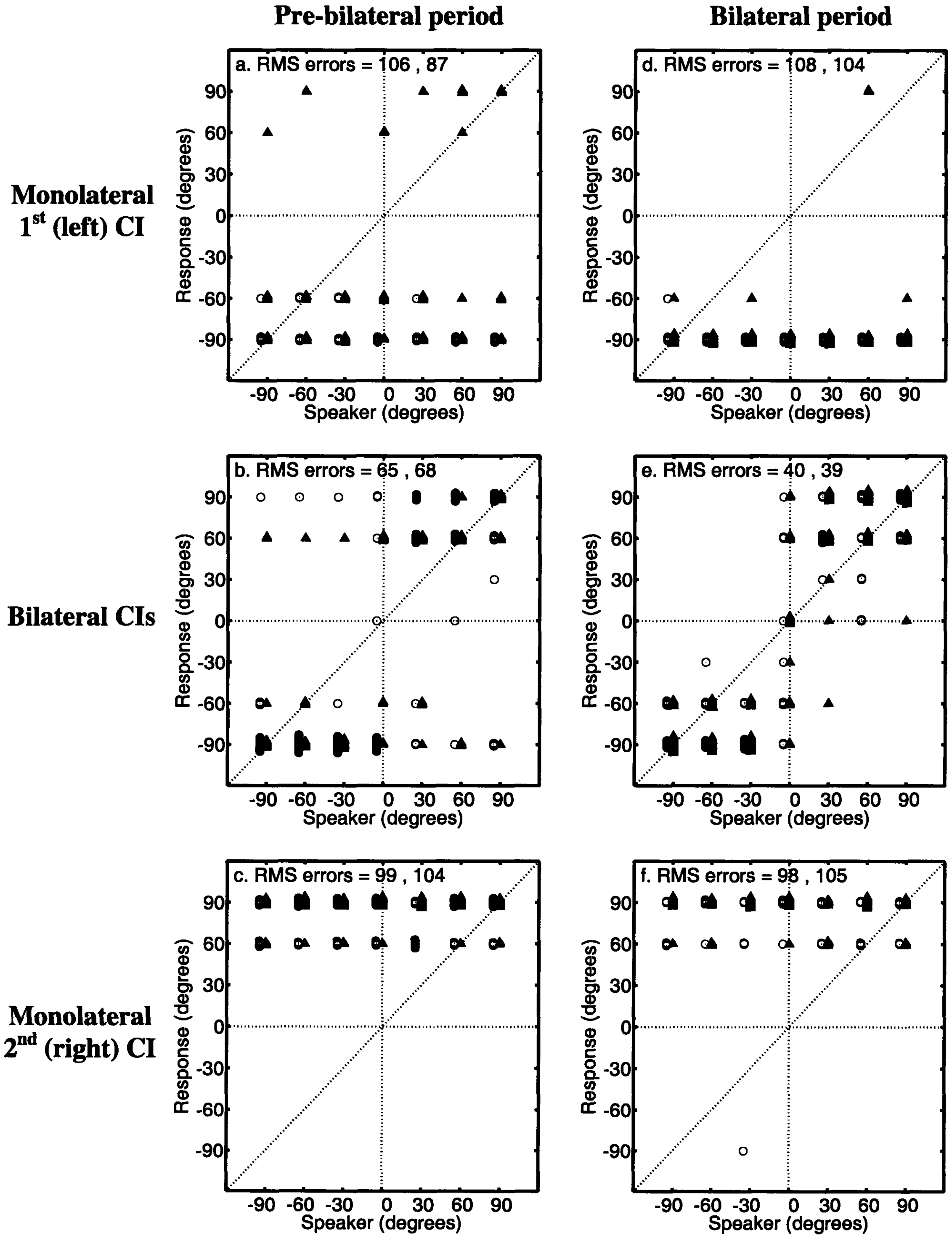


Figure 5: C109's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 3 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance.

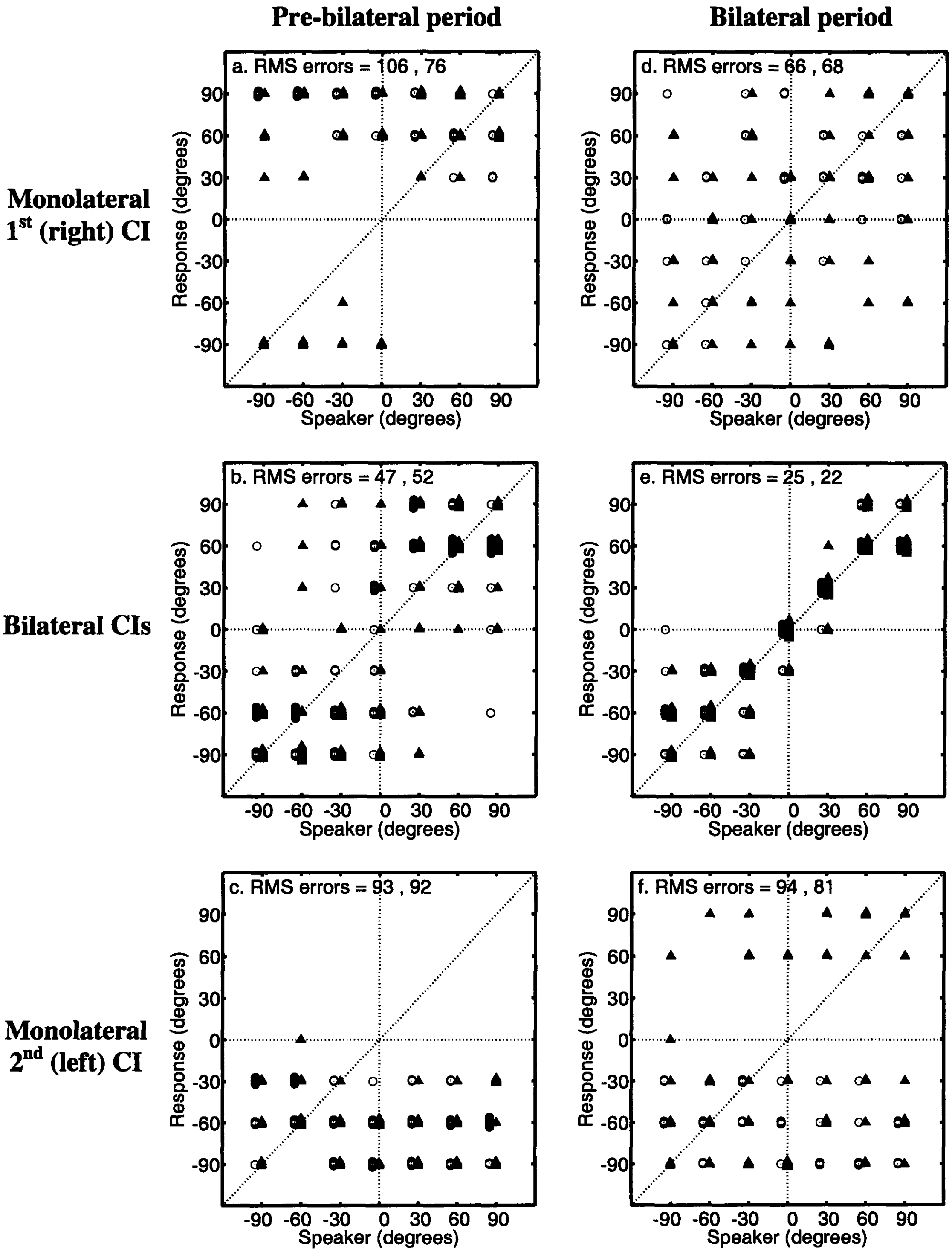


Figure 6: C120's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 6 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance. ["NA" indicates data not available.]

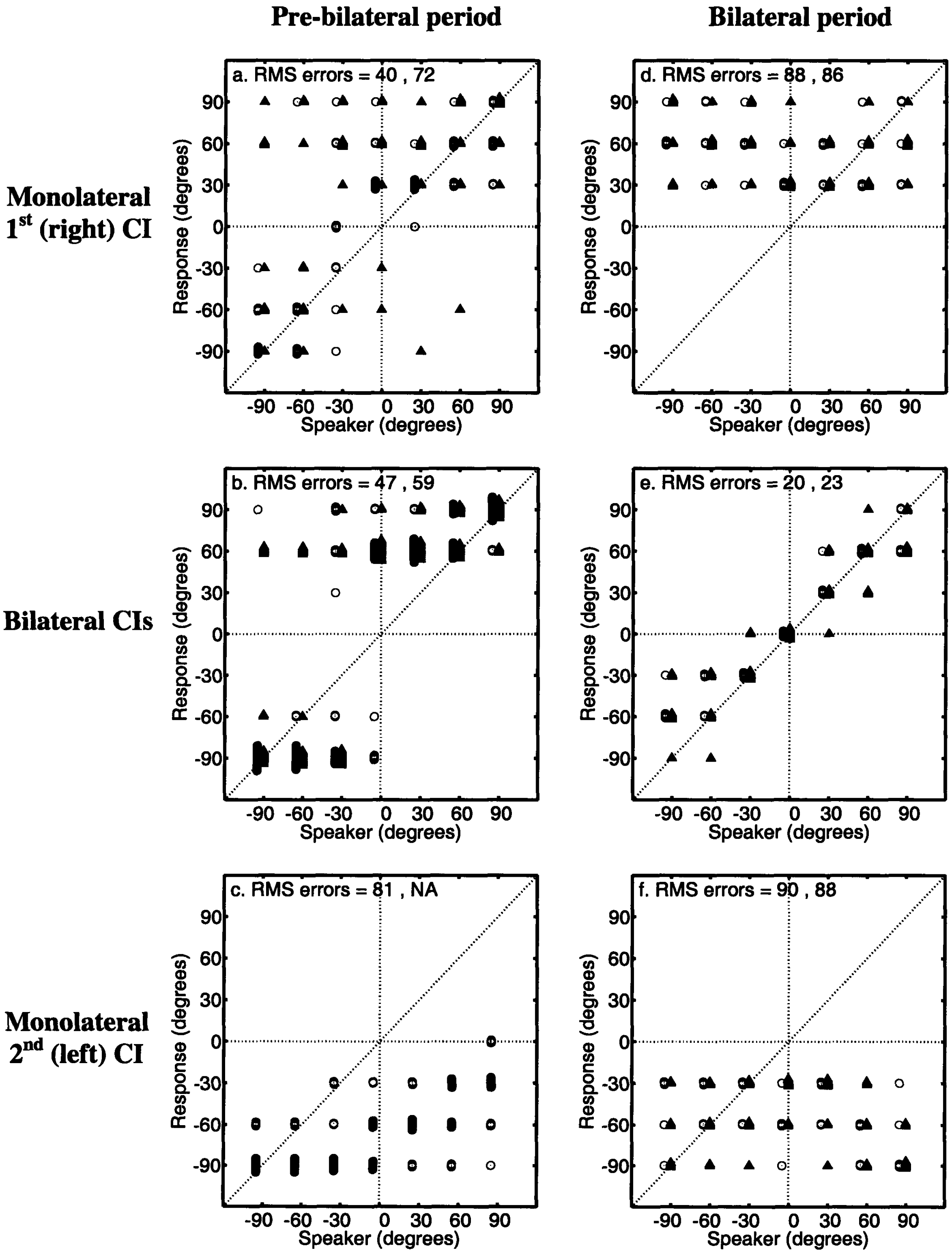


Figure 7: C128's stimulus-response matrices. The left-column panels (a – c) show performance without bilateral experience. The right-column panels (d – f) show performance with 7 months of bilateral experience. Data for constant-level (o) and roving-level stimuli (▲) are offset horizontally for clarity. The first RMS error listed corresponds to the constant-level performance, and the second RMS error corresponds to the roving-level performance.

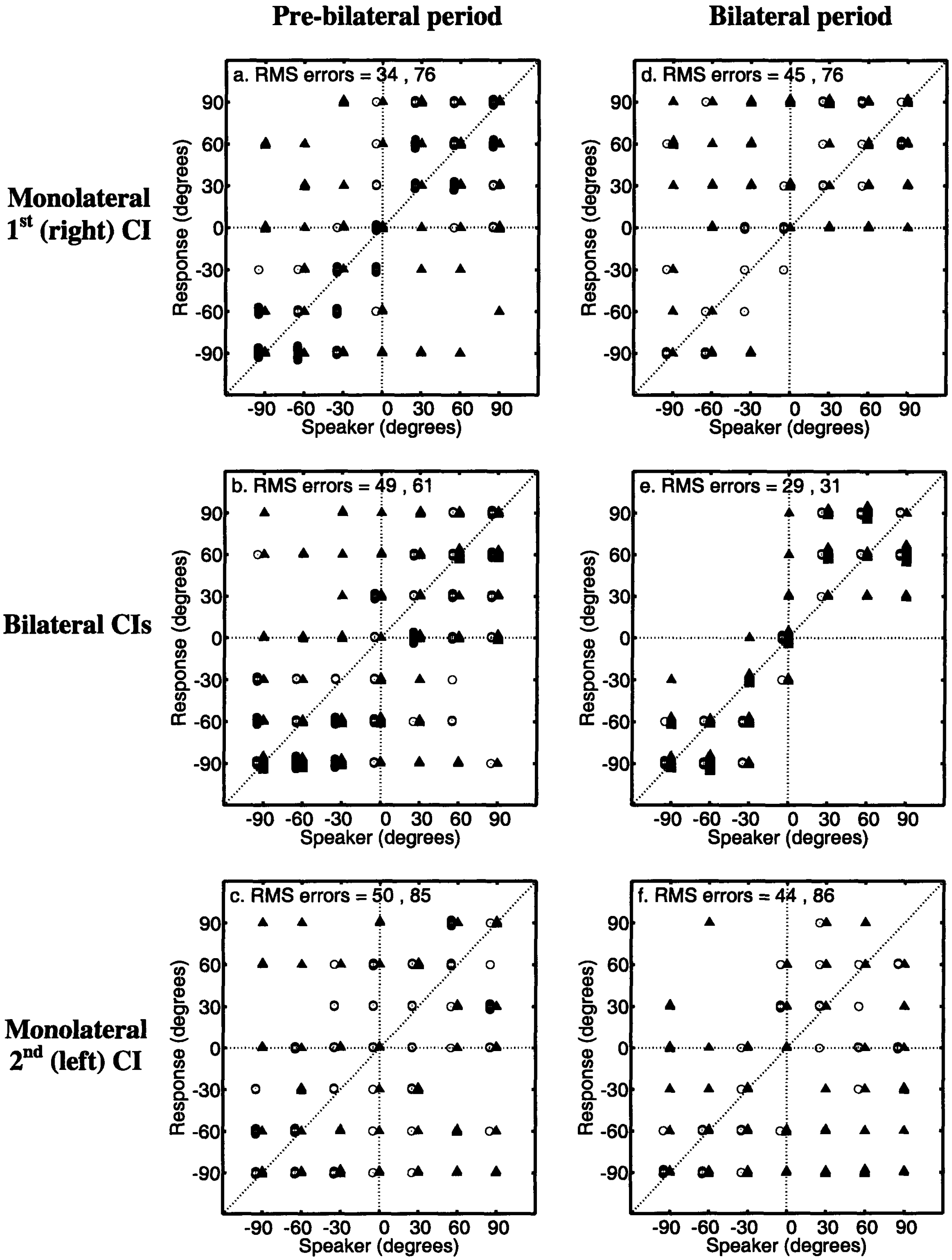


Figure 8: Monolateral-First-CI performance with constant-level (unfilled bars) and roving-level (filled bars) stimuli as a function of bilateral experience. The top-dashed line marks chance performance (RMS error = 85°; see Figure 2b). The lower dashed lines show chance performance for being able to discriminate source hemifield with center speaker errors (RMS error = 43°; see Figure 2c) and without center speaker errors (RMS error = 35°; see Figure 2d). ["NA" indicates data not available.]

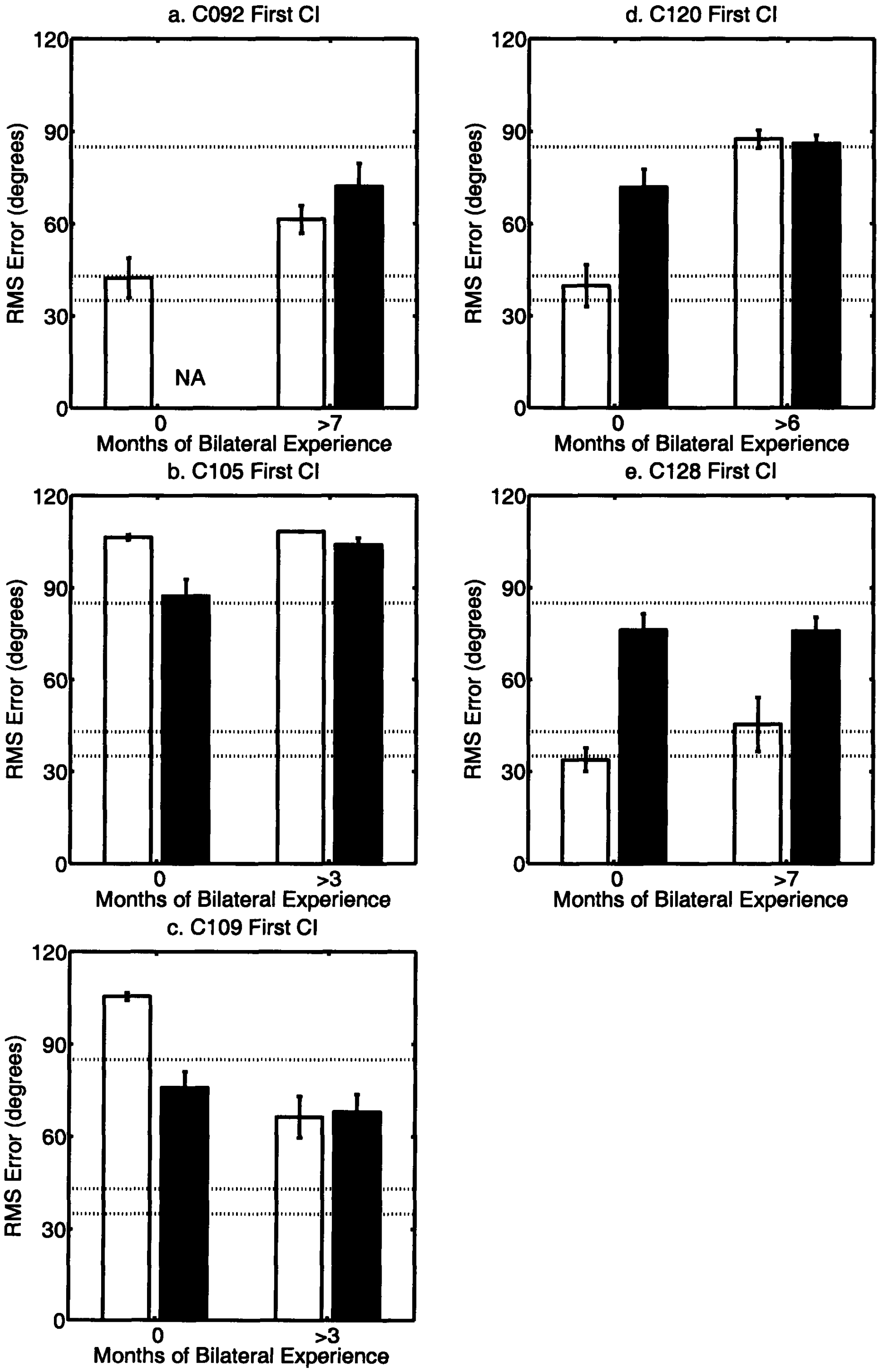
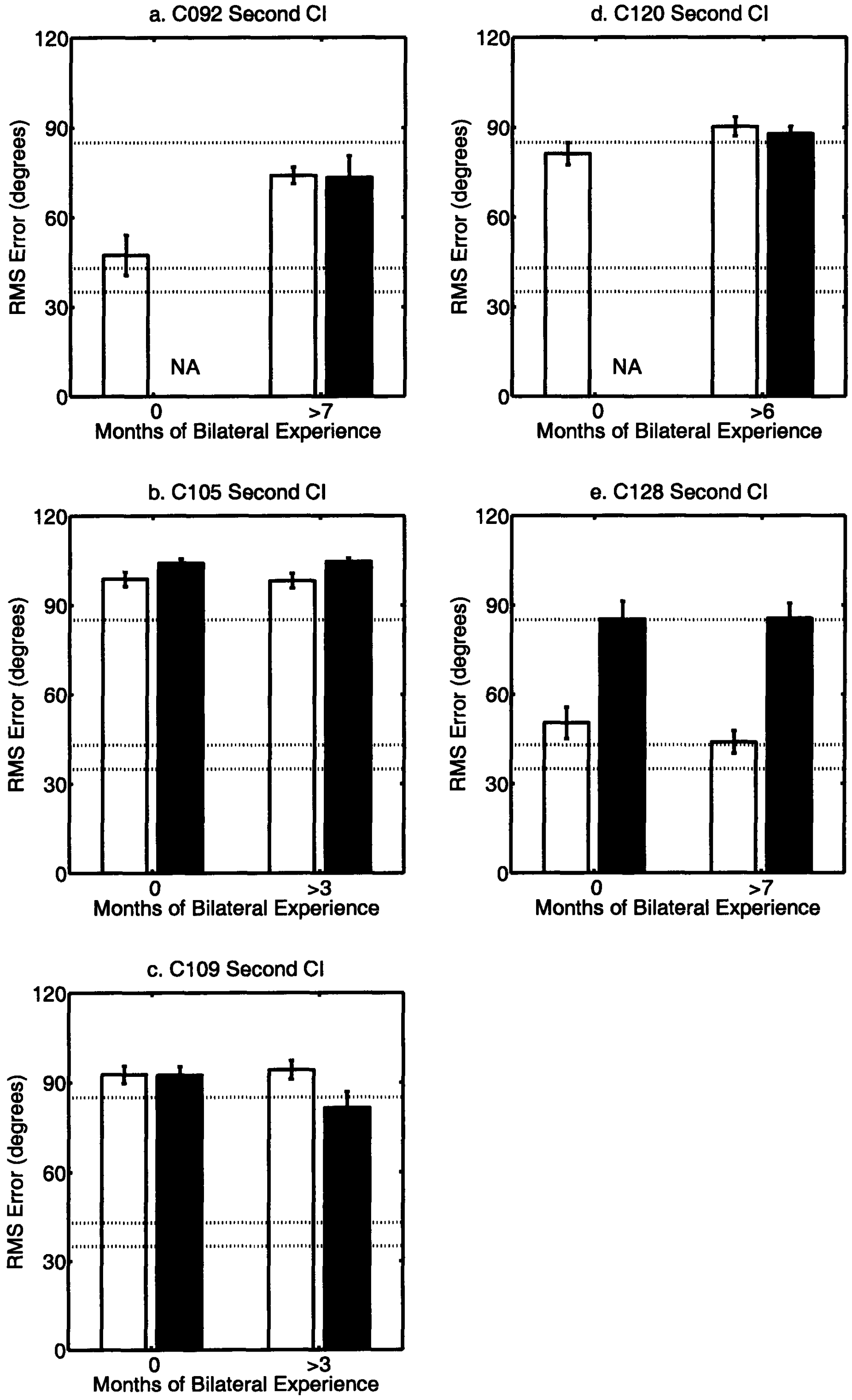


Figure 9: Monolateral-Second-CI performance with constant-level (unfilled bars) and roving-level (filled bars) stimuli as a function of bilateral experience. The dashed lines are the same as those described in Figure 8. ["NA" indicates data not available.]


a. C092 Second CI

d. C120 Second CI

b. C105 Second CI

e. C128 Second CI

c. C109 Second CI

Figure 10: Bilateral-CI performance with constant-level (unfilled bars) and roving-level (filled bars) stimuli as a function of bilateral experience. The dashed lines are the same as those described in Figure 8. ["NA" indicates data not available.]

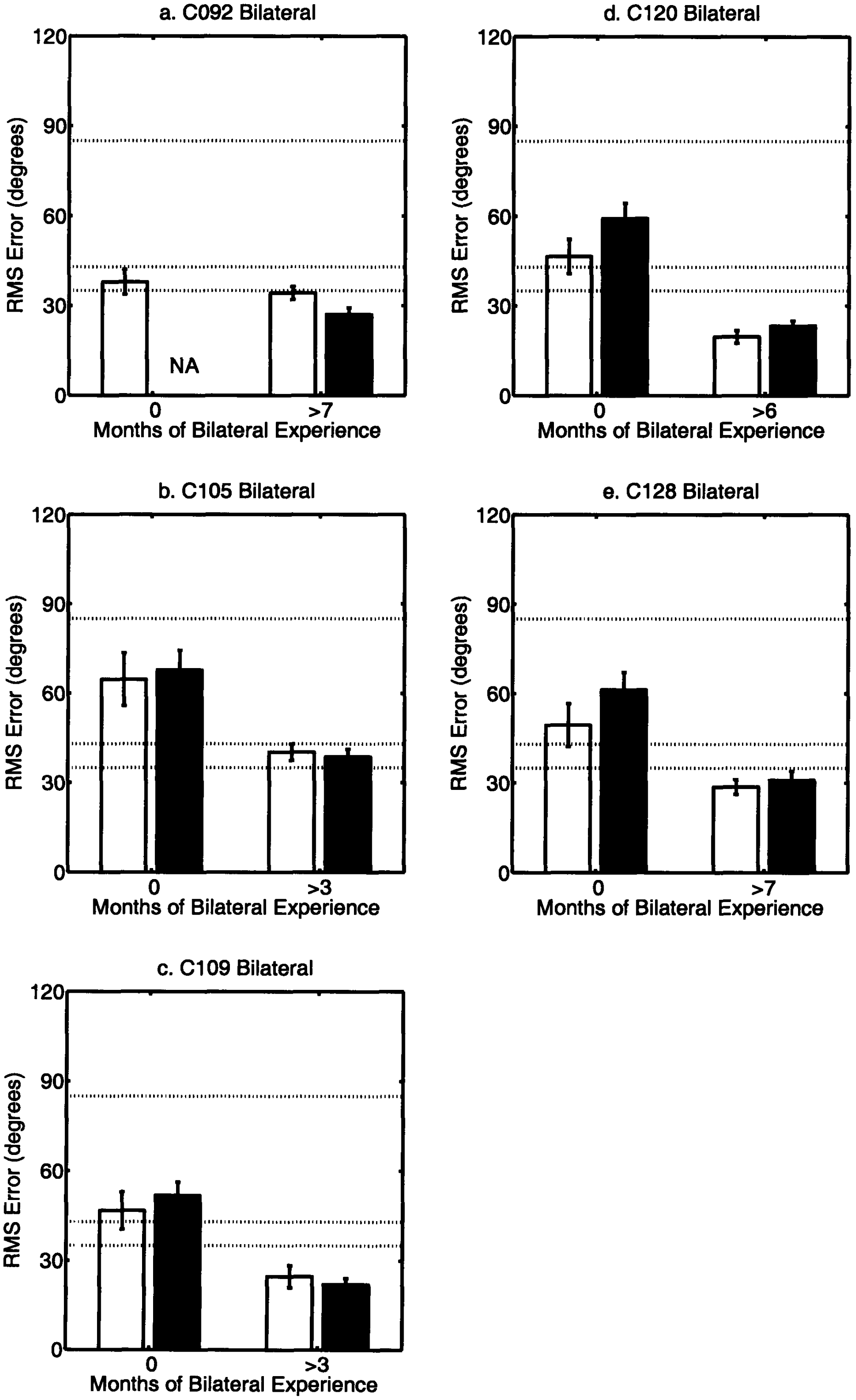
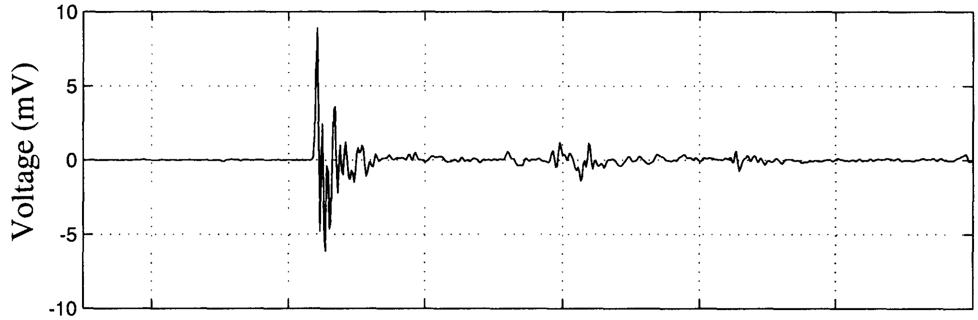


Figure 11: An example pair of head-related impulse responses (HRIRs) for a source at –90°. The upper panel shows the response measured at the left microphone while the lower panel shows the response measured at the right microphone.

a. Left HRIR



b. Right HRIR

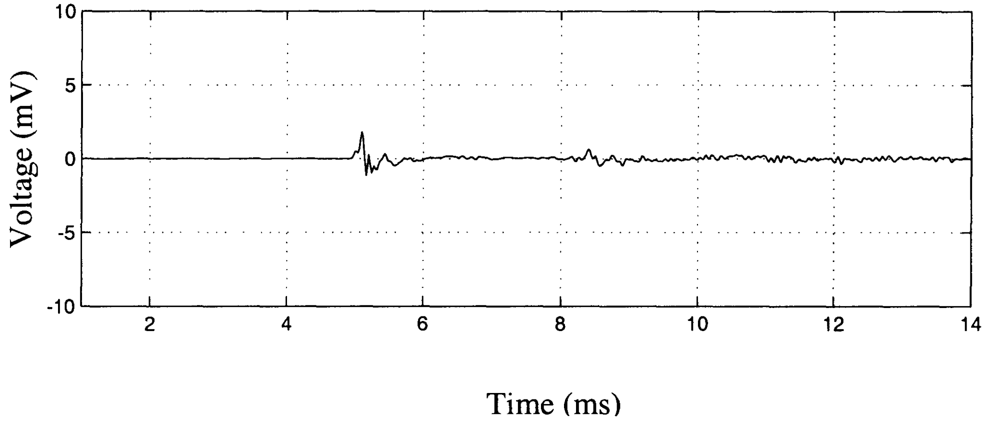
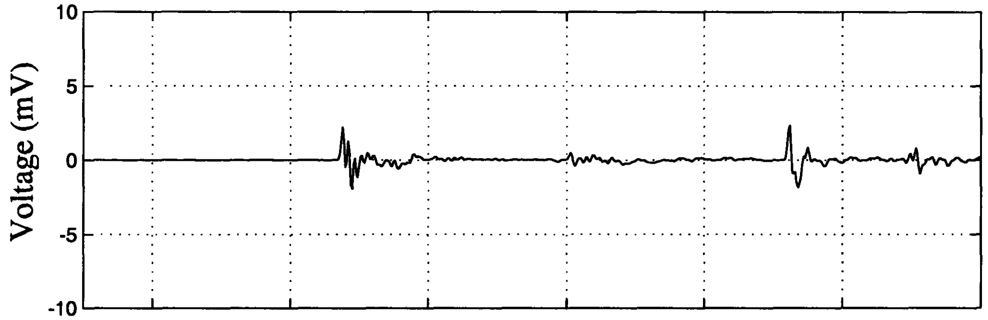


Figure 12: An example pair of head-related impulse responses (HRIRs) for a source at +30°. The upper panel shows the response measured at the left microphone while the lower panel shows the response measured at the right microphone.

a. Left HRIR



b. Right HRIR

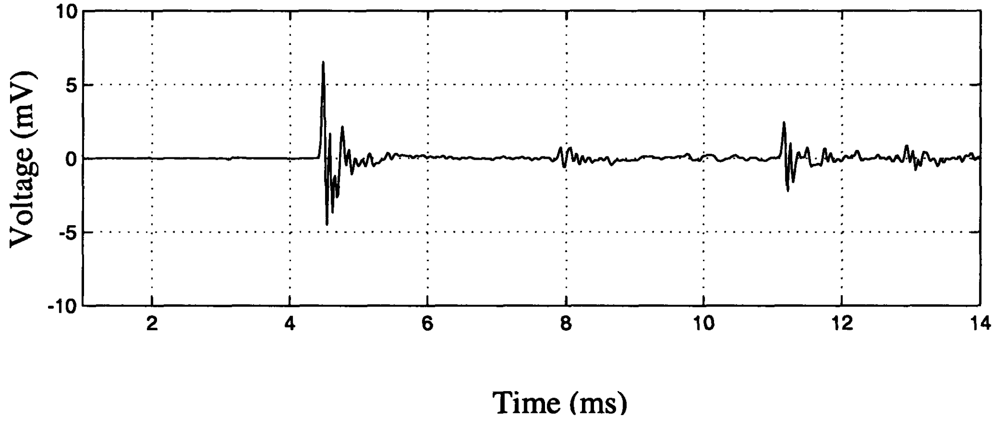


Figure 13: Result of the cross correlation of the truncated (7-ms duration) left and right head-related impulse responses with minimal reverberation for the source at –90° shown in Figure 11. The upper panel shows the entire correlation function while the lower panel zooms in to the +/- 1 ms lag time.

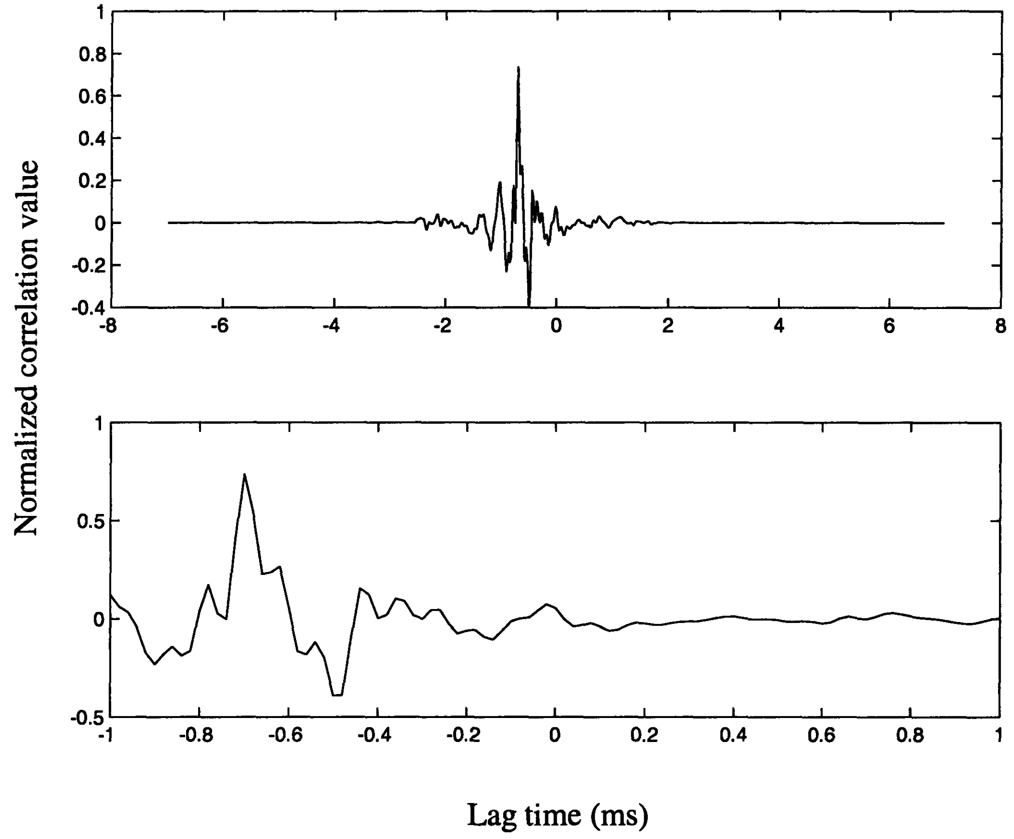


Figure 14: Result of the cross correlation of the truncated (7-ms duration) left and right head-related impulse responses with minimal reverberation for the source at +30° shown in Figure 12. The upper panel shows the entire correlation function while the lower panel zooms in to the +/- 1 ms lag time.

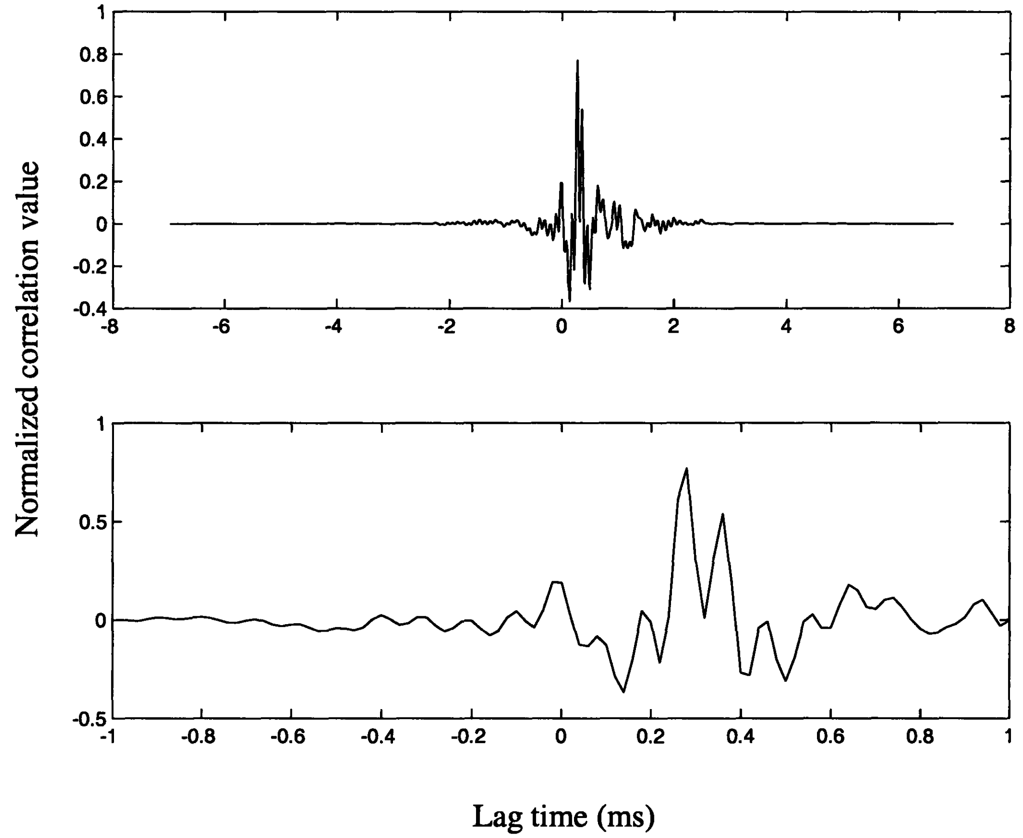


Figure 15: ITDs corresponding to the maximum values of the cross-correlation functions of the truncated (7-ms duration) HRIRs for each speaker position. The ITDs are the same in the reverberant (10-ms duration) HRIRs when the maximum values of the cross-correlation functions are taken within +/- 1 ms lag time. Each symbol represents data for each subject with their microphones behind the ears (BTE), on the headpieces, or at the entrances of the ear canals (T-Mic).

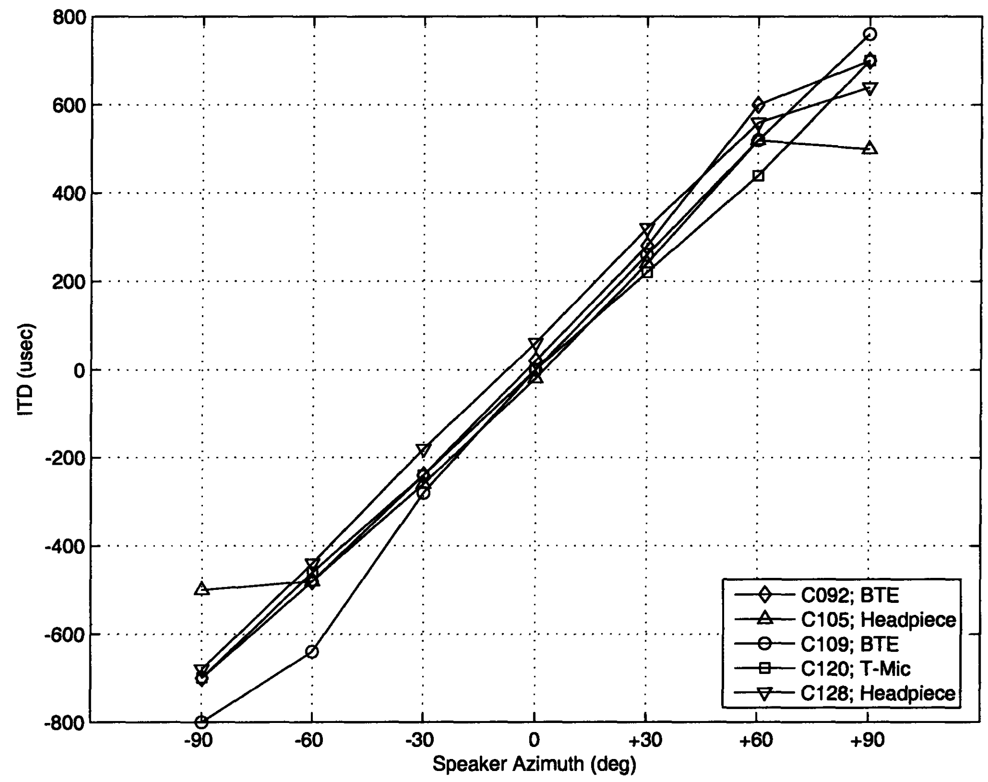


Figure 16: Result of the cross correlation of the (100-ms duration) left and right head-related impulse responses with reverberation for the source at –90° shown in Figure 11. The upper panel shows the entire correlation function while the lower panel zooms in to the +/- 14 ms lag time.

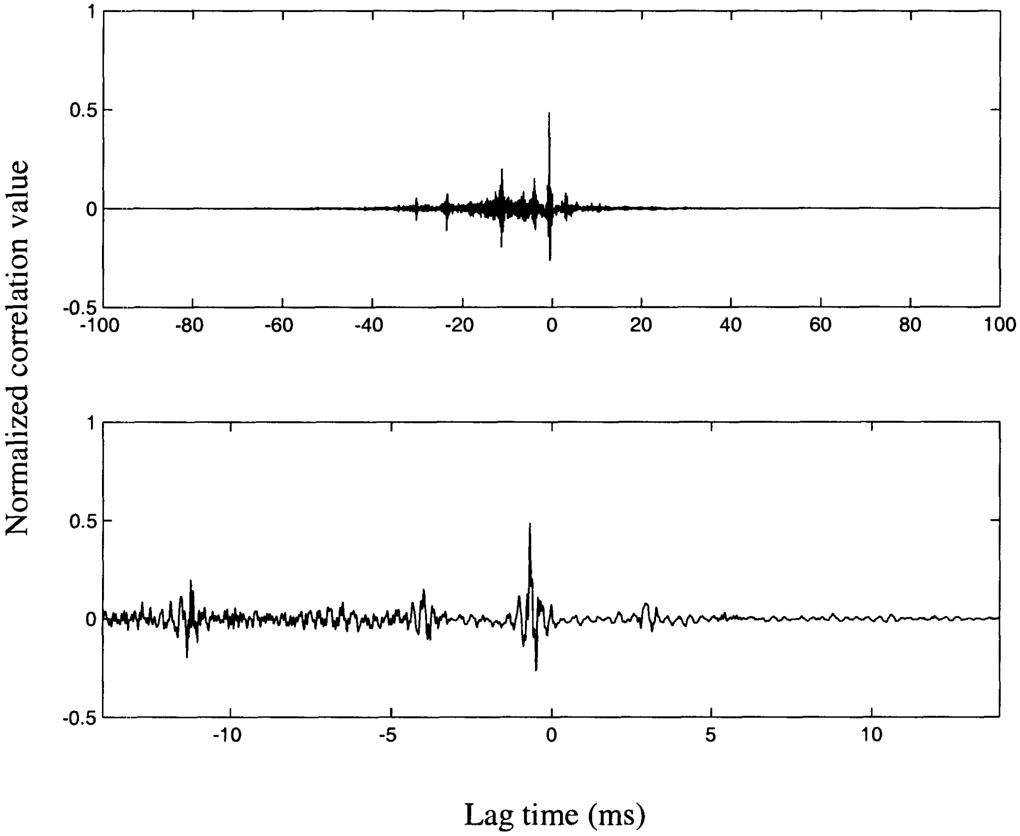


Figure 17: Result of the cross correlation of the (100-ms duration) left and right head-related impulse responses with reverberation for the source at +30° shown in Figure 12. The upper panel shows the entire correlation function while the lower panel zooms in to the +/- 14 ms lag time.

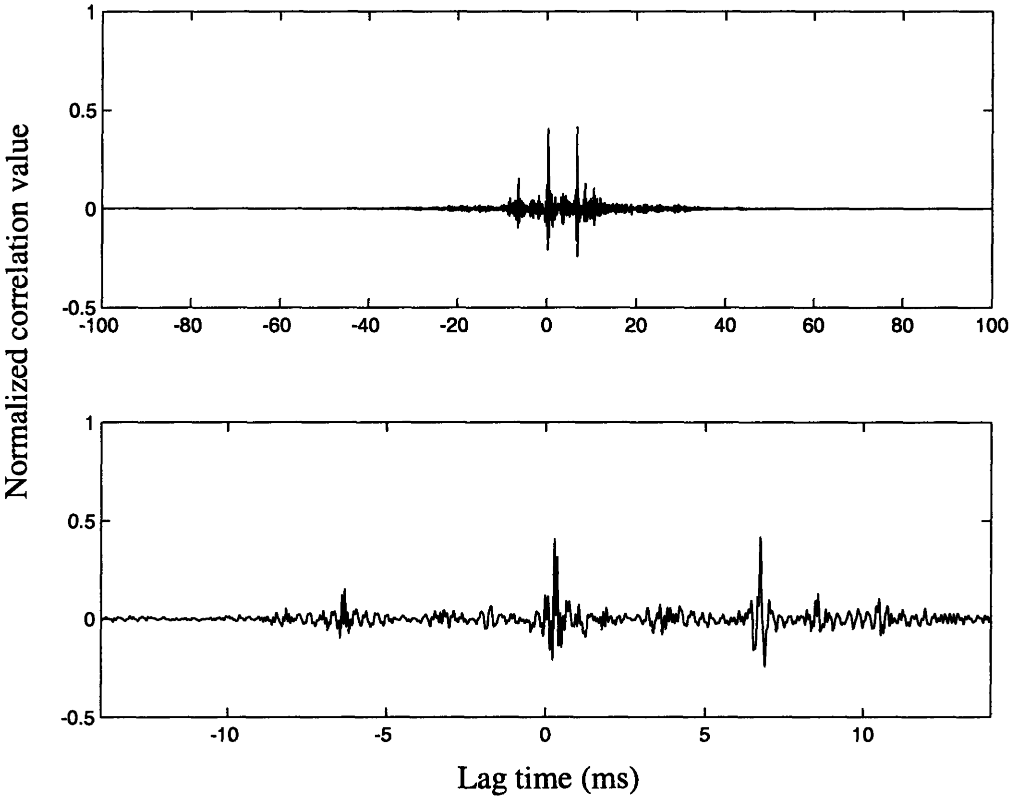


Figure 18: ITDs corresponding to the maximum values of the cross-correlation functions of the reverberant (100-ms duration) HRIRs for each speaker position when the entire cross-correlation functions were evaluated. Each symbol represents data for each subject with their microphones behind the ears (BTE), on the headpieces, or at the entrances of the ear canals (T-Mic).

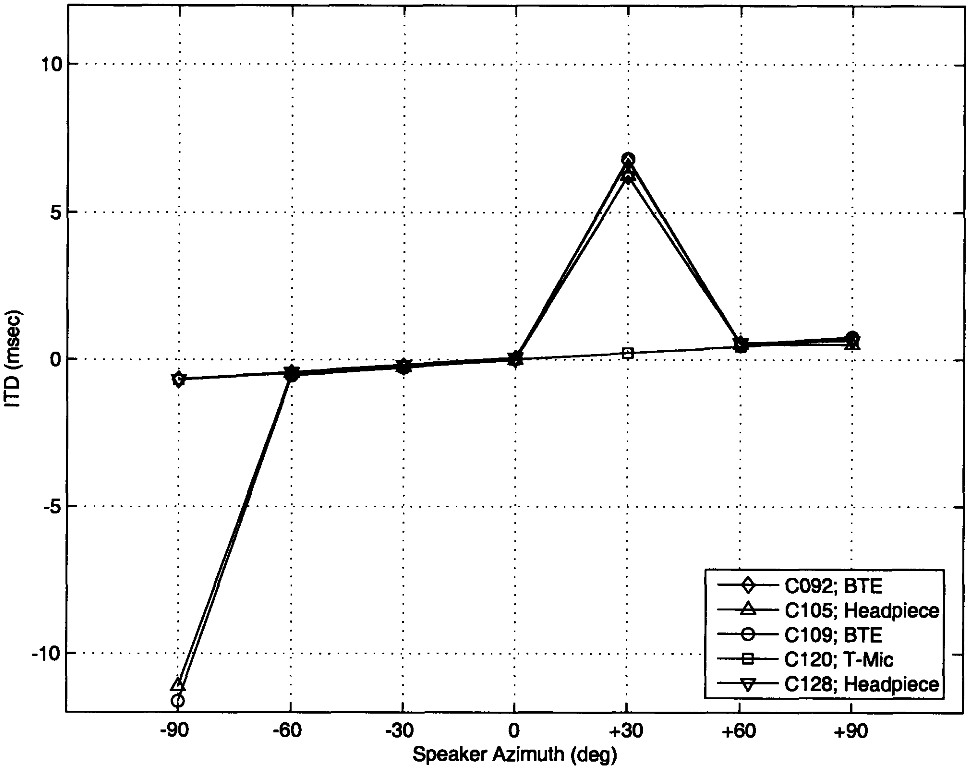


Figure 19: ILDs corresponding to the ratio of the average power of the truncated (7-ms duration) impulse responses for each speaker position with minimal reverberation. Each symbol represents data for each subject with their microphones behind the ears (BTE), on the headpieces, or at the entrances of the ear canals (T-Mic).

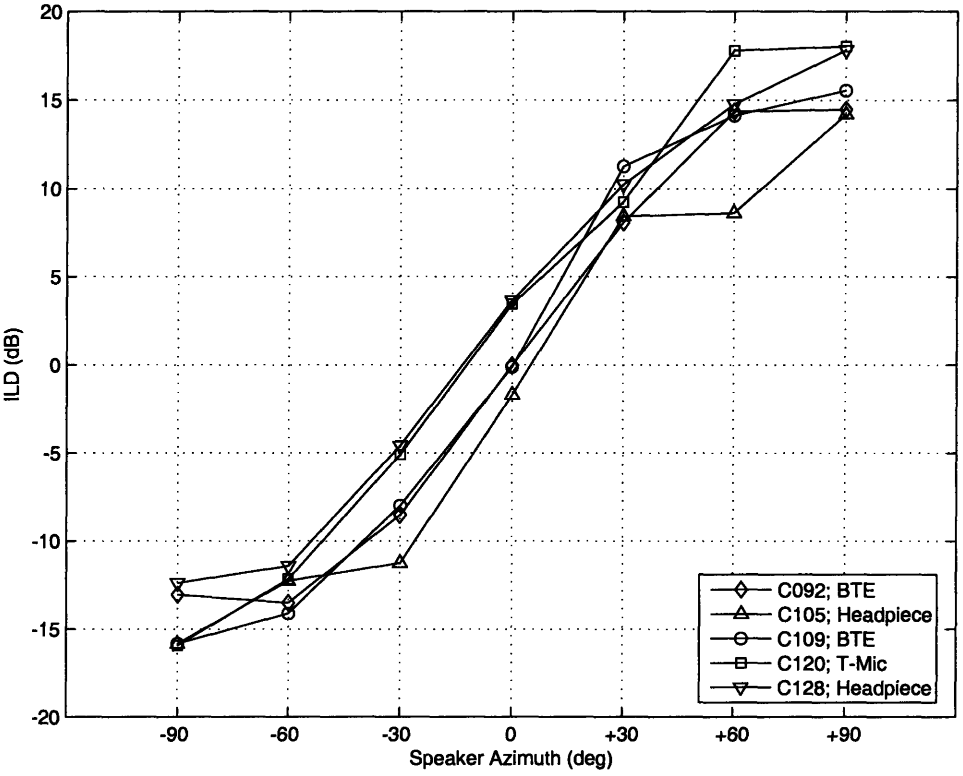


Figure 20: ILDs corresponding to the ratio of the average power of the reverberant (100-ms duration) HRIRs for each speaker position. Each symbol represents data for each subject with their microphones behind the ears (BTE), on the headpieces, or at the entrances of the ear canals (T-Mic).

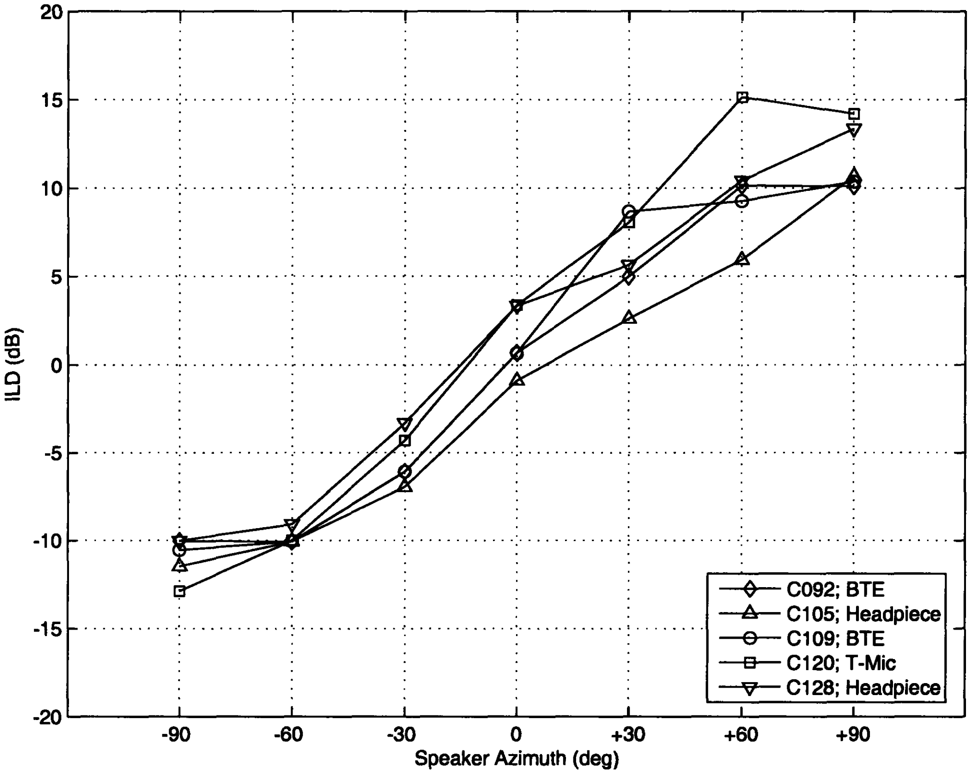


Figure 21: A simple decision model for source identification. $p(X|0°)$ is the conditional, probability density function for the internal decision variable, X, given a sound was presented from the source at 0°. For the current experiment with seven speakers from –90° to +90°, a set of response criteria was assumed to be halfway between two speaker positions ($C_0 = -\infty$, $C_1 = -75°$, $C_2 = -45°$, $C_3 = -15°$, $C_4 = +15°$, $C_5 = +45°$, $C_6 = +75°$, and $C_7 = \infty$). The observer responds R_k if and only if $C_{k-1} < X \leq C_k$.

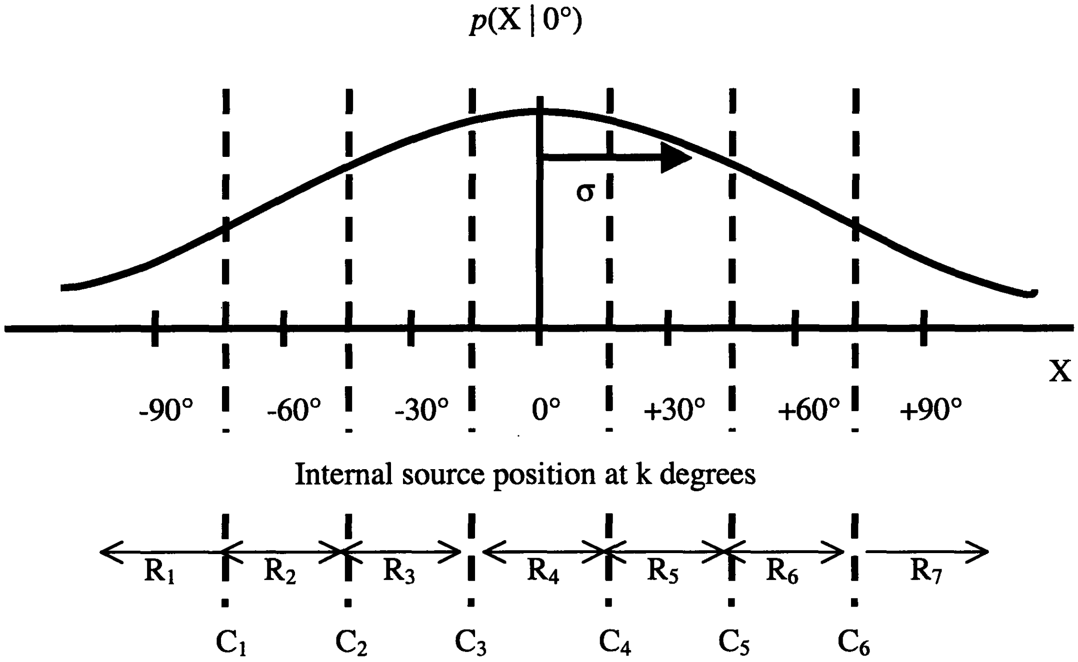


Figure 22: Measured and modeled performance for the center (0°) speaker predicted from the subjects' ITD and ILD JNDs. The dashed line represents chance performance (RMS error = 60°; subject equally likely to choose any one of the seven responses when the center speaker is activated.

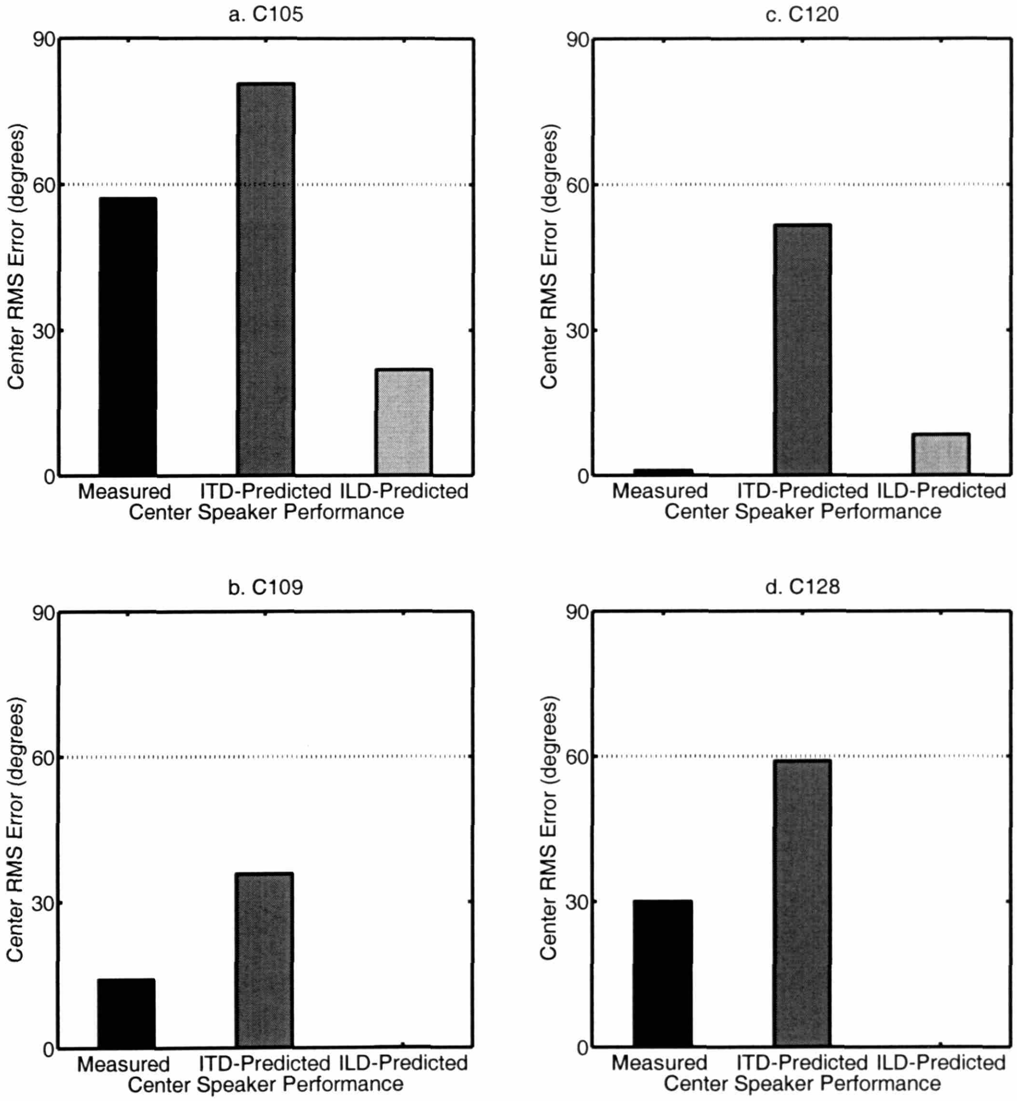


Figure 23: Mean RMS error (bars) and standard deviation (error bars) for all subjects in the current study and in three other studies. Moving from left to right in each panel, the first bar (N=5 subjects) represents the current study results measured during the *bilateral period* with constant-level stimuli; the second bar (N=1) represents data from van Hoesel et al. (2002); the third bar (N=5) data from van Hoesel and Tyler (2003); and the fourth bar (N=17) data from Litovsky et al. (2004). Individual data (if reported) are marked by 'x'. The left and right panels show performance using the left- or right-CI alone. Bilateral performance is shown in the middle panel.

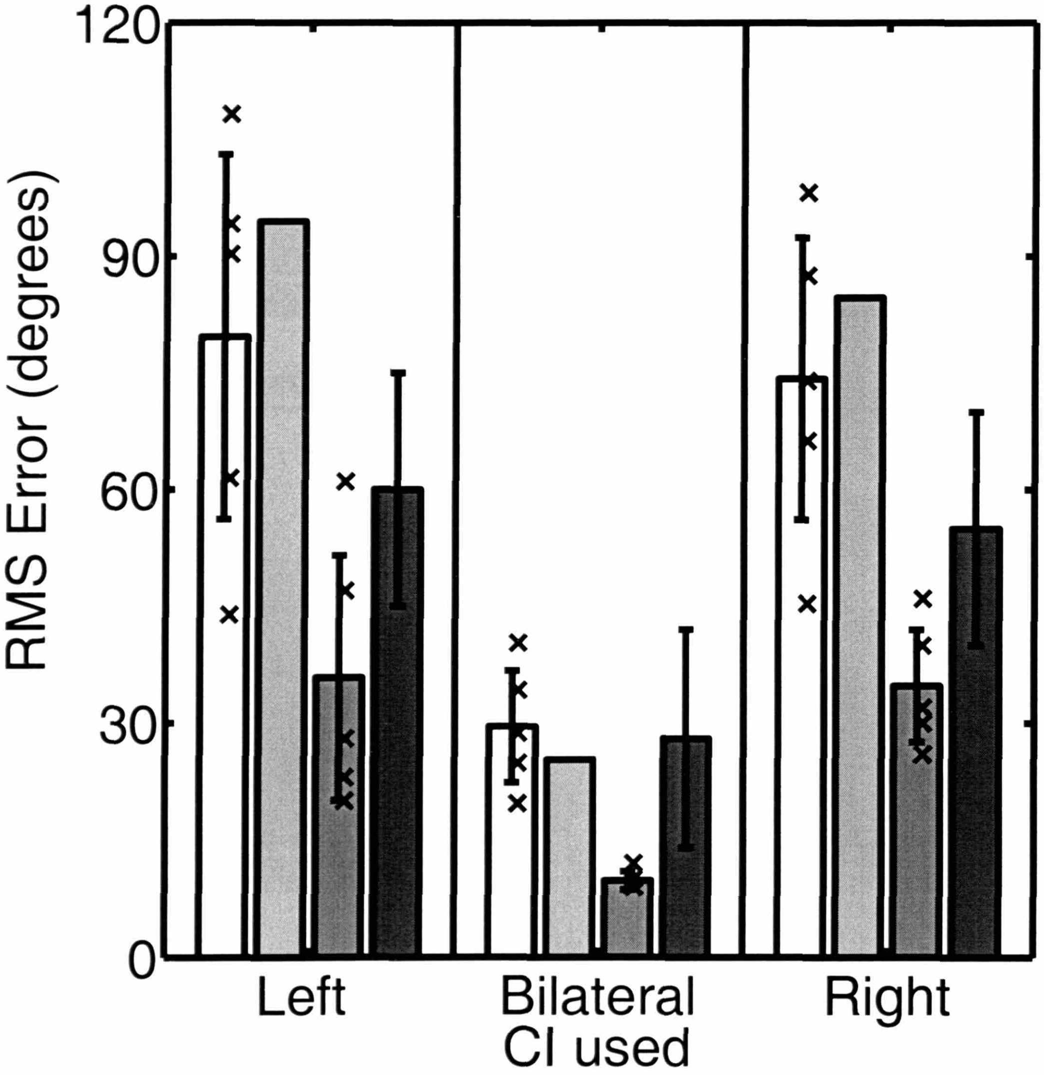


Figure 24: Means (bars) and standard deviations (error bars) for deviation, *d*, [as defined in Nopp et al (2004)] of all subjects in the current study and in the study by Nopp et al. (2004). The first bar (N=5 subjects) represents the current study results measured during the *bilateral period* with roving-level stimuli. The second bar (N=20) represents the data from Nopp et al. (2004). Individual data are marked by 'x'. The left and right panels show performance using the left and right CI alone. Bilateral performance is shown in the middle panel.

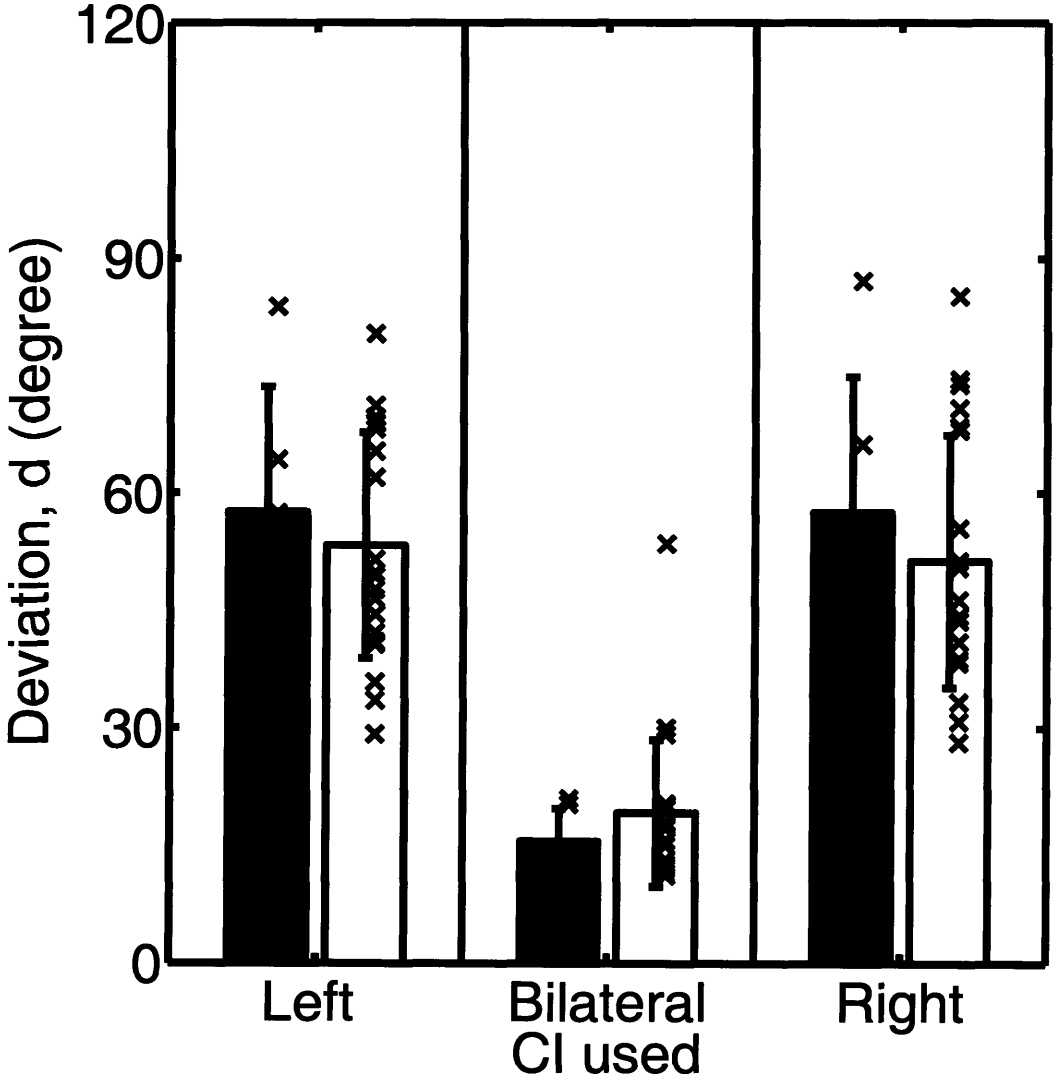


Figure 25: Two methods of evaluation of bilateral benefit with constant-level data. The upper panel shows the prevailing method of evaluation comparing monolateral (left bar above each subject ID) and bilateral (right bar above each subject ID) performance measured after months of bilateral listening (white bars). The lower panel shows a more appropriate method of evaluation of bilateral benefit by comparing the experienced bilateral performance (white bars) with the experienced monolateral performance measured prior to the onset of bilateral CI use (gray bars). * indicates significant difference between the monolateral and bilateral measurements with $p<0.05$. The dashed lines are the same as those described in Figure 8.

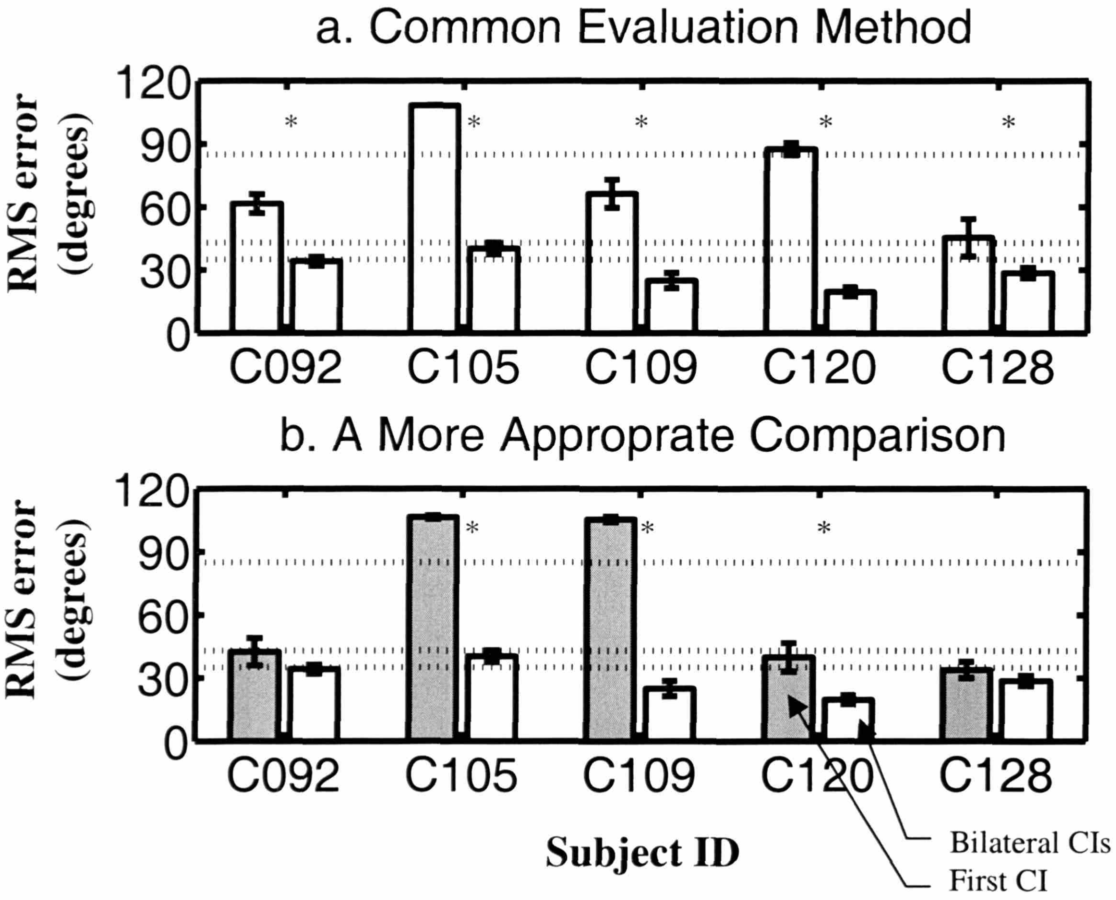
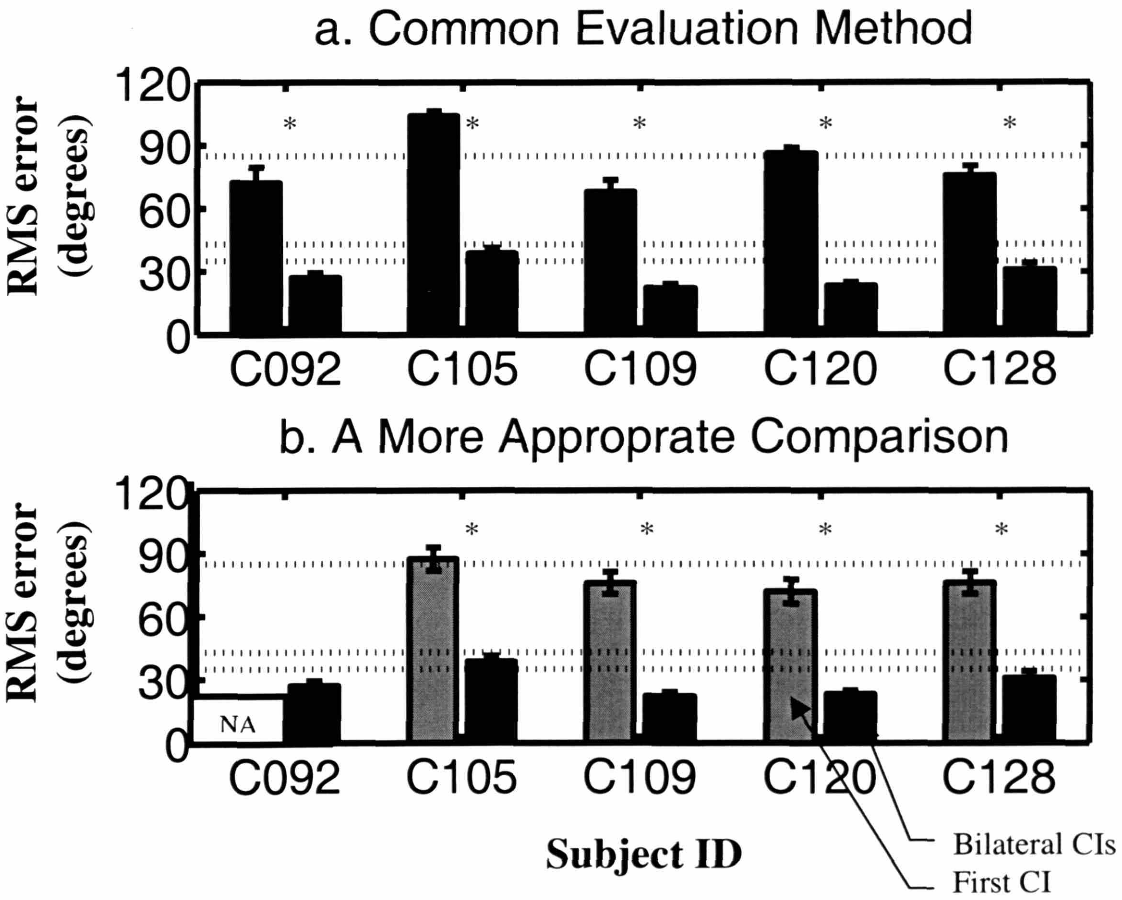


Figure 26: Two methods of evaluation of bilateral benefit with roving-level data. The upper panel shows the prevailing method of evaluation comparing monolateral (left bar above each subject ID) and bilateral (right bar above each subject ID) performance measured after months of bilateral listening (black bars). The lower panel shows a more appropriate method of evaluation of bilateral benefit by comparing the experienced bilateral performance (black bars) with the experienced monolateral performance measured prior to the onset of bilateral CI use (gray bars). * indicates significant difference between the monolateral and bilateral measurements with $p<0.05$. The dashed lines are the same as those described in Figure 8. ["NA" indicates data not available.]



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Chapter 3

Effects of Number of Pulses and Repetition Rate on Interaural Time Sensitivity with Bilateral Cochlear Implants

ABSTRACT

Poor ITD sensitivity may be one reason that bilateral cochlear implant (CI) listeners' sound localization performance is poor compared to that of normal-hearing listeners. To improve ITD sensitivity, a first step is to characterize the ITD sensitivity in CI listeners for single, interaural electrode pairs stimulated with pulse trains, the basic stimulation waveform used in most sound processors. The work reported here studied the dependence of ITD sensitivity on the repetition rate and the number of pulses in the unmodulated pulse trains.

Sensitivity to ITD was measured with four bilateral CI subjects using stimulation of single, interaural electrode pairs and stimulation through their sound processors. Just noticeable differences (JNDs) for ITD were measured using two-interval, two-alternative, forced-choice, adaptive tests. For direct stimulation on single, interaural electrode pairs, the stimuli were unmodulated, biphasic (27 μs/phase), pulse trains at 50 pulses per second (pps) with 2 – 30 pulses and trains at 800 pps with 2 – 240 pulses. The single-pulse case was also tested. Dependence of ITD JNDs on both the repetition rate and the number of pulses were observed. At 50 pps, each subject's ITD JND improved with increasing number of pulses, indicating integration of ongoing ITD cues. The subjects' best ITD JNDs were 85 – 354 μs measured using these 50-pps trains. Using 800-pps trains, two subjects' ITD JND degraded with increasing number of pulses, losing sensitivity to the onset ITD. Two subjects were insensitive to ITD up to 2 ms in 800-pps trains.

For stimulation through the processors, the stimuli were a single, monophasic (100 μs/phase) pulse and trains of unmodulated, monophasic pulses at 50 pps with 2 – 30 pulses. Improvement of ITD JND with increasing number of pulses was observed. While subjects were insensitive to ongoing ITD in unmodulated, high-rate pulse trains delivered to single, interaural electrode pairs, they were sensitive to ongoing ITDs in the slow-varying modulator of high-rate pulse trains in the through-processor case. A next step toward greater understanding of bilateral electric hearing is to investigate the degree to which subjects are sensitive to ITD using modulated pulse trains.

I. INTRODUCTION

In order to restore binaural advantage using bilateral cochlear implants, it is important to understand how listeners perceive the primary binaural cues, interaural time and level differences (ITD and ILD), with bilateral electric stimulation. Testing with a number of bilateral CI users has shown that these subjects perceived single, fused, auditory images when certain interaural electrode pairs were stimulated (Balkany et al., 1988; Pelizzone et al., 1990; Green et al., 1992; Lawson et al., 1998b; Long et al., 2003). The fused images could often be moved inside the head by manipulating ITD and ILD. These results suggest that it is possible for bilateral electric stimulation to elicit bilateral neural activity that the brain interprets in a manner similar to binaural acoustic stimulation.

For interaural level difference (ILD), normal-hearing listeners can detect a just noticeable difference (JND) of 1dB for many different kinds of signals (Durlach and Colburn, 1978). Studies of bilateral CI listeners using unmodulated pulse trains on single interaural electrode pairs also report ILD JNDs of about 1dB (van Hoesel et al., 1993, Lawson et al., 1998b; Lawson et al., 2001). For interaural time difference (ITD), normal-hearing subjects' averaged ITD JNDs are between 10 μs and 80 μs for broadband stimuli and tone bursts with frequencies below 1500 Hz (Klumpp and Eady, 1956; Wright and Fitzgerald, 2001). The ITD cues are available in the onset and the ongoing (fine structure) portion of these stimuli. Studies of bilateral CI listeners' ITD sensitivity, however, report poor ITD JNDs compared to those of normal-hearing listeners even though both onset and ongoing (pulse-to-pulse) ITD cues are presented in the direct stimulation of single, interaural electrode pairs with unmodulated pulse trains.

Figure 1 shows a histogram of all reported ITD JNDs measured in bilateral CI listeners using unmodulated pulse trains on single, interaural electrode pairs. Only responses elicited from pitch-matched, interaural electrode pairs are included. Except for the bin representing JNDs greater than 700 μs, all bins are 20 μs wide. This distribution includes results from 15 subjects using a total of 55 test configurations (NU4 of Lawson et al., 1996; P1, P2 of van Hoesel and Clark, 1997; NU5, ME2 of Lawson et al., 1998a; NU6 of Lawson et al., 2002; MA1 of van Hoesel et al., 2002; C092, C105, C109 of Nam and Eddington, 2003; A, B, C, D, and E of van Hoesel and Tyler, 2003). A test configuration is defined as a particular pair of interaural electrodes stimulated by a train of pulses at a specific repetition rate. For example, stimulating the same pair of electrodes in one subject with an unmodulated pulse train at 50 pulses per second (pps) and 100 pps would represent two test configurations. Differences in other stimulus parameters, such as stimulus duration, are not considered separately because the information was not reported with some of the data in the literature.

Figure 1 shows a wide range of reported ITD JNDs. About a third of the ITD JNDs (20 out of 55) are between 81 – 200 μs. Another third (17 out of 55) are spread between 241 – 660 μs. The last third (17 out of 55) are greater than 700 μs. Considering an average head size of 17 cm, the physiological range of ITD experienced by a person is 0 μs to about 700 μs. The sensitivity of one third of the test conditions is not sensitive to ITD within the human physiological range.

To see how the wide variation and the poor sensitivity in the reported ITD JNDs may be related to the test configurations, ITD JND for each test configuration in Figure 1 is plotted in Figure 2 as a function of the repetition rate of unmodulated pulse trains. Each symbol represents one subject. Lines connect symbols representing measurements made using the same electrode pair at different rates. At each repetition rate tested, large intersubject differences are evident. Intra-subject differences are also observed when different interaural electrode pairs were stimulated at the same rate (e.g. NU5, NU6). Across repetition rates, the connected symbols show that the ITD JND for some electrode pairs tend to increase with increasing rate (e.g. A, C, D, E, MA1, NU6), and some remain constant or decreased (e.g. P1, P2, NU6). ITD JNDs out of the physiological range are mainly those of P1 and P2 (van Hoesel and Clark, 1997), but ITD JNDs for MA1 (van Hoesel et al., 2002) were also greater than 700 μs at 500 pps. For pulse repetition rates less than 500 pps, MA1's ITD JNDs were within physiological range. The only ITD JND close to normal sensitivity for broadband stimuli or tone bursts with frequencies below 1500Hz (10 - 80μs) was one out of four NU5's pairs stimulated at 800 pps (Lawson et al., 1998a).

From the ITD JNDs shown in Figure 2, it is difficult to determine a clear relationship between ITD sensitivity and repetition rate. Most of the electrode pairs were only tested at one or two rates. Repetition rate alone seems insufficient to explain the wide variation seen in these data and the poor ITD sensitivity of bilateral CI listeners when envelope and fine-structure ITD cues are presented (Lawson et al., 1996;van Hoesel and Clark, 1997; Lawson et al., 1998a; Lawson et al., 2002; van Hoesel et al., 2002; Nam and Eddington, 2003; van Hoesel and Tyler, 2003). The relationship between ITD sensitivity and other stimulus parameters, such as number of pulses in the stimulus train or train duration, have not been investigated.

The current study focused on the effects on ITD sensitivity of two basic stimulation parameters: the number of pulses and the repetition rate of unmodulated pulse trains delivered to a single, binaurally-matched, interaural electrode pair. ITD JNDs were measured using lateralization tests with four bilateral CI subjects. Bilateral CI subjects' results were compared to normal-hearing listeners' results in Hafter and Dye, 1983, who studied the effects on ITD sensitivity of the number of clicks and the repetition rate of high-frequency click trains. The subjects' ITD JNDs were also compared to those computed based on signal detection theory from single-unit recordings in the cats' inferior colliculus (IC) in response to intracochlear electric stimulation.

In addition to the measurements made by stimulating single, interaural electrode pairs, ITD JNDs were measured for stimuli processed by the subjects' sound processors as a first step to examine the degree to which multi-channel stimulation and CI sound processing may affect ITD sensitivity.

II. METHODS

A. Subjects

Four bilateral cochlear implant users (C105, C109, C120, and C128) participated in this study. Subjects' age ranges from 40 to 78 years old with etiologies listed in Table II. The idiopathic loss (C105) was sudden onset, and the autoimmune loss (C120) was rapidly progressive. All subjects were postlingually deafened and presumably developed normal-binaural hearing prior to the onset of their hearing loss. Table I gives the age of each subject at the onset of hearing loss, hearing aid use, and cochlear implant use.

Table I: Subject History

Subject	Etiology	Age (yr) at Onset of Hearing Loss		Age (yr) at First Hearing-Aid Use		Age (yr) at Onset of CI use		Months of CI Use at Time of Testing	
		R	L	R	L	R	L	R	L
C105	Idiopathic	62	70	N/A	N/A	76	74	18mo	39mo
C109	Genetic	30	30	37	34	48	50	37mo	20mo
C120	Autoimmune	34	34	36	36	40	43	38mo	3mo
C128	Genetic	11	11	17	17	36	39	38mo	6mo

All subjects were monolateral CI users for at least 18 months before implantation of the second ear. Both ears of all subjects received the Clarion C2 HIFOCUS electrode array (16 electrodes in each cochlea). The first implanted cochlea of all subjects also included an electrode "positioner" designed to push the array into a modiolar position. Only C105 and C109 have a positioner in their second implanted cochlea. Two asynchronous sound processors control the electric stimulations to the electrodes in each cochlea. Without changing the assignment of analysis channels to electrodes of the first implant, the mapping of analysis channels to electrodes of the second implant was based on three measures of binaural sensation (fusion, interaural pitch matching, and interaural time sensitivity). These binaural assessments, documented in Eddington et al., 2003, were made before fitting the second cochlear implant.

At the time of this study, C105 and C109 had been listening bilaterally for over 1.5 years. C120 and C128 had used bilateral sound processing for 3 to 6 months. Monolateral use was restricted to acute laboratory testing. Table II gives details of each subject's implant devices, and their most recent single-syllable word (NU-6 test) score (measured monolaterally) using their implants.

Table II: Subject Device and Performance

Subject ID	CI type R&L	Electrode R&L	Positioner		Strategy	Pulse Rate (pps)	Pulse Width (μs)	Most Recent NU-6 Score (%correct)	
			R	L				R	L
C105	Clarion	HIFOCUS	Yes	Yes	CIS-16	1450	21.6	28%	38%
C109	Clarion	HIFOCUS	Yes	Yes	CIS-16	1450	21.6	94%	86%
C120	Clarion	HIFOCUS	Yes	No	CIS-16	2320	13.5	84%	70%
C128	Clarion	HIFOCUS	Yes	No	CIS-16	2320	13.5	84%	86%

B. Stimulus Generation and Delivery

1. Stimulation on Single, Interaural Electrode Pairs

Each bilateral CI subject's ITD sensitivity was measured using a single pulse and trains of fixed-amplitude pulses. Each pulse is biphasic with phase duration of 27 μs per phase. These stimuli were delivered to two intracochlear electrodes, one in each cochlea (interaural). The repetition rates of the pulse trains were 50 pps or 800 pps. At the 50 pps rate, trains of 2, 3, 7, 15, and 30 pulses were tested, corresponding to 40-ms, 60-ms, 150-ms, 300-ms, and 600-ms durations. At the 800pps rate, trains of 2, 8, 17, 30, 60, 120, and 240 pulses were tested, corresponding to 2.5-ms, 10-ms, 21.25-ms, 37.5-ms, 75-ms, 150-ms, and 300-ms durations. For one subject (C109), additional testing was conducted using trains of 30, 108, 217, and 435 pulses (21-ms, 75-ms, 150-ms, and 300-ms durations) at 1450pps, which is the rate of the electric pulse train used in that subject's CI processors. In order to compare results more directly to those in the literature, C109 was also tested with fixed-duration (300 ms) pulse trains at 10 pps, 25 pps, 50 pps, 100 pps, 400 pps, 800 pps, and 1450 pps. The order of test condition was randomized within each test session.

Custom software developed in the Massachusetts Eye and Ear Infirmary and the Clarion Research Interface (CRI2 manufactured by Advanced Bionics Corporation, Inc) were used to control the subjects' bilaterally implanted receivers/stimulators. The external control system is inductively coupled to the implanted unit. With one clock in the CRI2 controlling two stimulators, the pulse trains delivered to the two ears were synchronized to within 1 μs. The stimulation at each electrode was controlled by the pulse table in each implanted-stimulator's memory, and two modulation signals (one for each implant) were sent to the receiver/stimulator in real time. Interaural time delays (ITDs) were always produced by delaying one modulation signal relative to the other. The resolution of the ITD was 13.44 μs.

Current level was specified in peak-to-peak micro-amperes (μApp). All tests were conducted at a comfortable sensation level. Prior to each run, the level of the monolateral-left stimulus was adjusted to elicit a comfortable sensation. The level of the monolateral-right stimulus was then adjusted by asking the subject whether the stimulus in the right ear was equally loud compared to the stimulus in the left ear. Once comfortable and matched sensation levels were obtained, the stimulus in each ear was played simultaneously (ITD = 0 μs). If a "centered" image was not elicited inside the head, the current level in the right ear was adjusted to "center" the image. The "centered" image condition with zero ITD was considered the "zero ILD" condition even though the actual stimulation levels may differ in the two ears. The current levels at the two ears were kept constant through out each block of trials.

Each ITD was generated by delaying the stimulation to one electrode relative to the other. The delayed side (left or right) was chosen at random in each trial. This is a whole-waveform delay that produces onset and ongoing ITDs (Figure 3).

Monopolar stimulation was used with the case of the implant serving as the extracochlear return electrode. Only interaural electrode pairs assigned to the same frequency analysis channel in the two asynchronous sound processors used by each subject in daily life were tested. Through out this study, these electrode pairs are referred as *frequency-matched interaural electrode pairs* and are denoted by the subject ID followed by the left and right electrode number in parentheses (e.g. C109 (L3, R3)). Each subject has an array of 16 electrodes in each cochlea with electrode number 1 being most apical and 16 most basal.

2. Stimulation Through Sound Processors

To examine the degree to which multi-channel stimulation and CI sound processing may affect ITD sensitivity, sensitivity to ITD was measured using a single pulse and trains of fixed-amplitude pulses delivered to the external input of the subjects' CI processor. Two trains with 15 and 30 pulses (300-ms and 600-ms durations) at 50 pps were tested. Each pulse is monophasic with phase duration of 100 μs per phase (μs/ph). The stimuli were computer generated, sent to the sound card (sampling frequency of 44.1 kHz), and delivered to the sound processor's external input bypassing the acoustic path. Since these stimuli are broadband, all the active electrodes in each cochlea were stimulated according to the continuous interleaved stimulation (CIS) strategy. In contrast to the synchronized stimulation of single, interaural electrode pairs, through-processor stimulation of frequency-matched interaural electrode pairs was asynchronous because of rate and phase differences between the basic clocks of the two processors.

The same loudness-balance and image-centering procedures used in testing with single, interaural electrode pairs were used in testing through sound processors. Each ITD was generated by a whole-waveform delay of the pulse train to one of the implants relative to the other. The delayed side (left or right) was chosen at random in each trial. The whole-waveform delay produces onset and ongoing ITDs.

C. Lateralization Test with a Fixed ITD

The lateralization test with a fixed ITD of 700 μs was used to survey the ITD sensitivity of the frequency-matched, interaural electrode pairs. The results from this test were used to identify an ITD sensitive electrode pair in each subject for use in testing the effects of the stimulus parameters on ITD sensitivity. The stimulus was a 50 pps (27μs/phase, 300 ms) unmodulated pulse train with a whole-waveform delay of 700 μs randomly applied to the left or the right ear at each trial. The 50 pps pulse train was selected because (1) all subjects tested in our laboratory show some sensitivity to this waveform for at least a few electrode pairs and (2) many subjects in other studies (Figure 1) have also been tested with this waveform. The fixed ITD at 700 μs is near the maximum ITD experienced by people with an average head width of 17 cm. If stimulation of a particular electrode pair did not show sensitivity to this large ITD, the ITD sensitivity of that particular electrode pair would be outside of the physiological range, indicating the subject gets little useful ITD information from that electrode pair.

A two-interval, two-alternative, forced-choice (2I-2AFC) procedure was used to make these measures. The first interval contained the reference condition (ITD = 0 μs). In the second interval, the 700-μs delayed condition was presented with either the left or the right ear delayed. After each presentation, the subject answered the question, "Did the second sound move to the left or the right of the first sound?" by entering "1" for left and "2" for right on a keyboard. Feedback was given on the computer screen after each trial. The testing order of the frequency-matched, interaural electrode pairs was chosen randomly. Each run consisted of 20 trials. To demonstrate significant sensitivity to the ITD of 700 μs at the 95% confidence level, there must be more than 15 correct responses (75%) out of the 20 trials.

D. Adaptive Lateralization Test

For direct stimulation of single, interaural electrode pairs and through-processor stimulation, the just noticeable difference (JND) of ITD was measured using a 2I-2AFC adaptive test. A two-down, one-up adaptive procedure was used to target the 70.7% level on the psychometric function (Levitt, 1970; Leek, 2001). With a 2I-2AFC procedure, the first interval contained the reference condition (ITD = 0 μs). The second interval contained the test condition with an ITD based on the response of the previous trial. After each presentation, the subject answered the question, "Did the second sound move to the left or the right of the first sound?" by entering "1" for left and "2" for right on a keyboard. Feedback was given on the computer screen after each trial.

Informal testing was done at the beginning of each run to estimate the threshold ITD and to pick the initial start ITD and the step size. The start ITD was typically greater than the estimated threshold by four times the initial step size to ensure that the test began at the 100% level on the psychometric function. To save time and to improve the resolution of the test, the step size is reduced by a half after the first peak reversal and is reduced by a half again after the second peak reversal in the adaptive track. Hence, the final step size is one-fourth the initial step size. Unless the subject showed poor sensitivity in the informal testing, most adaptive runs started at an ITD of 700 μs and an initial step size of 107.76 μs (i.e. final step size = 26.94 μs). An adaptive run was terminated after tracking 14 reversals. If an adaptive track at the final step size had an upward or downward slope greater than 1, the result from that run was discarded. Given the limited test time and/or the ITD sensitivity of the subjects, not all test conditions were repeated. For conditions measured with one run, the ITD JND for each run was computed as the mean of the last 8 reversals (4 peaks and 4 valleys). The standard deviation of the last 8 reversals was also calculated. For conditions with repeated measures, the ITD JND was computed as the mean of the 8 reversals from all runs. For example, with 3 repeated runs on one condition, the ITD JND was calculated from 24 reversals. The number of reversals for each ITD JND is given in the figure captions.

III. RESULTS

A. ITD Sensitivity of Single, Interaural Electrode Pairs

1. Sensitivity to ITD of 700 μs

To compare ITD sensitivity across electrode pairs, sensitivity to an ITD of 700 μs was measured. The bar graphs in Figure 4 show the percent of correctly lateralized responses for each subject using frequency-matched interaural electrode pairs used by each subject's sound processors. To demonstrate sensitivity to an ITD of 700 μs at the 95% confidence level, the score must be greater than 75% correct (dotted line).

Figure 4a shows that C105 has only two electrode pairs with scores > 75%, demonstrating significant sensitivity to an ITD of 700 μs. In contrast, every electrode pair tested in C109 and C120 meets the test of significance (Figures 4b and 4c). For C128, 9 out of 17 electrode pairs show significant sensitivity (Figure 4d).

Both C105 and C109 had more than two years of bilateral CI experience at the time of testing. It is unlikely that their ITD sensitivity will change with more bilateral experience. On the other hand, C120 and C128 had 3 months and 6 months of bilateral CI experience, respectively. While C120 has significant sensitivity on all electrode pairs, additional bilateral CI listening may improve C128's ITD sensitivity. To capture the effect of bilateral experience on C128's ITD sensitivity, the same measurement was made on each electrode pair after two additional months of daily bilateral CI use. The two sets of data (six and eight months of bilateral experience) are shown in Figure 5. All nine electrode pairs with scores > 75% at six months maintained scores > 75% at eight months. For the eight electrode pairs with scores < 75% at six months, five (☆) of those pairs have scores > 75% at eight months. For C128, increasing bilateral experience increased the number of electrode pairs that are sensitive to the 700-μs ITD.

Based on the data of Figure 4 and results from the other ITD JND testing in the laboratory, a single, ITD sensitive, interaural electrode pair in each subject was chosen for further study. For C105, (L2, R1) was chosen for two reasons. (L2, R1) is one of two electrode pairs sensitive to 700-μs delay in Figure 4a, and it is an apical electrode pair that has shown consistent sensitivity to ITD out of the18 electrode pairs tested by me and others (some interaural pairs not those paired in the sound processors). For C109, (L3, R3) was chosen because it is an apical electrode pair showed sensitivity soon after the second implantation with minimal bilateral-listening experience. It is also one of the most ITD-sensitive pairs out of 19 electrode pairs tested by me and others. For C120, 10 out of the 18 electrode pairs (tested by me and others) demonstrated ITD JNDs of less than 200 μs soon after the second implantation. Of these 10 pairs, the most apical pair (L2, R1) was chosen. In contrast, of the 10 electrode pairs tested four months after the activation of C128's second sound processor, there was not a pair that demonstrated an ITD JND of less than 700 μs. Three of C128's electrode pairs, (L2, R4), (L4, R6), and (L9, R10), with the highest scores in Figure 4d were chosen for initial testing. After three test sessions, (L9, R10) was selected for additional testing because it demonstrated the most consistent ITD sensitivity using a 300-ms, low-rate pulse train. It was also the only pair that showed ITD sensitivity to single-pulse stimuli.

Based on the testing described above and the testing conducted in the laboratory by others after the testing reported here, interaural electrode pairs other than these test pairs have not been identified that show greater ITD sensitivity.

2. ITD Sensitivity Using a Single Biphasic Pulse

For each subject, the ITD JND using a single biphasic pulse was measured for each of the selected interaural electrode pairs using the adaptive lateralization test. Figure 6 shows the results for all subjects. The ITD JND for each run is plotted as a function of test session. Repeated measurements within a test session were made for C109 (L3, R3) (○). The same session number is shown for ITD JND values measured in the same test session. The order of testing within a session proceeds from left to right with the leftmost being the first measurement in that session.

The C109 (L3, R3) data show considerable test-to-test variance. In Test Session 7, for example, the standard deviation of the ITD JNDs from run-to-run is 51μs. The standard deviation of the ITD JNDs from Test Sessions 1 to 5 is 96 μs, and from Test Sessions 8 to 10 is 46 μs. The ITD JNDs measured in Test Session 1 to 5 are not significantly ($p<0.05$) different from the ITD JNDs measured in Test Session 7. ITD JNDs measured in Test Sessions 8 to 10 are significantly ($p<0.05$) different from those in Test Session 7.

At the time of Test Session 1, C109 had used bilateral implants for 20 months. Test Sessions 1 to 10 span a period of 9 months. It is unlikely that the variability in the C109

(L3, R3) data is related to months of bilateral experience. Evaluation of the C109 (L3, R3) data against the stimulus current level for each run also does not account for the observed variability. For example, stimulating (L3, R3) with a single pulse at 2000 μApp in the first run of Test Session 2 elicited an ITD JND that is not significantly different from that with stimulation at 3800 μApp in the second run of Test Session 5. Also, the stimulus level for all except the first run was kept at 2800 μApp in Test Session 7, and considerable variance was observed.

The inherent variability in ITD JND using a single pulse is also observed with the C120 (L2, R1) data (□). The standard deviation of the ITD JNDs across test sessions is 45μs. C105 (upward triangle) and C128 (downward triangle) were unable to lateralize a single pulse with an ITD of less than 600 μs even though (L2, R1) and (L9, R10), respectively, are their most ITD-sensitive electrode pairs.

3. Effect of Number of Pulses at 50 pps

Figure 7 shows ITD JNDs for all subjects using a train of 15 pulses at 50 pps plotted as a function of test session. In contrast to the ITD JNDs measured using a single pulse, these data show less variability. The standard deviations of the ITD JNDs measured across test sessions for C109 (L3, R3), C120 (L2, R1), and C128 (L9, R10) are 22 μs, 19 μs, and 21 μs, respectively. In addition, while C105 (L2, R1) and C128 (L9, R10) showed poor sensitivity to ITD in a single pulse, ITD JNDs of less than 600 μs were measured using the train stimuli.

To characterize the effect of the number of pulses on ITD sensitivity, ITD JND was measured using pulse trains of 2, 3, 7, 15, and 30 pulses presented at 50 pps. Figure 8 shows ITD JNDs for C105 (L2, R1), C109 (L3, R3), C120 (L2, R1) and C128 (L9, R10) plotted as a function of the number of pulses. Each ITD JND is the mean of the total number of reversals from all the runs measured under the same test configurations. The error bar is the standard deviation of the total number of reversals. For example, the ITD JND plotted in Figure 8 for C109 (L3, R3) using a train of 15 pulses is the mean and standard deviation of 56 reversals, which are the 8 reversals from each of the 7 runs for C109 (L3, R3) in Figure 7. The number of reversals for each ITD JND calculation is provided in the figure caption.

For all subjects, significant ($p<0.05$) differences are measured between ITD JNDs using a single pulse and trains of 15 or 30 pulses. Except for the 2-pulse condition, this difference between the ITD JNDs measured for C109 and C120 were not significantly different. However, C105's ITD JNDs and C128's ITD JNDs are significantly ($p<0.05$) different from each other and different from those of C109 and C120 at all conditions. Since the ITD JND using 2 or 3 pulses per train were not significantly different ($p<0.05$) from that using a single pulse for C109 (L3, R3) and C120 (L2, R1), these measurements were not made with C105 and C128.

Two-way analysis of variance (ANOVA) analyses were performed to assess the impact of the number of pulses per train and subject on ITD JND. Only data for 1, 7, 15, and 30 pulses per train were included in the ANOVA analysis since all four subjects were tested with these stimuli. The results are listed in Table III. There is no interaction measure because there are no repeated entries in the ANOVA analysis. Across the four subjects, there are significant effects for the number of pulses per train ($p=0.025$) and subject ($p=0.043$). Comparison of C109 and C120's data also shows significant effects of both factors ($p=0.0002$; $p=0.041$). Comparison of C105 and C128's data shows no significant effect ($p=0.07$; $p=0.95$).

Table III: Results of Two-Way ANOVA Tests for ITD JNDs Using 50-pps trains

	Factor 1	Factor 2
Data Included in Two-Way ANOVA	Number of Pulses per 50-pps Train	Test Subject
C105, C109, C120, C128	**p = 0.025**	**p = 0.043**
C109, C120	**p = 0.0002**	**p = 0.041**
C105, C128	p = 0.07	p = 0.95

4. Effect of Number of Pulses at 800 pps and 1450 pps

To characterize the effects of the number of pulses on ITD sensitivity using high-rate pulse trains, the ITD JND was measured with 800-pps trains of 2, 8, 17, 30, 60, 120, and 240 pulses. In addition, C109 was tested with trains of 30, 108, 217, and 435 pulses at 1450 pps, which is the pulse rate for the CIS strategy currently used by C109's sound processors. C105 and C128 were not able to lateralize these stimuli at 800 pps.

Figure 9 shows the ITD JND results for C109 (L3, R3) and C120 (L2, R1) as a function of number of pulses in the stimulus. Each line connects the ITD JNDs measured with one subject in one test session. ITD JNDs for the single-pulse data from Figure 6 are also re-plotted for all four subjects. For pulse trains at 800 pps, the C109 (L3, R3) data (solid line with open circles) show that the ITD JND is similar to the single-pulse case for trains with less than 30 pulses. With trains of more than 30 pulses, the ITD JND tends to increase. Data from C120 (L2, R1) (dotted line with open squares) show a more abrupt increase in ITD JND with increasing number of pulses. The ITD JND using a train of 240 pulses at 800 pps is significantly ($p<0.05$) larger than that using a train of 8 pulses at 800 pps for both C109 (L3, R3) and C120 (L2, R1).

For pulse trains at 1450 pps, the trend for the C109 (L3, R3) data (dotted line with open diamonds) is similar to the ITD JNDs measured using 800-pps trains (solid line with closed circles). The ITD JNDs using trains with 30, 108, and 217 pulses at 1450 pps were not significantly ($p > 0.05$) different from those measured using trains with 30, 120, and 240 pulses at 800 pps, respectively. The results of a two-way ANOVA for these data show that there is no effect of repetition rate ($p=0.38$), but there is an effect of pulse number ($p=0.01$). Hence, C120 was only tested with 800pps trains. Using 800 pps rather than 1450 pps avoids possible ITD ambiguity in an adaptive test when ITDs greater than half of the inter-pulse-interval (690μs / 2 = 345μs) for 1450 pps trains are presented to a subject.

5. Effect of Stimulus Duration

Stimulus duration alone does not limit the ITD sensitivity of single, interaural electrode pairs. Figure 10 shows ITD JNDs measured with 50pps trains and 800pps trains for C109 (L3, R3) (○) and C120 (L2, R1) (□) as a function of stimulus duration. ITD JNDs using a single pulse are plotted as 0-ms duration. Unlike the low-rate data, increasing duration degrades the ITD JND for high-rate stimuli for both subjects. At 300-ms duration, the ITD JNDs for 50-pps trains are significantly ($p<0.05$) different from those of 800-pps trains. The 50-pps ITD JNDs remain relatively small when the stimulus duration is increased to 600 ms.

6. ITD JND as a Function of Pulse Rate with a Fixed 300-ms Duration

ITD JNDs reported in the literature were often measured using fixed-amplitude and fixed-duration pulse trains at one or two pulse rates (Lawson et al., 1996;van Hoesel and Clark, 1997; Lawson et al., 1998a; Lawson et al., 2002; van Hoesel et al., 2002; Nam and Eddington, 2003; van Hoesel and Tyler, 2003). To compare with the performance reported for other bilateral CI subjects and to characterize ITD sensitivity of a single electrode pair at multiple rates, one of the subjects, C109 (L3, R3), was tested with 300-ms duration pulse trains at 10 pps, 25 pps, 100 pps, and 400 pps in addition to the measurements made at 50 pps, 800 pps, and 1450 pps. The literature data and C109 (L3, R3) data are plotted in Figure 11. Only those data tested with a 300-ms pulse train from Figure 2 are included. ITD JNDs measured with 50-pps, 300-ms trains for C105 (L2, R1), C120 (L2, R1), and C128 (L9, R10) are also plotted for comparison.

Using 300-ms pulse trains at 50 pps seems to elicit the smallest ITD JND from subjects (except P1 and P2) who were tested at multiple rates. At 50 pps, ITD sensitivity of C109 (L3, R3) (○) and C120 (L2, R1) (□) coincides with the best ITD JND of Subject A ("x", van Hoesel and Tyler, 2003). ITD JND of C128 (L9, R10) (▽) at 50 pps is at the level of Subject C while ITD JND of C105 (L2, R1) (△) is greater than that of Subject A – E (van Hoesel and Tyler, 2003). [Note that over two years of bilateral experience, the ITD JND of both C109 (L3, R3) (☆, ○) and C105 (L2, R1) (▷, △) improved.] Unlike the ITD JNDs of P1 and P2 (△ ▽; van Hoesel and Clark, 1997), the ITD JNDs of the other subjects are within the physiological range at rates less than 800 pps. Consistent with data in van Hoesel and Tyler, 2003, ITD JND tends to increase as the rate increases from 50 pps to 800 pps. Additional data were collected in the current study using lower repetition rates of 10 pps and 25 pps for one subject (C109 (L3, R3)) that show increasing ITD JND below 50 pps.

B. ITD Sensitivity Through Speech Processors

1. Effect of Number of Pulses at 50 pps

In addition to measuring the subjects' ITD JNDs through single-interaural-electrode-pair stimulation, the subjects' ITD JNDs were measured using fixed-amplitude, monophasic, pulse trains at 50 pps delivered to the auxiliary port of the sound processors. Figure 12 shows ITD JND as a function of the number of pulses measured using through-processor stimulation (filled bars) and single-interaural-electrode-pair stimulation (unfilled bars) for C109, C120 and C128. C105 was not able to lateralize the stimuli. Single-interaural-electrode-pair data from the same or the previous test session are used to compare with the through-processor data.

ITD JNDs measured through the processors resemble those measured using direct, single interaural electrode pair stimulation. All three subjects' through-processor ITD JNDs using a train of 30 pulses are significantly ($p<0.05$) smaller than those using a single pulse. For C109, the difference between the two stimulation methods is significant ($p<0.05$) for the single-pulse condition but not for the 15- and 30-pulse conditions. For C120, the difference is significant only for the 30-pulse condition. For C128, there are significant differences between the two stimulation methods for all three conditions. Comparing to ITD JNDs measured using direct stimulation, these data show that stimulation through processors may improve ITD JNDs for some subjects. In the case of C105, however, the ITD JND for all conditions was worse than the single-electrode-pair case. This is not surprising since only two interaural pairs used by the sound processors showed sensitivity to 700-μs ITDs (see Figure 4a).

III. DATA ANALYSIS

A. Dependence of ITD Sensitivity on Number of Pulses and Repetition Rate of the Stimulus

1. Results of Single, Interaural Electrode-Pair Stimulation

To compare ITD sensitivity across different combinations of number of pulses and repetition rates, the ITD JND for each stimulus condition was normalized by the ITD JND for the single-pulse condition. The effectiveness of ongoing ITDs in successive pulses in increasing ITD sensitivity was assessed by plotting the normalized ITD JND for *n* pulses against *n* number of pulses in a log-log scale. According to the optimal integration model of signal detection theory (Houtgast and Plomp, 1968; Hafter and Dye, 1983), the ITD JND for *n* pulses (*JND[n]*) can be predicted by:

$$JND[n] = JND[1] / n^{0.5} \tag{3.1}$$

if: (1) a single neuron's responses to the separate pulses are independent of one another, leading to the $\sqrt{n}$ reduction in the standard error of the internal noise, (2) the total number of neural events for a group of neurons evoked by the clicks is proportional to n pulses, and (3) the performance is held constant for each click. In the logarithmic form,

$$\log\left(\frac{JND[n]}{JND[1]}\right) = -0.5\log n \tag{3.2}$$

Thus, perfect independence and summation of the information predict a slope of –0.5 on a log-log scale as *JND[n]/JND[1]*, or the normalized ITD JND, declines with the square root of n.

Figure 13 shows the normalized ITD JND data for the 50-pps trains (Figure 8) on a log-log scale. The dot-dashed line (slope = -0.5) represents the integration model prediction for summation of independent responses to each pulse in the stimulus. The horizontal dotted line at zero marks the ITD JND of a single pulse. Average performance of four normal-hearing listeners using high-frequency filtered click trains at 100 clicks per second (cps) (Hafter and Dye, 1983) are also shown by the solid line. The improvement in performance observed at 50 pps for C109 (L3, R3), C120 (L2, R1), and C128 (L9, R10) with increasing number of pulses is qualitatively consistent with the prediction and the normal-hearing data.

The slope of a line forced through (0,0) in the log-log scale was estimated for each set of data using the least-square fit (minimizing χ^2). The estimated slope (and the standard deviation of the estimated slope) is –0.30 ± 0.16 for C105 (L2, R1), –0.39 ± 0.32 for C109 (L3, R3), –0.26 ± 0.25 for C120 (L2, R1), and –0.60 ± 0.14 for C128 (L9, R10). The poor ITD JND using a single pulse for C128 (L9, R10) may have exaggerated the benefit of increasing the number of pulses.

As indicated by the least-square-fitted slopes, the amount of improvement in ITD JND for C105 (L2, R1), C109 (L3, R3) and C120 (L2, R1) seems smaller than that predicted by the integration model. However, all the subjects' estimated slopes are not significantly different ($p > 0.15$) from the model prediction of –0.5. All the subjects' estimated slopes are also not significantly different ($p > 0.12$) from the slope of the normal-hearing listeners' data (slope = –0.41) using high-frequency filtered click trains at 100 cps in Hafter and Dye (1983).

At 800 pps, Figure 14 shows that the performance of C109 (L3, R3) and C120 (L2, R1) do not follow the model prediction. The least-square-fitted slopes (0.10 ± 0.28 for C109 (L3, R3) and 0.29 ± 0.44 for C120 (L2, R1)) are significantly different ($p = 0.04$ for C109 and $p = 0.06$ for C120) from the model prediction. For small numbers of pulses (up to 30 pulses for C109 (L3, R3) and 8 pulses for C120 (L2, R1)), performance was not significantly different from that of a single pulse. As the number of pulses increased from one to 30 pulses, it appears that the ongoing ITDs provided by the additional pulses beyond the onset ITD of the first pulse in 800pps trains were ignored. For pulse trains with large numbers of pulses (up to 240 pulses), performance with additional pulses at 800pps indicated a degradation of ITD sensitivity. Comparison with normal-hearing listeners' performance from Hafter and Dye (1983) using click trains at 1000 cps shows no significant difference ($p > 0.23$).

2. Results of Through-Processor Stimulation

Measurement of ITD sensitivity using pulse trains through the auxiliary port of the processors (dashed lines with open symbols in Figure 13) also demonstrates similar dependence of ITD JND on the number of pulses and the repetition rate of the input waveform. C109, C120 and C128 were sensitive to increasing numbers of pulses for the implant-processed, 50-pps pulse trains. There is no through-processor data for C105 in

Figure 13 because she was not able to lateralize the stimuli even though direct stimulation on C105's (L2, R1) electrode pair elicited some ITD sensitivity. The slopes (and the standard deviation of the estimated slope) of the least-square-fitted lines through the subjects' data are –0.11 ± 0.15 for C109, –0.52 ± 0.20 for C120, and –0.27 ± 0.27 for C128. While the slope for C109 is significantly different ($p = 0.02$) from the model prediction, the slopes for C120 and C128 are not different ($p > 0.3$) from the model prediction. Comparison with the normal-hearing data (slope = –0.41) shows that only C109's estimated slope was significantly different ($p = 0.05$) from normal-hearing data.

In an attempt to better understand the through-processor results, the outputs of the 16 analysis channels were recorded from one subject's (C109's right CI) sound processor. Figures 15 and 16 are the waveforms at one of the 16 output channels (Channel 8 centered at 1300 Hz with 200 Hz bandwidth) for the single-pulse and the 50-pps-train conditions, respectively. For the single-pulse input, the channel output (Figure 15) was a burst of pulses at 1450 pps. The duration and the amplitude of the burst of pulses were related to the CI processing and the analysis-channel filter. For the 50-pps, 300-ms train input with 15 pulses, the channel output (Figure 16) was 15 bursts of pulses at 1450 pps. Each burst in Figure 16 resembled the single burst in Figure 15. These outputs at one channel show that the subjects are receiving 15 copies of the single-pulse output at the corresponding interaurally-matched electrodes when 50-pps, 300-ms trains were presented bilaterally through the processors. For the outputs of the other analysis channels, even though the single-pulse outputs are different across the channels with different center frequencies and bandwidths, the output for a through-processor-50pps-300-ms train at each analysis channel still resemble 15 copies of the single-pulse output of the same channel. Hence, the improvement in ITD JNDs of C109, C120, and C128 for the through-processor stimulation in Figure 13 suggests that these subjects might be integrating the ITD information in the additional bursts of pulses at the interaural electrode pairs across the ears.

IV. DISCUSSION

A. Comparison to Normal-Hearing Listeners' ITD sensitivity Using Click Trains and Integration Model Prediction

In studying the sensitivity to ITDs in the temporal features of a signal regardless of the spectral frequency, Hafter and Dye (1983) measured normal-hearing listeners' ITD JNDs using trains of high-frequency filtered clicks with a focus on the interaction of click rate and the number of clicks in a train. The clicks were bandpass-filtered at 4000 Hz, and there were 1 to 32 clicks per train at click rates of 100 clicks per second (cps) and 1000 cps. Normal-hearing listeners' ITD sensitivity to these stimuli is interesting from a CI perspective because there is no fine-structure ITD information in the stimuli, which is similar to the removal of fine structure information by CI processing.

For normal-hearing listeners' performance with low-repetition rate (100 cps), the best-fitted slope for the average data across four listeners was –0.41. The average best-fitted slope (and standard deviation) across the four CI subjects using 50-pps trains (Figure 13) was –0.40 ± 0.23 with single-electrode-pair stimulation and –0.30 ± 0.21 for stimulation through processors. The slope for the normal-hearing listeners is within one standard deviation of the slopes of the bilateral CI subjects. Hence, the effect of pulse number measured with our bilateral CI listeners using both type of stimulations is consistent with the effect of click number measured with normal-hearing listeners at low-repetition rate.

For normal-hearing listeners' performance with high repetition rate (1000 cps), the best-fitted slope for the average data across four listeners was –0.14. The average best-fitted slope (and standard deviation) across the two CI subjects using 800-pps trains (Figure 14) was 0.20 ± 0.36. The slope for the normal-hearing listeners is within one standard deviation of the slope of the bilateral CI listeners. However, given that: (1) ITD JND degraded as pulse number increased beyond 30 pulses, (2) data are not available for normal-hearing listeners' performance beyond 32 clicks, and (3) two of the four CI subjects were not sensitive to ITD using 800-pps trains, the effect of pulse number on CI listeners' ITD JNDs appears to be different from the effect of click number on normal-hearing listeners' ITD JNDs. Further studies with normal-hearing listeners with more clicks may allow better comparison of normal-hearing listeners' and CI listeners' performance using high-rate click/pulse trains.

Overall, the negative slopes of bilateral CI listeners' performance using low-rate pulse trains show integration of ITD information as the number of pulses increased. The model predicted slope (–0.5) is within one standard deviation away from the average best-fitted slopes for both single-electrode-pair and through-processor stimulations. For bilateral CI listeners' performance using high-rate pulse trains on single, electrode pairs, the positive slopes suggest a lack of integration of ITD information as the number of pulses increased even though the model prediction (–0.5) is just within two standard deviations away from the average slopes from two subjects' data.

B. Comparison to ITD JND Predicted from Neural Recordings

Animal models can be used as another approach to study ITD sensitivity with bilateral cochlear implants by recording neural responses in the brainstem evoked by bilateral intracochlear stimulation. In Smith (2006), single-unit recordings were made in the inferior colliculus of acutely deafened, anesthetized cats in responses to electric stimulation delivered through bilaterally-implanted intracochlear electrodes. The stimulus was a 300-ms, biphasic pulse train at 40 pps. [See Smith (2006) for details of the experiment.] To relate the neural responses to ITD-discrimination performance, Smith (2006) calculated the standard separation (Sakitt, 1973), or *D*, from two distributions of spike counts elicited by two different ITDs to quantify the ITD discrimination of the single neurons. *D* is defined as:

$$D_{ITD+\Delta ITD} = \frac{\left|\mu_{ITD} - \mu_{ITD+\Delta ITD}\right|}{\sqrt{\left(\sigma_{ITD} + \sigma_{ITD+\Delta ITD}\right)/2}} \tag{3.3}$$

where μ_{ITD} and $\mu_{ITD+\Delta ITD}$ are the means of the spike counts, and σ_{ITD} and $\sigma_{ITD+\Delta ITD}$ are the standard deviations. Standard separation is analogous to the *d'* commonly used to quantify discrimination of two stimuli (Green and Swets, 1974). The optimum ITD JND was specified as the change in ITD (ΔITD) needed for the standard separation *D* to be 1, which corresponds to about 69% correct in a two-interval discrimination task.

Figure 17 plots the mean ITD JNDs (◆) from Smith (2006) for 20 neurons with various ITD sensitivities, and the ITD JNDs of the bilateral CI subjects from Figure 8. Consistent with the human subjects' performance, neural ITD JND improves with increasing number of pulses. The neural ITD JNDs also fall between the best and worst human subjects' performance with single-electrode-pair stimulation.

In Figure 18, mean neural ITD JNDs from Smith (2006) in response to 300-ms trains at 40 pps, 80 pps, 160 pps, and 320 pps are plotted with ITD JNDs of the bilateral CI subjects with 300-ms trains as a function of pulse rate. Similar to CI subjects' performance, the neural ITD JND tends to increase with pulse rate. As repetition rate increased, Smith (2006) observed that the neural responses were increasingly restricted to the stimulus onset as they became less sensitive to ITD. Neural recordings were not made with unmodulated pulse trains above 320 pps. Hence, data are not available to compare with bilateral CI subjects' performance at 800 pps.

The consistency between our bilateral CI listeners' ITD JNDs and the cats' neural ITD JNDs encourages more integrated studies with human and cats. While human psychophysical testing measures the global auditory system responses to electric hearing, physiological studies with cats allow one to study the responses at different stages of the system and relate it to the overall psychophysical responses.

C. ITD JNDs Measured by Stimulating Single, Interaural Electrode Pairs

Figure 11 shows ITD JND vs. repetition rate for C105 (L2, R1), C109 (L3, R3), C120 (L2, R1), C128 (L9, R10), and other bilateral CI subjects in the literature. Using a fixed 300-ms pulse train, the tendency for ITD sensitivity to degrade with increasing repetition rate above 50 pps is observed with C109 (L3, R3) and C120 (L2, R1). This is consistent with the observation made with Subject A, C, D, E (van Hoesel and Tyler, 2003), MA1 (van Hoesel et al., 2002; unknown duration), and NU6 (Lawson et al., 2002; unknown duration). The best ITD JNDs in the current study were those of C109 and C120 measured at 50 pps, which is also the case for Subject A, C, D, and E. The two measurements at rates below 50 pps show a degradation of ITD sensitivity.

There are two potential reasons for bilateral CI listeners' best ITD JNDs measured at 50 pps. From the cats' IC data in Smith (2006), one reason is that neural responses were increasingly restricted to the stimulus onset as the rate increased, and some neurons cease to fire at high rate of stimulation. The limited neural responses for repetition rate above 50 pps reduced the amount of information available for integration and degraded ITD sensitivity. Perhaps, at low rates of 50 pps and below, each ongoing pulse comes at such a slow rate that the binaural system considers the ongoing ITDs as many onset ITDs. As the rate increase above 50 pps, however, each ongoing pulse comes quicker and quicker, and the binaural system sees only one onset ITD.

Another possible reason is related to the number of pulses within a binaural integration period. The period of integration was defined by Buell and Hafter (1988) as the time after which increasing the number of clicks (*n*) in the stimulus did not add more information or did not further reduce the subject's ITD JNDs (slope ~ 0 in Figure 13). Buell and Hafter, 1988, estimated that the integration period for normal-hearing listeners was approximately 250 ms using high-frequency filtered click trains at 76 cps. Assuming that bilateral CI listeners also have an integration period of about 250 ms, 13 of the 15 pulses in a 50-pps, 300-ms pulse train are within the integration period. For rates below 50 pps, however, a 300-ms pulse train consists of fewer pulses. There are only 3 pulses in a 10-pps train and 7 pulses in a 25-pps train. Using the least-square fit for C109 (L3, R3) data in Figure 13 and her single-pulse ITD JND of 254 μs, the predicted ITD JND for 3 pulses and 7 pulses in a 50-pps train are 165 μs and 119 μs, respectively. As opposed to the best ITD JND (80 μs) with 15 pulses in a 50-pps trains, fewer pulses may mean fewer ITDs to integrate within the period of binaural integration to enhance ITD sensitivity.

A complete explanation of the changes in ITD sensitivity as a function of repetition rate with fixed-duration pulse trains (Figure 11) is still absent. Another issue is that the best ITD JNDs of bilateral CI listeners measured using waveforms with onset and ongoing ITDs (Figure 3) are near the ITD JNDs of normal-hearing listeners using waveforms with envelope ITDs (e.g. SAM tones or high-frequency click trains) rather than waveforms with fine-structure ITDs (e.g. pure tones). When the ITD cue is only available in the stimulus envelope, normal-hearing subjects' ITD JNDs range from 80 – 300 μs (Bernstein and Trahiotis, 1994; Bernstein, 2001; Bernstein and Trahiotis, 2002). Envelope ITDs cannot be detected for modulation frequencies above 512 Hz. Our bilateral CI subjects' ITD JNDs for a 50-pps, 300-ms pulse train fall within the normal-hearing listeners' ITD-JND range for stimuli with ITD only in the envelope. This may imply that bilateral CI subjects are processing the ITD information in the 50-pps, unmodulated, pulse trains on single, interaural electrode pairs in the same fashion as normal-hearing listeners process envelope ITD without fine-structure ITD information.

D. Future Work

The current study characterized bilateral CI listeners' ITD sensitivity using unmodulated pulse trains on single, interaural electrode pairs and through the sound processors. These were two extreme methods of stimulation. The stimulation on a single, interaural electrode pair consists of simple pulse trains (Figure 3), and the stimulation through the processors consists of amplitude-modulated pulse trains (Figures 15 and 16) on multiple electrode pairs with the continuous-interleaved-stimulation strategy. Data from these two extreme methods of stimulation helps to identify two factors that may limit bilateral CI users' ITD sensitivity: the impact of amplitude modulation with electrical stimulation and the impact of multiple-electrode stimulation. Further studies of these two factors using stimulation methods in between the two extremes are the initial steps toward improving performance with bilateral CIs.

The impact of amplitude modulation with electrical stimulation should be studied because the results of the current study show that bilateral CI subjects are insensitive to ongoing ITDs in unmodulated, high-rate (above 800 pps) pulse trains on a single, interaural electrode pair, but they are sensitive to ongoing ITDs in the modulation of high-rate (1450pps) pulse trains in the through-processor case. Also, neural data from Smith (2006) suggest that some neurons in the inferior colliculus that were not sensitive to ITD in the unmodulated pulse train at high rate became sensitive to the ITD (in the carrier) of the same pulse trains when the train is sinusoidally modulated. To examine bilateral CI listeners' sensitivity to modulation ITDs and carrier ITDs without the effect of CI processing and multiple-electrode stimulation, ITD sensitivity for sinusoidal-amplitude modulated pulse trains with ITD in the modulator should be tested on single, interaural electrode pairs as a function of modulation frequency with a constant high-rate carrier. The carrier rate should be greater than 800 pps since data in the current study show that most bilateral CI users have poor ITD sensitivity at this rate with unmodulated pulse trains. To measure subjects' sensitivity to modulation ITD, the carrier ITD should be held constant (e.g. 0 μs). To measure subjects' sensitivity to carrier ITD, the modulation ITD should be held constant (e.g. 0 μs). Subjects' sensitivity to whole-waveform delayed with the same ITD in both the modulation and the carrier could also be tested.

Another factor that may limit bilateral CI users' performance is the impact of multiple-electrode stimulation. It is uncertain how bilateral CI users' ITD sensitivity with multiple-electrode stimulation through the processors may depend on the number of ITD-sensitive, interaural electrode pairs. Another uncertainty is how does stimulation of both ITD-sensitive and ITD-insensitive, interaural electrode pairs affect listeners' through-processor ITD sensitivity. One (C105) of the four subjects in the current study was not sensitive to ITD with through-processor stimulation. Figure 4 shows that C105 has the least number of ITD sensitivity interaural, electrode pairs used with her sound processors. To address these issues and to better explain C105's performance, different combinations of ITD-sensitive and ITD-insensitive electrode pairs should be tested with custom-made hardware/software that can stimulate multiple electrode pairs, bypassing the processors to eliminate the effect of CI processing.

The data from the proposed studies will be a valuable addition to the limited reports on ITD sensitivity using amplitude-modulated pulse trains on single, interaural electrode pairs (van Hoesel et al., 2002; Nam and Eddington, 2003; van Hoesel and Tyler, 2003) and multiple-electrode stimulation (through processors: Lawson et al., 2001; Laback et al., 2004). Once the impact of amplitude modulation and the impact of multiple-electrode stimulation have been studied individually, it may be possible to predict through-processor performance and identify other factors that may be limiting ITD sensitivity with bilateral CIs.

V. CONCLUSIONS

ITD sensitivity of four bilateral cochlear implant listeners to unmodulated pulse trains presented to single, interaural electrode pairs was systematically characterized in terms of two stimulation parameters: 1) number of pulses and 2) pulse repetition rate. The results from this study show that ITD sensitivity depended on both of these parameters. At low rates, such as 50 pps, increasing the number of pulses from 1 to 30 pulses improved ITD JNDs. At high rates, such as 800 pps, increasing the number of pulses beyond 8 to 30 pulses degraded ITD JNDs. The results showed a capability for CI users to integrate onset and ongoing ITDs in low-rate but not high-rate pulse trains. The amount of integration is near that of normal-hearing listeners listening to high-frequency filtered click trains (Hafter and Dye, 1983). With high-rate pulse trains, subjects mainly used onset ITD for lateralization.

Three of four subjects' ITD JNDs measured through the processors resemble those measured using single, interaural electrode-pair stimulation. However, for one (C105) out of the four subjects with the least number of ITD-sensitive electrode pairs, through-processors stimulation degraded her performance. Dependence of ITD JND on the number of pulses in the through-processor input stimuli were observed. Recordings of the analysis-channel outputs showed a burst of modulated pulses for every input pulse. Subjects were able to integrate the ongoing ITDs in the modulation of the CI-processed waveforms.

Predicted ITD JNDs from physiological data (Smith, 2006) measured at the cats' inferior colliculus using low-frequency stimuli were consistent with the psychophysical results with bilateral CI listeners in the current study. Similar to human subjects' ITD JNDs, neural ITD JND improved with increasing number of pulses using a low-rate, unmodulated pulse trains on a single, interaural electrode pair. As repetition rate increased with fixed duration, the neural ITD JNDs also degraded. The observed consistencies between human ITD JNDs and neural ITD JNDs encourage further integrated studies to better relate binaural processing at different stages of the auditory pathway and human psychophysical performance.

The results of this study are a first step in characterizing basic psychophysical performance for bilateral listening in cochlear implant users. Further studies with modulated pulse trains on single and multiple interaural electrode pairs are needed for greater understanding of ITD sensitivity with electric hearing and to improve listeners' ITD sensitivity with waveforms that can more effectively deliver ITD information to bilateral CI users.

LIST OF FIGURES

Figure 1: Histogram of all reported ITD JNDs measured in bilateral cochlear implant subjects (15 subjects, 29 electrode pairs) using 55 different test configurations (NU4 of Lawson et al., 1996; P1, P2 of van Hoesel and Clark, 1997; NU5, ME2 of Lawson et al., 1998a; NU6 of Lawson et al., 2002; MA1 of van Hoesel et al., 2002; C092, C105, C109 of Nam and Eddington, 2003; A, B, C, D, and E of van Hoesel and Tyler, 2003). A test configuration is defined as a particular pair of interaural electrodes stimulated by a train of unmoduated pulses at a specific repetition rate. Only responses elicited from pitch-matched, interaural electrode pairs are shown. Except for the bin representing JNDs greater than 700 μs, all bins are 20 μs wide. Each tick on the abscissa marks the center value of a bin. For example, 50 μs is shown for an ITD-JND bin of 41 μs – 60 μs.

Figure 2: ITD JND vs. rate of the unmodulated pulse-train stimulus for the 15 bilateral cochlear implant subjects (29 electrode pairs) of Figure 1. All test configurations are plotted. The number of electrode pairs tested with each subject is indicated in the legend. The connected symbols show results for an electrode pair tested at more than one pulse rate. The lowest pulse rate tested for all subjects was 50 pps. Some data points at 50 pps and other rates are horizontally offset for clarity. The horizontal line at 700-μs ITD represents the physiological limit that a person with an average head width of 17 cm would experience.

Figure 3: Illustration of a whole-waveform delayed, biphasic stimulus with onset and ongoing ITDs. [Adapted from Long et al., 2003.]

Figure 4: Sensitivity to a fixed 700-μs ITD (50-pps, 300-ms unmodulated pulse trains) as a function of the frequency-matched, interaural electrode pair. Each panel presents results for one of the four subjects tested (C105, C109, C120, and C128). Only the electrode pairs used with the subjects' bilateral CI processors were tested. The list of electrode pairs is next to each panel. To demonstrate significant sensitivity at the 95% confidence level, the score must be above 75% correct (dotted line). [* indicates the chosen electrode pair for the current study.]

Figure 5: C128's sensitivity to 700-μs ITD measured at two times: 6 months and 8 months bilateral listening. The electrode pairs that became sensitive to ITD of 700 μs are indicated by * next to the filled bars. See Figure 4d for the list of interaural electrode pairs tested.

Figure 6: ITD JNDs measured for the four subjects using a single, biphasic (27 μs/ph) pulse measured as a function of test session. The symbols are the means and the error bars are the standard deviations of the last 8 reversals from the adaptive runs.

Figure 7: ITD JNDs measured for the four subjects using a train of 15 pulses at 50 pps measured as a function of test session. The symbols are the means and the error bars are the standard deviations of the last 8 reversals from the adaptive runs.

Figure 8: ITD JND as a function of the number of pulses in 50-pps pulse trains. The symbols are the means and the error bars are the standard deviations of the number of reversals given in the legend for each subject.

Figure 9: ITD JND vs. the number of pulses in a pulse train for repetition rates of 800 pps and 1450 pps. The symbols are the means and the error bars are the standard deviations of the number of reversals given in the legend for each subject.

Figure 10: ITD JND of C109 (L3, R3) and C120 (L2, R1) using 50-pps and 800-pps trains plotted as a function of stimulus duration. The symbols are the means and the error bars are the standard deviations of the number of reversals given in the legend for each subject.

Figure 11: ITD JND vs. repetition rate with 300-ms pulse trains for this study's four subjects and subjects in whom single, interaural electrode pairs were tested at more than one repetition rate in Figure 2 (van Hoesel and Clark, 1997; Nam and Eddington, 2003; van Hoesel and Tyler, 2003). The format of this plot is the same as in Figure 2. Data from this study are bolded.

Figure 12: ITD JND measured using 50-pps pulse trains through the auxiliary port input vs. single, interaural electrode pair stimulation as a function of number of pulses for C109, C120 and C128. The symbols are the means and the error bars are the standard deviations of the last 8 reversals from the adaptive runs. Significant differences ($p<0.05$) are indicated by *.

Figure 13: Log-log plot of normalized ITD JND as a function of number of pulses in the 50-pps pulse trains for single, interaural electrode-pair stimulation and through sound-processor stimulation. The single pulse reference, model prediction, and averaged data from four normal-hearing listeners (NHL) using high-frequency, filtered click trains at 100 clicks per second (cps) (Hafter and Dye, 1983) are plotted for comparison.

Figure 14: Log-log plot of normalized ITD JND as a function of number of pulses in the 800-pps pulse trains for single, interaural electrode-pair stimulation. The single pulse reference, model prediction, and averaged data from four normal-hearing listeners (NHL) using high-frequency, filtered click trains at 1000 clicks per second (cps) (Hafter and Dye, 1983) are plotted for comparison.

Figure 15: An example waveform at the output of one (Channel 8: center frequency = 1300 Hz, bandwidth = 200 Hz) of the 16 analysis channels for a single (100 μs/ph) pulse delivered to the auxiliary port of a sound processor. The upper panel shows the entire response while the lower panel shows the response on a 0 – 30 ms time scale.

Figure 16: An example waveform at the output of one (channel 8) of the 16 analysis channels for a 50-pps, 300-ms, 100 μs/ph, pulse train delivered to the auxiliary port of a sound processor. The upper panel shows the entire response while the lower panel shows the response on a 0 – 50 ms time scale.

Figure 17: Mean ITD JND vs. number of pulses in low-frequency pulse train stimulus, 50 pps in human subjects and 40 pps in cats (Smith, 2006).

Figure 18: Mean neural ITD JND measured with 30-ms, unmodulated pulse trains at 40, 80, 160, and 320 pps (Smith, 2006) and ITD JND of bilateral CI subjects with 300-ms, unmodulated pulse trains at 10, 25, 50, 100, 400, and 800 pps.

Figure 1: Histogram of all reported ITD JNDs measured in bilateral cochlear implant subjects (15 subjects, 29 electrode pairs) using 55 different test configurations (NU4 of Lawson et al., 1996; P1, P2 of van Hoesel and Clark, 1997; NU5, ME2 of Lawson et al., 1998a; NU6 of Lawson et al., 2002; MA1 of van Hoesel et al., 2002; C092, C105, C109 of Nam and Eddington, 2003; A, B, C, D, and E of van Hoesel and Tyler, 2003). A test configuration is defined as a particular pair of interaural electrodes stimulated by a train of unmoduated pulses at a specific repetition rate. Only responses elicited from pitch-matched, interaural electrode pairs are shown. Except for the bin representing JNDs greater than 700 μs, all bins are 20 μs wide. Each tick on the abscissa marks the center value of a bin. For example, 50 μs is shown for an ITD-JND bin of 41 μs – 60 μs.

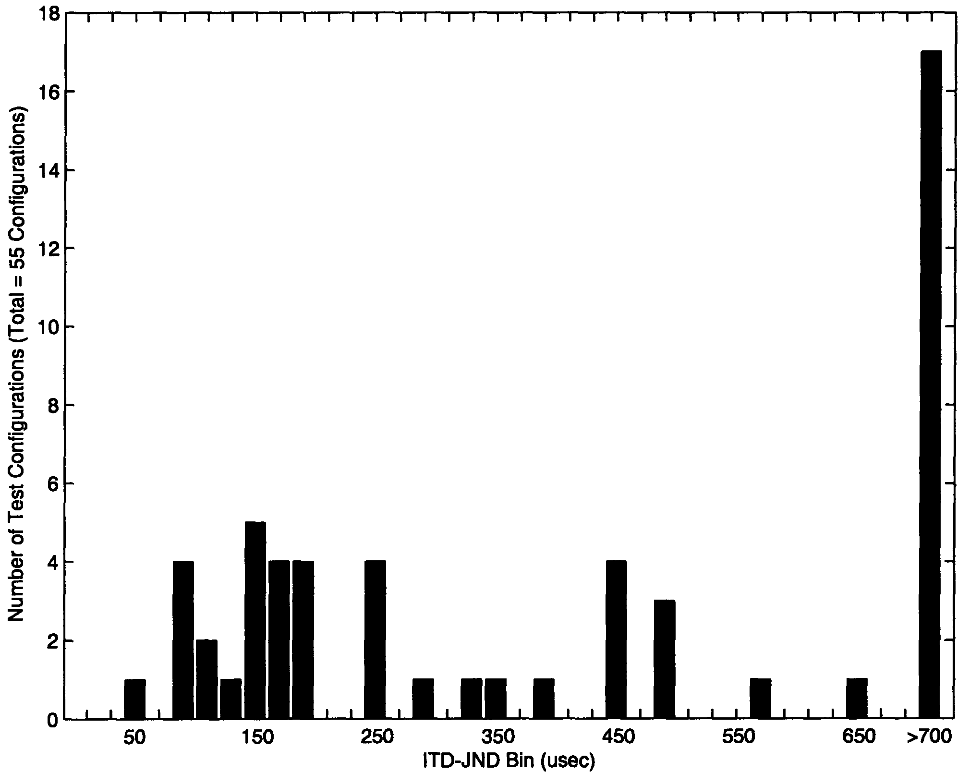


Figure 2: ITD JND vs. rate of the unmodulated pulse-train stimulus for the 15 bilateral cochlear implant subjects (29 electrode pairs) of Figure 1. All test configurations are plotted. The number of electrode pairs tested with each subject is indicated in the legend. The connected symbols show results for an electrode pair tested at more than one pulse rate. The lowest pulse rate tested for all subjects was 50 pps. Some data points at 50 pps and other rates are horizontally offset for clarity. The horizontal line at 700-μs ITD represents the physiological limit that a person with an average head width of 17 cm would experience.

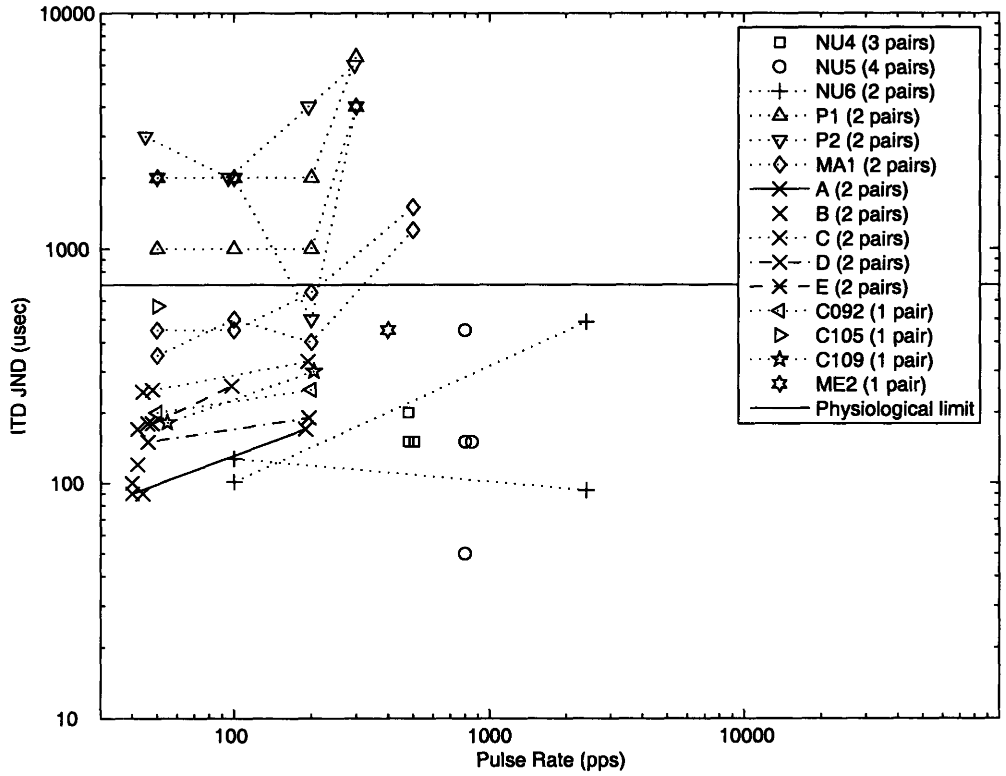


Figure 3: Illustration of a whole-waveform delayed, biphasic stimulus with onset and ongoing ITDs. [Adapted from Long et al., 2003.]

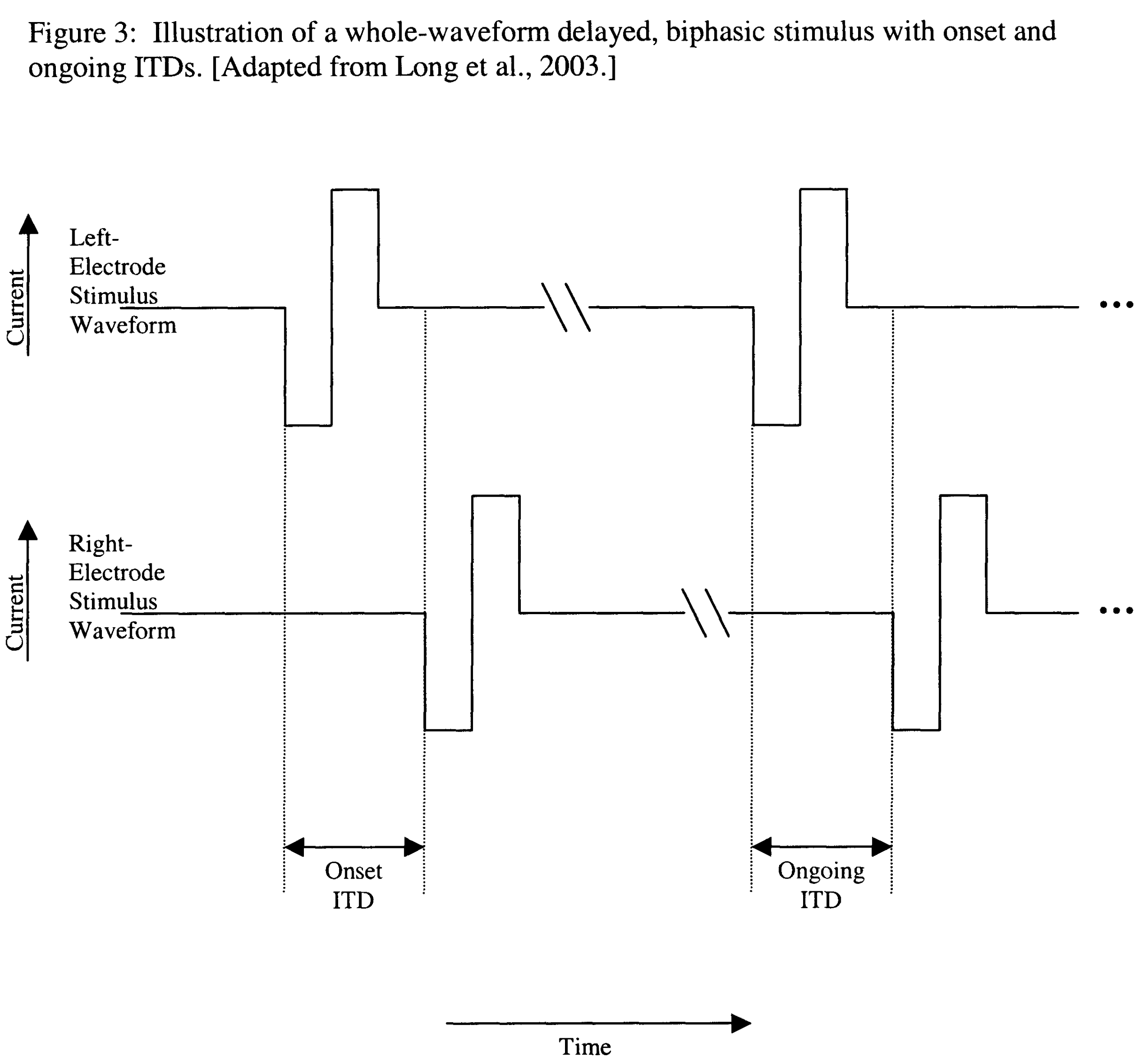
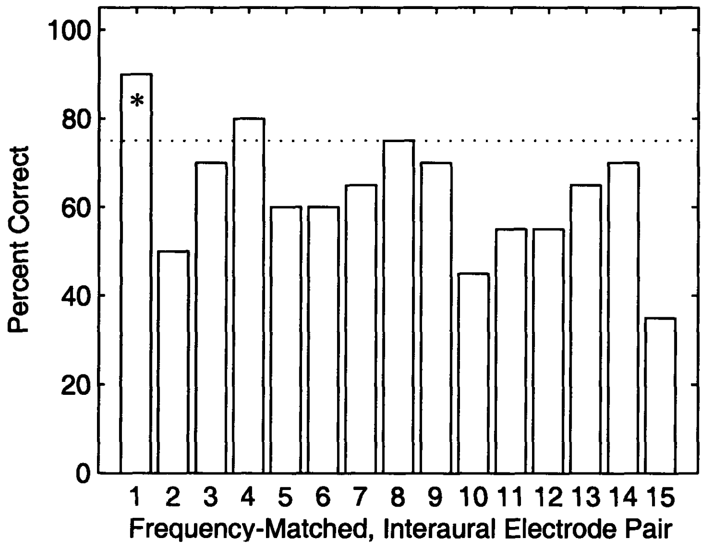


Figure 4: Sensitivity to a fixed 700-μs ITD (50-pps, 300-ms unmodulated pulse trains) as a function of the frequency-matched, interaural electrode pair. Each panel presents results for one of the four subjects tested (C105, C109, C120, and C128). Only the electrode pairs used with the subjects' bilateral CI processors were tested. The list of electrode pairs is next to each panel. To demonstrate significant sensitivity at the 95% confidence level, the score must be above 75% correct (dotted line). [* indicates the chosen electrode pair for the current study.]

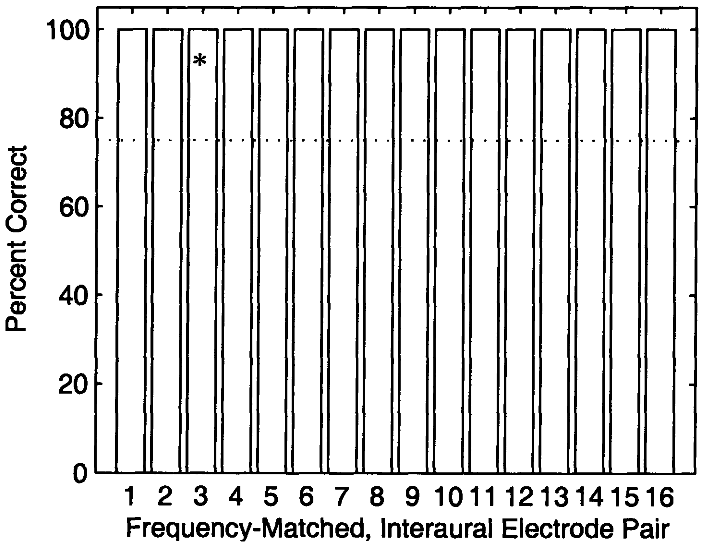
a. C105



Pairs Tested for C105

1. (L2, R1)*
2. (L3, R2)
3. (L4, R3)
4. (L5, R4)
5. (L6, R5)
6. (L7, R6)
7. (L8, R7)
8. (L9, R8)
9. (L10, R9)
10. (L11, R10)
11. (L12, R11)
12. (L13, R12)
13. (L14, R13)
14. (L15, R14)
15. (L16, R15)

b. C109

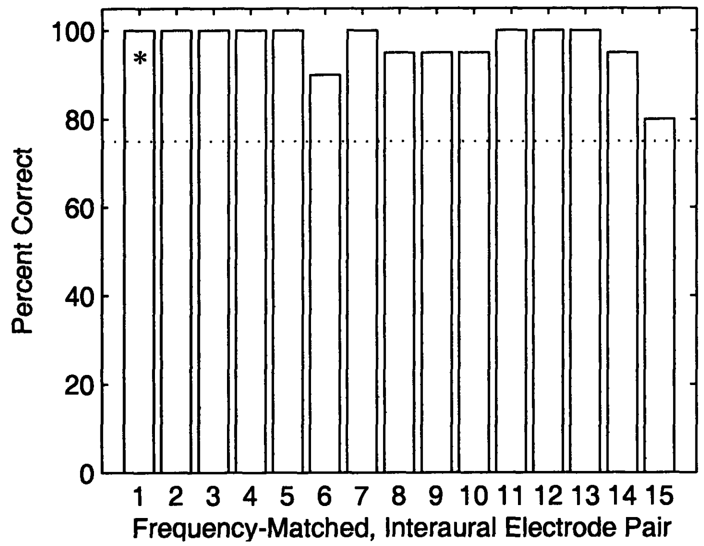


Pairs Tested for C109

1. (L1, R1)
2. (L2, R2)
3. (L3, R3)*
4. (L4, R4)
5. (L5, R5)
6. (L6, R6)
7. (L7, R7)
8. (L8, R8)
9. (L9, R9)
10. (L10, R10)
11. (L11, R11)
12. (L12, R12)
13. (L13, R13)
14. (L14, R14)
15. (L15, R15)
16. (L16, R16)

Figure 4 (Continued)

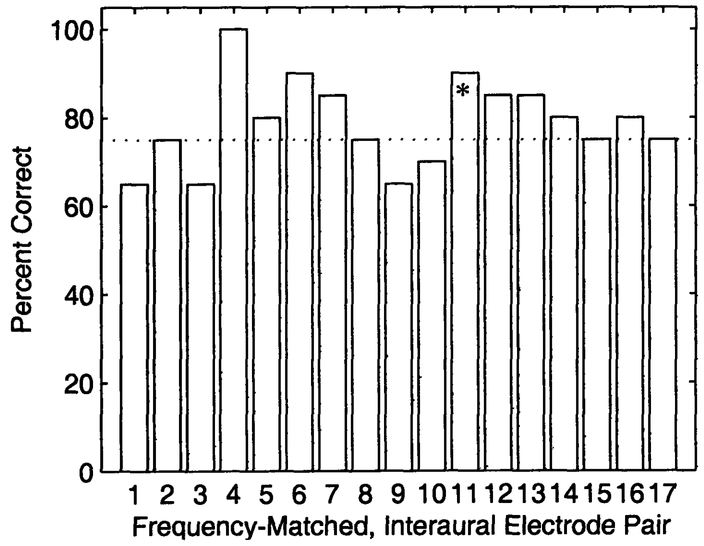
c. C120



Pairs Tested for C120

1. (L2, R1)*
2. (L3, R2)
3. (L4, R3)
4. (L5, R4)
5. (L6, R5)
6. (L7, R6)
7. (L8, R7)
8. (L9, R8)
9. (L10, R9)
10. (L11, R10)
11. (L12, R11)
12. (L13, R12)
13. (L14, R13)
14. (L15, R14)
15. (L16, R15)

d. C128



Pairs Tested for C128

1. (L1, R1)
2. (L1, R2)
3. (L1, R3)
4. (L2, R4)
5. (L3, R5)
6. (L4, R6)
7. (L5, R7)
8. (L6, R8)
9. (L7, R9)
10. (L8, R9)
11. (L9, R10)*
12. (L10, R11)
13. (L11, R12)
14. (L12, R13)
15. (L13, R14)
16. (L14, R15)
17. (L15, R15)

Figure 5: C128's sensitivity to 700-μs ITD measured at two times: 6 months and 8 months bilateral listening. The electrode pairs that became sensitive to ITD of 700 μs are indicated by * next to the filled bars. See Figure 4d for the list of interaural electrode pairs tested.

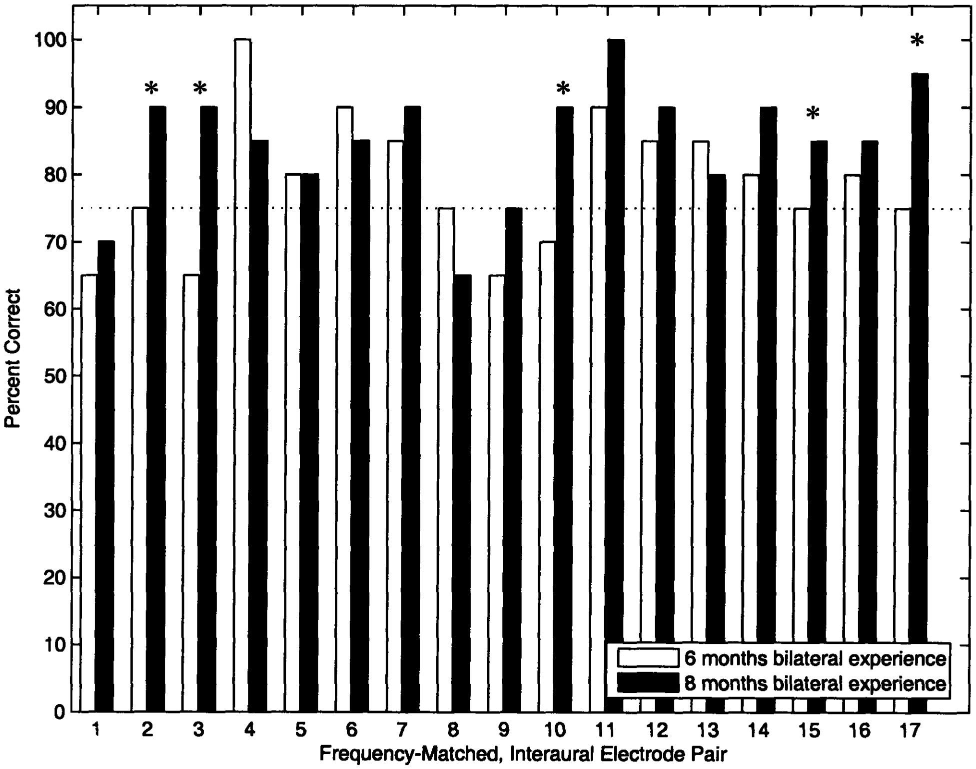


Figure 6: ITD JNDs measured for the four subjects using a single, biphasic (27 µs/ph) pulse measured as a function of test session. The symbols are the means and the error bars are the standard deviations of the last 8 reversals from the adaptive runs.

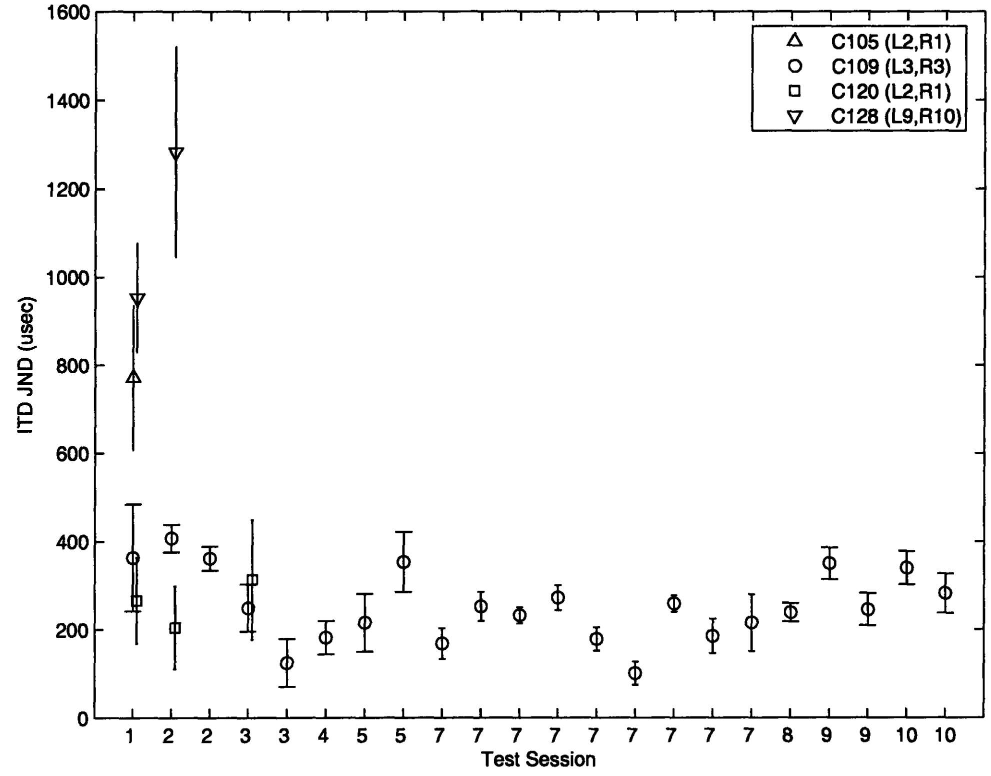


Figure 7: ITD JNDs measured for the four subjects using a train of 15 pulses at 50 pps measured as a function of test session. The symbols are the means and the error bars are the standard deviations of the last 8 reversals from the adaptive runs.

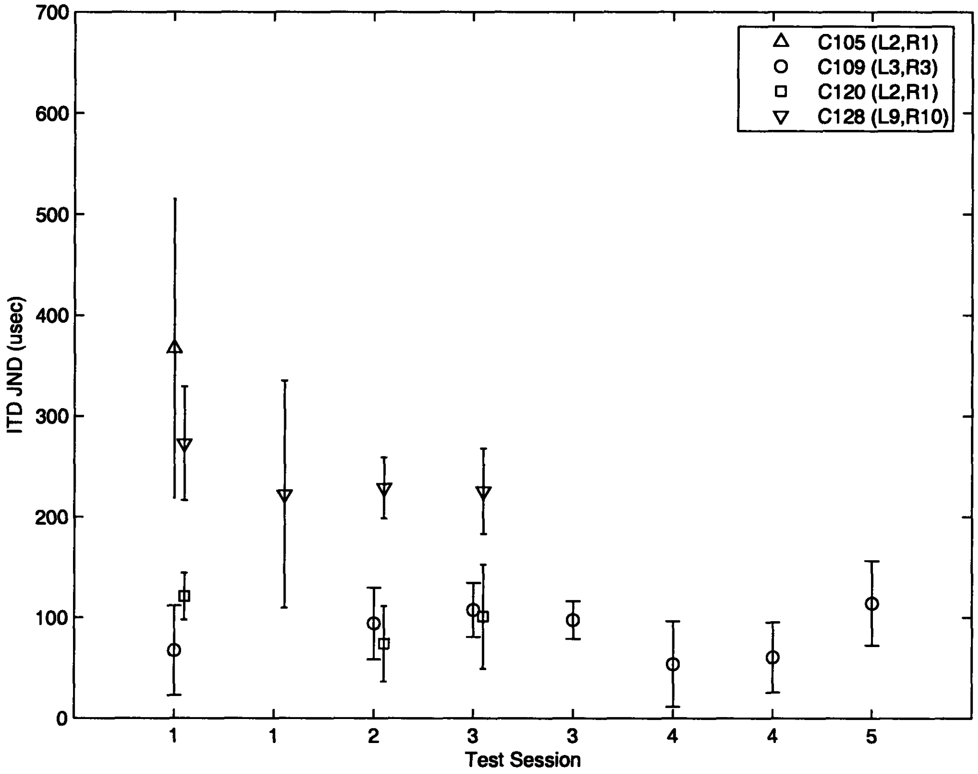


Figure 8: ITD JND as a function of the number of pulses in 50-pps pulse trains. The symbols are the means and the error bars are the standard deviations of the number of reversals given in the legend for each subject.

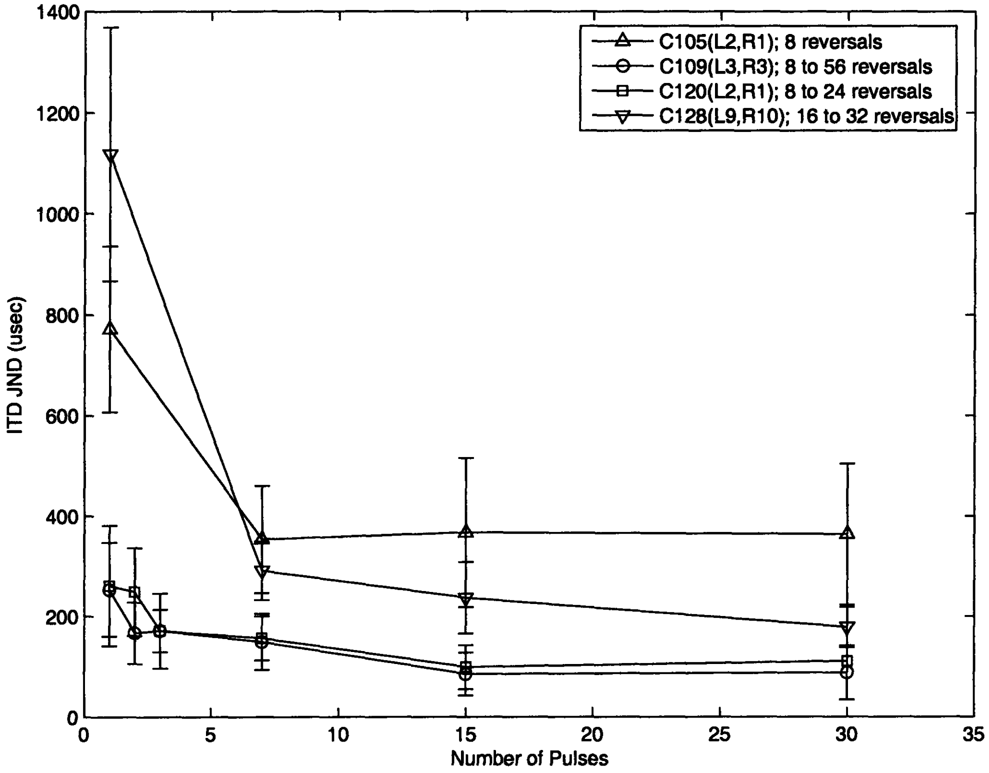


Figure 9: ITD JND vs. the number of pulses in a pulse train for repetition rates of 800 pps and 1450 pps. The symbols are the means and the error bars are the standard deviations of the number of reversals given in the legend for each subject.

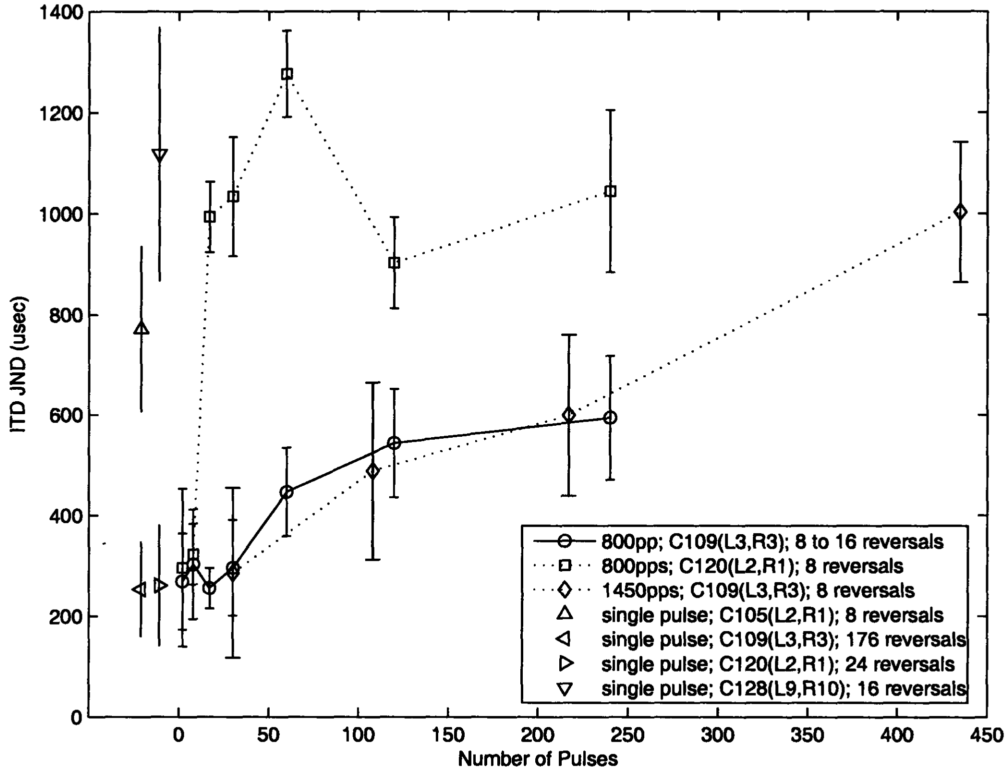


Figure 10: ITD JND of C109 (L3, R3) and C120 (L2, R1) using 50-pps and 800-pps trains plotted as a function of stimulus duration. The symbols are the means and the error bars are the standard deviations of the number of reversals given in the legend for each subject.

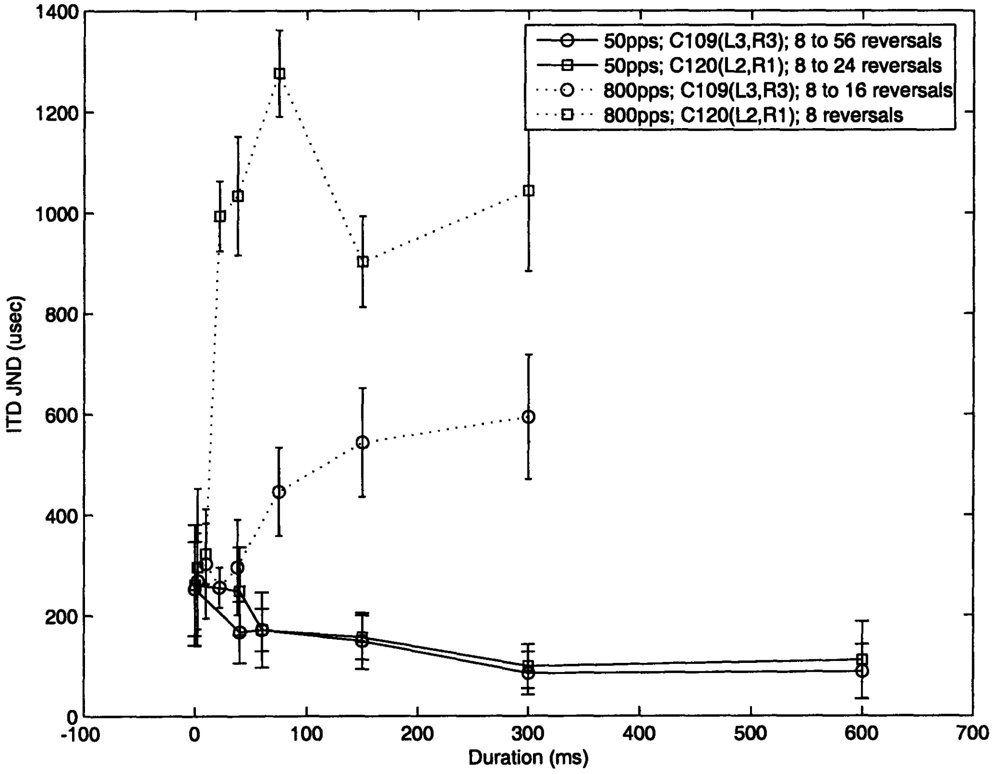


Figure 11: ITD JND vs. repetition rate with 300-ms pulse trains for this study's four subjects and subjects in whom single, interaural electrode pairs were tested at more than one repetition rate in Figure 2 (van Hoesel and Clark, 1997; Nam and Eddington, 2003; van Hoesel and Tyler, 2003). The format of this plot is the same as in Figure 2. Data from this study are bolded.

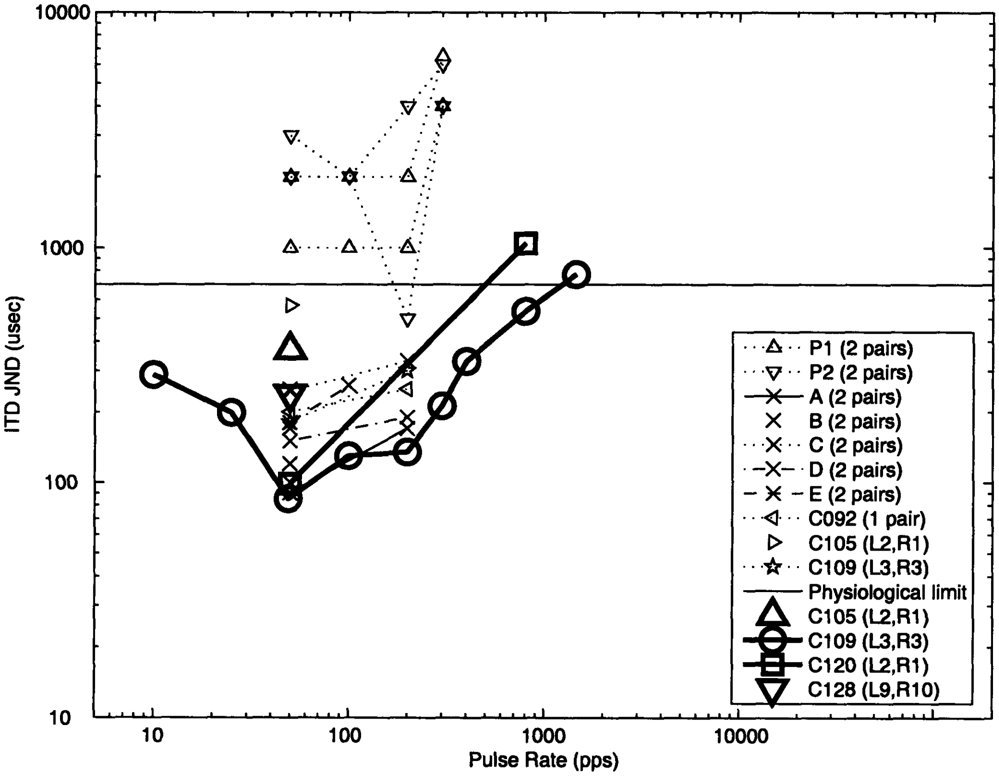
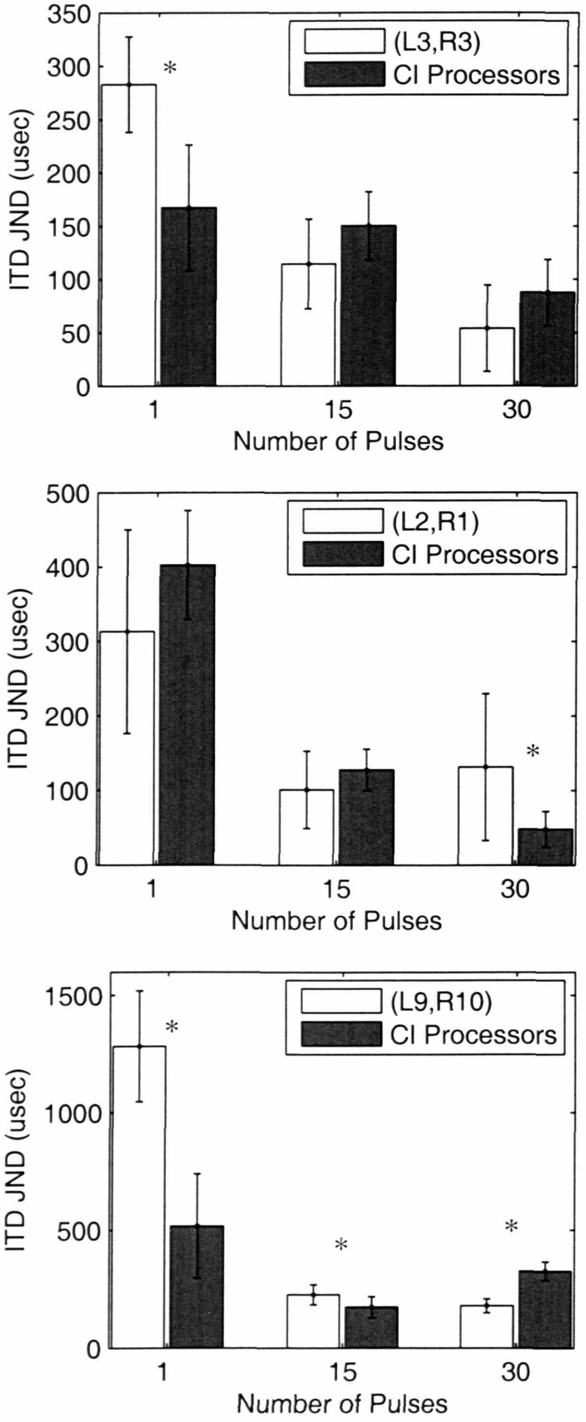


Figure 12: ITD JND measured using 50-pps pulse trains through the auxiliary port input vs. single, interaural electrode pair stimulation as a function of number of pulses for C109, C120 and C128. The symbols are the means and the error bars are the standard deviations of the last 8 reversals from the adaptive runs. Significant differences (p<0.05) are indicated by *.



a. C109

b. C120

c. C128

Figure 13: Log-log plot of normalized ITD JND as a function of number of pulses in the 50-pps pulse trains for single, interaural electrode-pair stimulation and through sound-processor stimulation. The single pulse reference, model prediction, and averaged data from four normal-hearing listeners (NHL) using high-frequency, filtered click trains at 100 clicks per second (cps) (Hafter and Dye, 1983) are plotted for comparison.

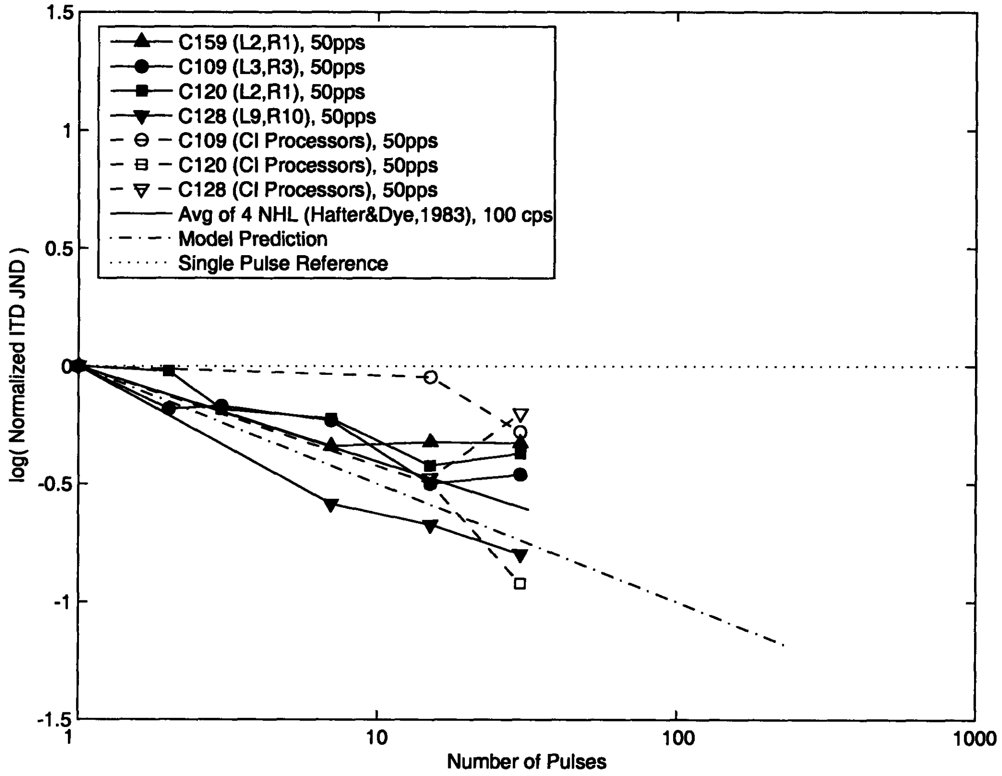


Figure 14: Log-log plot of normalized ITD JND as a function of number of pulses in the 800-pps pulse trains for single, interaural electrode-pair stimulation. The single pulse reference, model prediction, and averaged data from four normal-hearing listeners (NHL) using high-frequency, filtered click trains at 1000 clicks per second (cps) (Hafter and Dye, 1983) are plotted for comparison.

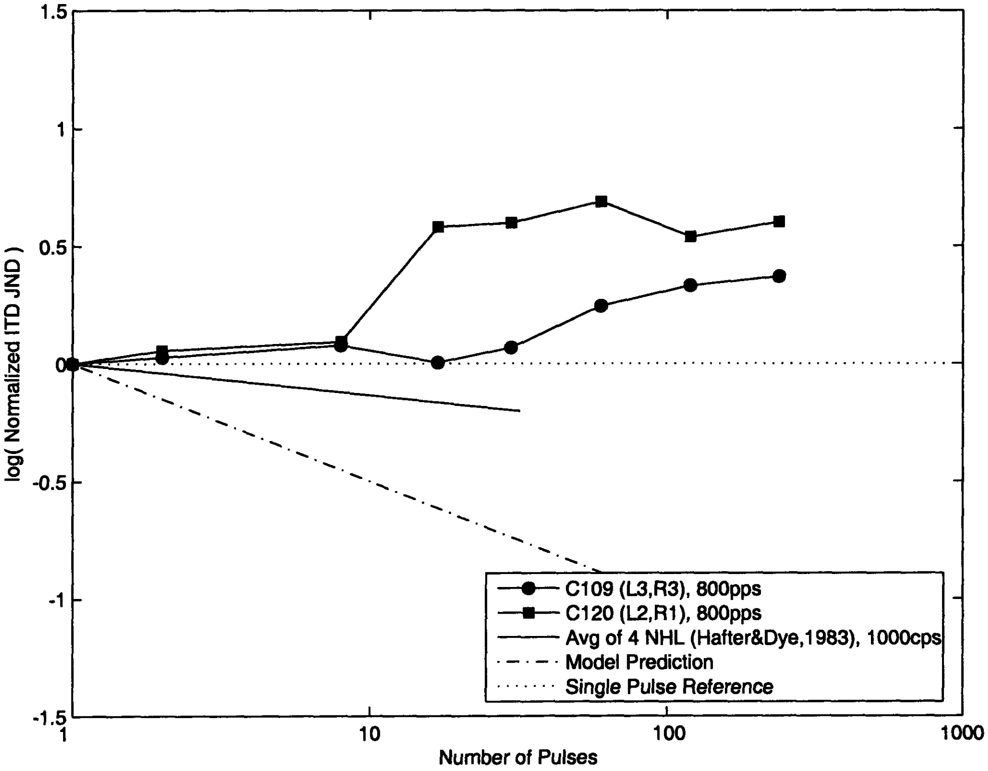


Figure 15: An example waveform at the output of one (Channel 8: center frequency = 1300 Hz, bandwidth = 200 Hz) of the 16 analysis channels for a single (100 μs/ph) pulse delivered to the auxiliary port of a sound processor. The upper panel shows the entire response while the lower panel shows the response on a 0 – 30 ms time scale.

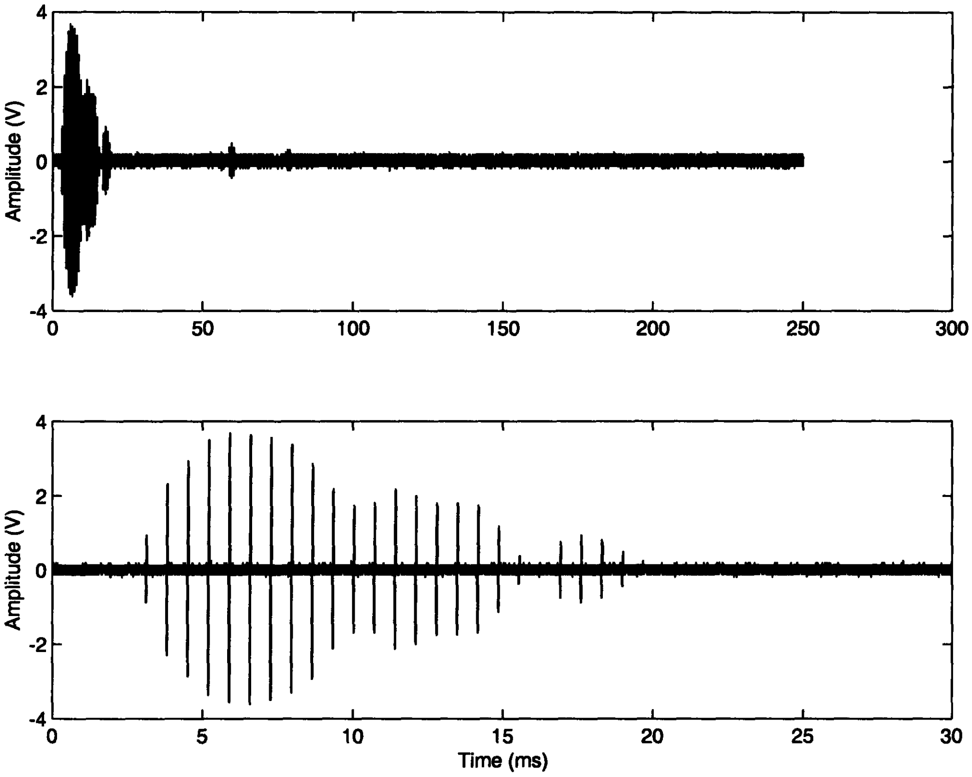


Figure 16: An example waveform at the output of one (channel 8) of the 16 analysis channels for a 50-pps, 300-ms, 100 μs/ph, pulse train delivered to the auxiliary port of a sound processor. The upper panel shows the entire response while the lower panel shows the response on a 0 – 50 ms time scale.

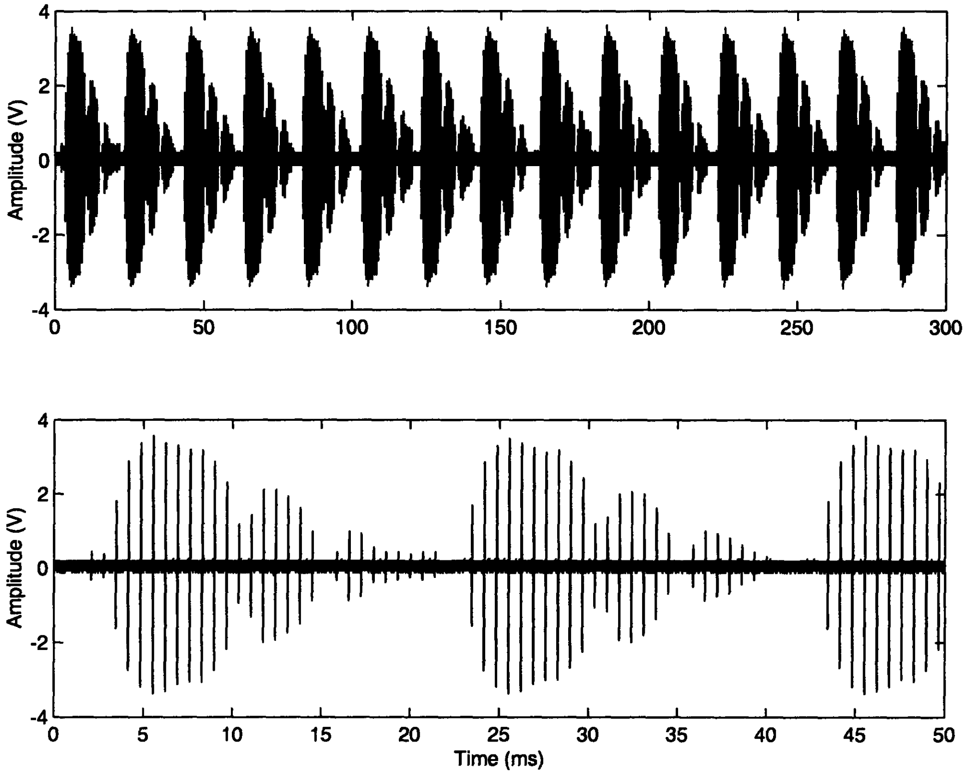


Figure 17: Mean ITD JND vs. number of pulses in low-frequency pulse train stimulus, 50 pps in human subjects and 40 pps in cats (Smith, 2006).

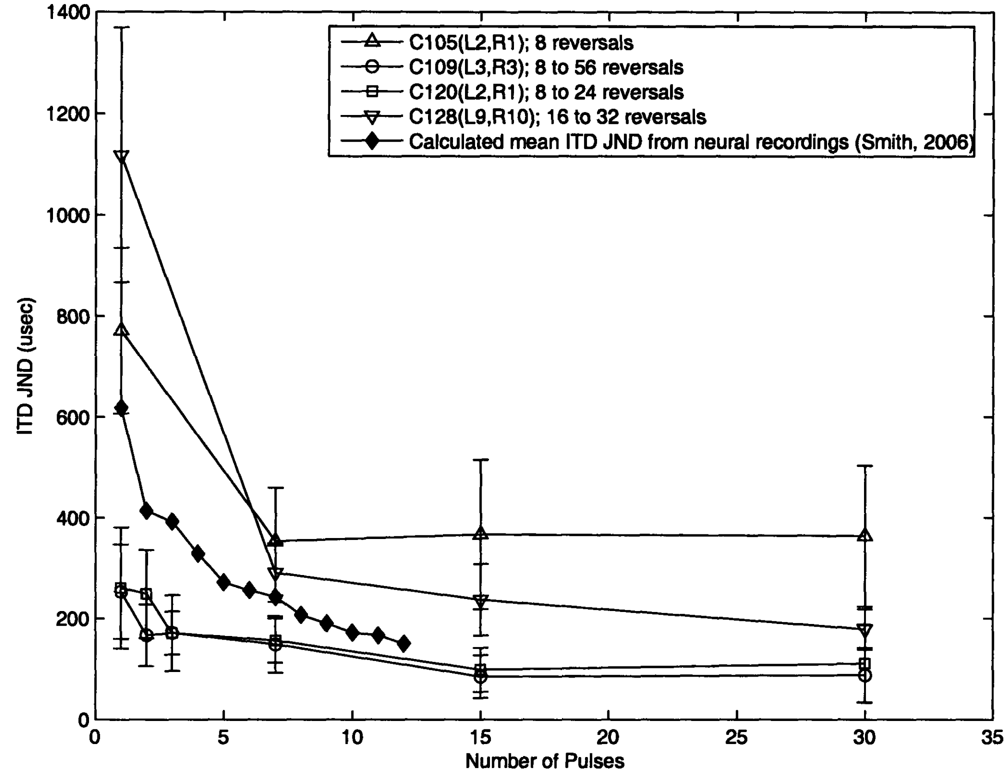
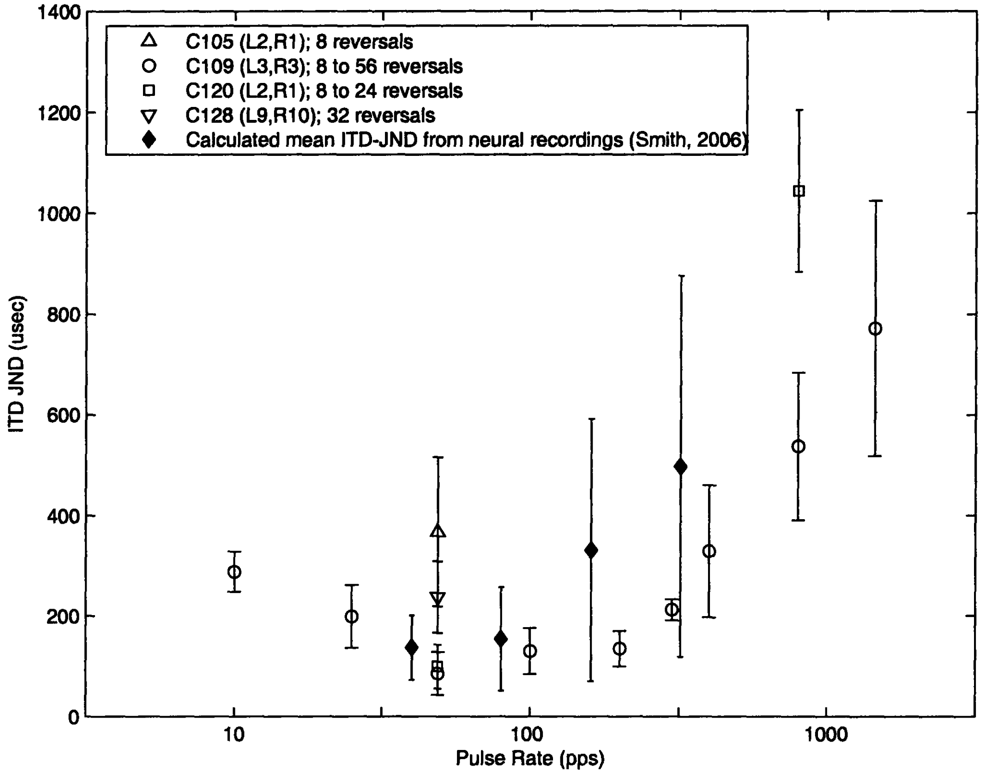


Figure 18: Mean neural ITD JND measured with 30-ms, unmodulated pulse trains at 40, 80, 160, and 320 pps (Smith, 2006) and ITD JND of bilateral CI subjects with 300-ms, unmodulated pulse trains at 10, 25, 50, 100, 400, and 800 pps.



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Chapter 4

Summary and Conclusions

This thesis characterized the sound localization ability and ITD sensitivity of four to five subjects with bilateral cochlear implants. To evaluate the potential advantage of two independent implants over one, longitudinal measurements of sound localization performance under monolateral and bilateral CI listening conditions were made. In order to examine stimulus parameters relevant to imparting the ITD cue, ITD sensitivity of single, interaural electrode pairs was measured. ITD sensitivity was also measured using through-processor stimulation as a first step to examine multi-channel stimulation and the impact of CI processing on ITD sensitivity. Knowledge of how ITD sensitivity depends on different stimulation waveforms and how well subjects can localize sound sources with two independent implants will impact the design of future bilateral cochlear implants and future studies of the mechanisms underlying bilateral cochlear implant users' ability to lateralize and locate sound sources.

I. Sound Localization Performance with Monolateral and Bilateral Cochlear Implants

Five subjects who wore a monolateral implant for at least 14 months before undergoing implantation of the second ear were studied. Sound localization performance was measured with both monolateral and bilateral configurations. The source-identification test was conducted with seven loudspeakers in a sound-treated room. The stimuli were three bursts of white noise (500-ms burst duration, 300-ms inter-burst interval) played at constant and roving levels. For each subject, a first set of measurements (monolateral and bilateral) was made before the onset of extensive bilateral CI listening (*pre-bilateral* *period data*). The second set of measurements was made after months of bilateral CI experience (*bilateral-period data*).

Between the two test sessions, bilateral performance improved for four of the five subjects using both constant- and roving-level stimuli. Some subjects' monolateral performance also changed between the two sessions. For constant-level stimuli, some subjects' monolateral performance degraded significantly after the onset of bilateral listening. For these subjects, the benefit to localization of bilateral implantation will be over estimated by the prevailing method that compares monolateral and bilateral performance measures made after months of bilateral listening experience. A more appropriate approach is to compare monolateral performance measured after months of monolateral use to bilateral performance after months of bilateral use. All five of our subjects showed better bilateral performance using the prevailing method but only three using the appropriate method. In the case of roving-level stimuli, all subjects showed better bilateral than monolateral performance, independent of the comparison method used.

All five subjects could identify the source hemifield with two CIs. Three of the five subjects demonstrated an ability to localize the sound sources better than expected from simple left/right hemifield identification. Microphone positions did not show a significant impact on the measured interaural cues. To explore the potential use of the ITD cue for localization, four subjects' ITD sensitivity to the stimulus from the center (0°) speaker was measured. [One subject (C092) was not available for further testing.] In these tests, the HRTF-convolved signal was presented directly to the subjects' auxiliary port. One subject (C105) has no ITD sensitivity to these through-processor stimuli. The other three subjects (C109, C120, and C128) obtained ITD JNDs between 319 μs – 588 μs, which is poor compared to normal-hearing listeners' ITD JNDs (< 100 μs). Even though ILD JNDs were not measured in the current study using HRTF-convolved noise bursts, the subjects' ILD JNDs for a single burst of noise through the processors were measured as a part of the battery of tests conducted by others in our laboratory. The subjects' ILD JNDs were between 0.4 and 3.4 dB, which is similar to normal-hearing listeners' ILD JNDs (1 to 2 dB).

Using a source identification model (Durlach and Braida, 1969), each subject's localization performance for the center (0°) speaker was predicted based on the measured ITD and ILD JNDs. Comparison of the predicted and the measured center RMS errors shows that the ILD-predicted errors are smaller than the measured errors. On the other hand, the ITD-predicted errors are larger than the measured errors. These model predictions suggest that subjects' ILD sensitivity alone could account for their localization performance with bilateral CIs. However, the subjects were not using the ILD cue optimally. One reason for the sub-optimal use of ILD may be related to the observation that ILD sensitivity decreases as the range of stimuli increases (Koehnke and Durlach, 1989). Another reason may be the interaction of ILD and ITD cues. It is conceivable that the subjects' normally developed binaural system forces the use of both ILD and the abnormal ITD cues. If both ILD and ITD cues must be used, improvement in the subjects' ITD sensitivity with bilateral CIs is needed. How to effectively convey ITD information to improve ITD sensitivity may be the key to improving sound localization capability of bilateral CI users.

II. ITD Sensitivity of Single, Interaural Electrode Pairs Using Synchronous, Unmodulated Pulse Trains

ITD sensitivity was measured on the best-performing single, interaural electrode pair in four subjects to examine the influence of two stimulation parameters using unmodulated pulse trains: number of pulses and pulse repetition rate. Single pulse and pulse-train (50-pps and 800-pps repetition rate) stimuli were tested. Each pulse was biphasic with phase width of 27 μs per phase. ITD was generated by delaying the whole waveform to one electrode relative to the other, giving onset and ongoing ITDs to the listeners. Subjects were asked to report the position of the elicited sound image.

The results show that ITD sensitivity depends on both the pulse number and repetition rate. Both onset and ongoing ITDs in low-rate, 50-pps, pulse trains were used by the subjects. Increasing the number of pulses from 1 to 30 pulses, which corresponds to a maximum duration of 600 ms for 50 pps, improves the subjects' ITD sensitivity. On the other hand, subjects are mainly sensitive to the onset ITD in high-rate, 800-pps, pulse trains with small number of pulses. Beyond about 30 pulses, which corresponds to a duration of 38 ms for 800 pps, ITD sensitivity degrades, indicating the onset ITD information became less salient. The ITD sensitivity of one subject (C109) was also tested using 1450-pps trains as a function of the number of pulses and showed results similar to those for 800-pps trains. Stimulus duration alone was not responsible for the difference in ITD sensitivity between low-rate and high-rate pulse trains. ITD sensitivity was related to the subjects' ability to integrate the ongoing ITD information in the low-rate but not the high-rate pulse trains.

III. ITD Sensitivity Through Asynchronous, Sound Processors

In this thesis, ITD sensitivity to signals processed by the asynchronous speech processors was measured using a single monophasic (100 μs/ph) pulse, and 50-pps, monophasic (100 μs/ph) pulse trains with different numbers of pulses. One subject (C105) was not able to lateralize any through-processor stimuli even though some ITD sensitivity was measured using direct stimulation on one interaural, electrode pair.

Data for the three subjects (C109, C120, and C128) showed that for pulse trains of low-repetition rate (50 pps), through-processor ITD discrimination improved as the number of pulses increases from 1 to 30 pulses. The relationships between ITD JND and the number of pulses for low-rate stimuli were consistent with those for the subjects' ITD JND measured by direct, electric stimulation of single, interaural electrode pairs. Measurements at the outputs of the processor's analysis channels showed that each pulse through the processor produced a burst of modulated, high-rate (1450 pps) pulses at the channel outputs. Improvement in ITD JND with increasing number of input pulses through the sound processors demonstrated the subjects' ability to integrate the ongoing-modulator ITD information across the ears just as they did with the ongoing ITD in the unmodulated pulse trains in single-interaural-electrode-pair stimulation for low-repetition rates.

Because the input signal to the external input of the sound processors was broadband, all the analysis channels were activated. One possible reason for C105's insensitivity to ITD using through-processor stimulation is the number of active electrode pairs that are ITD sensitive. Data in Chapter 3 (Section III.A.1) show that only two of C105's the active electrode pairs were ITD sensitive while almost all the active electrode pairs used in C109's, C120's, and C128's processors were ITD sensitive. Stimulation of a large number of ITD-insensitive electrode pairs might have degraded her ability to discriminate ITD. Further studies are needed to tease apart the impact on ITD sensitivity of multiple, ITD-sensitive and ITD-insensitive, electrode-pair stimulation and CI processing. Studies that characterize the ITD sensitivity using modulated pulse trains are also needed.

IV. Implications of the Similarity Between the ITD Sensitivity of Bilateral-CI and Normal-Hearing Listeners

The best ITD JNDs measured using unmodulated pulse trains fall within the ITD-JND range measured in normal-hearing listeners using sinusoidally amplitude-modulated (SAM) tones, high-frequency transposed stimuli, and high-frequency filtered click trains (Bernstein and Trahiotis, 1994; Bernstein, 2001; Bernstein and Trahiotis, 2002). The inability of bilateral CI listeners using unmodulated pulse trains to integrate ITD information as repetition rate increases from 50 pps to 800pps is consistent with normal hearing listeners' data using high-frequency, filtered click trains from 100 cps to 1000 cps (Hafter and Dye, 1983). Using SAM tones, transposed stimuli and high-frequency filtered click trains, normal-hearing listeners were only receiving ITD information in the envelope and not in the fine structure of the stimuli. The similar ITD JNDs and the observed trends between bilateral-CI and normal-hearing listeners' data may imply that bilateral CI listeners are processing the ITD information in the unmodulated pulse trains in the same way as normal-hearing listeners are processing envelope ITDs. This suggests that an understanding of the mechanisms underlying the relative poor ITD sensitivity of normal-hearing listeners to envelopes may also explain the poor ITD sensitivity of bilateral CI listeners.

V. Implications for Designs of Bilateral Cochlear Implants

Measures using stimuli processed by two asynchronous sound processors show poor ITD sensitivity compared to that of normal-hearing listeners for many acoustic stimuli. Simply synchronizing the electric pulse trains delivered to bilaterally matched, interaural electrode pairs may not improve ITD sensitivity of CI subjects from that using two independent processors. Typical cochlear implant devices stimulate each electrode at rates above 800pps. Results from this thesis show that CI subjects have ITD JNDs greater than 400μs with unmodulated pulse trains at this high rate. This leads one to conclude that subjects are unlikely to benefit from ITD cues in these relatively high-rate carriers.

The best ITD JNDs from our subjects were 80 μs and 99 μs for ITD imparted in low-rate, unmodulated pulse trains. ITD JNDs of 80 μs and 99 μs corresponds to deviations of 9.4° to 11.5° from the midline, respectively. This level of ITD sensitivity should be useful for sound localization and speech reception in noise with bilateral CIs. Unfortunately, if each electrode were stimulated at such a low-repetition rate, the representation of the acoustic signal in the modulation of the pulse train would be very poor. While it is not practical to design a processor with low-rate stimulation at all electrodes, it may be possible to have a subset of bilaterally matched electrode pairs stimulated at low-repetition rate with ITD imparted in the carrier. According to studies by Eddington et al. (1997) and Friesen et al. (2001), seven to eight analysis channels are sufficient for the high performing CIS users to achieve the same level of performance as normal-hearing subjects listening to sounds with the same amount of spectral reduction.

Current cochlear implants have at least 16 analysis channels and 16 electrodes inserted in to the cochleae. It is conceivable that a processor with half of the analysis channels and electrodes designated for imparting speech information and the other channels and electrodes designated for imparting ITD information may provide an advantage over current systems for bilaterally-implanted users.

ITD JNDs measured in this thesis with stimuli through asynchronous processors show that bilateral CI listeners can integrate ITDs in the modulation of electric pulse trains. These results suggest that future developments of speech-processing schemes may consider improving preservation of the envelope of acoustic signals with distinct temporal envelop. Feature extraction schemes may identify periodic signals within a binaural-temporal-integration time frame (Buell and Hafter, 1988) to enable listeners to integrate ITDs in the distinct temporal envelope as predicted by the integration model (Houtgast and Plomp, 1968; Hafter and Dye, 1983). For example, environmental sounds, such as telephone rings or footsteps, are periodic with distinct temporal-envelope characteristics. Monolateral CI listeners seem to be able to perceive and interpret this type of environmental sound easily (Reed and Delhorne, 2005). Better preservation of the distinct temporal envelopes after CI processing may allow bilateral CI listeners to use the ITD information to locate sound source.

VI. Baseline Performance for Animal Models and Psychophysical Models of Performance with Bilateral Cochlear Implants

ITD-JND results of this thesis are a first step in characterizing basic psychophysical performance for bilateral listening in cochlear implant users. These data establish the baseline performance against which models of auditory-system processing of bilateral, intracochlear stimulation can be tested. They also provide an important point of comparison for physiological data from animal studies. While there are many advantages to study with animal models, such as the ability to make invasive measurements in the auditory pathway and subject availability, there are also the drawbacks of working with a different system with differences in the frequency range of hearing, auditory pathway, and binaural processing. For example, the data of Abbas et al (1999) suggest that animals' nerves may be able to encode higher stimulation frequencies than human auditory nerve fibers (cf, Wilson et al., 1997) because there is less alternation in the ECAP data in Abbas et al. (1999).

Predicted ITD JNDs from single-unit data (Smith, 2006) measured in the cats' inferior colliculus are consistent with the psychophysical results reported in this thesis. Similar to the ITD JNDs of human subjects, neural ITD JNDs improve with increasing number of pulses using a low-rate, unmodulated pulse trains on a single, interaural electrode pair. As repetition rate increases with fixed duration, the neural ITD JNDs also degrade. The observed consistencies between human ITD JNDs and neural ITD JNDs encourage further integrated studies to better relate binaural processing at different stages of the auditory pathway and human psychophysical performance.

VII. Future Studies

Bilateral CI listeners' sound localization ability and ITD sensitivity with single-interaural-electrode-pair stimulation and through-processor stimulation measured in the current study provide a solid starting point for the next steps in studying binaural hearing with bilateral cochlear implants.

In terms of sound localization, testing should be done with a waveform like 50-pps, 300-ms pulse trains that provides better ITD sensitivity than the noise bursts used in the current study. Subjects' ITD sensitivity to the noise bursts through the processors was poor compared to ITD sensitivity to the 50-pps, 300-ms pulse trains through the processors. This would test the hypothesis that better ITD sensitivity will translate into better localization performance.

To further study the use of ITD and ILD cues in sound localization, virtual localization testing can be conducted using stimuli convolved with the subjects' HRTFs with manipulated ITD and ILD cues. Analysis in the current study suggests that bilateral CI listeners' ILD sensitivity can account for their localization performance, but sub-optimal use of ILD cues was observed. Virtual localization testing allows for better control of the ITD and ILD cues presented to the listeners. Manipulations, such as removal of reliable ITD or ILD cues as in Bronkhorst and Plomp (1988), can be done to the stimuli, and the resulting performance can be used to assess the importance of these cues for sound localization.

In terms of lateralization testing, two factors for further study have been identified from the results of this thesis: (1) the impact of amplitude modulation on electric pulse-train stimulation and (2) the impact of multiple-electrode stimulation. The impact of amplitude modulation with electric stimulation should be studied because the results of the current study show that bilateral CI subjects are insensitive to ongoing ITDs in unmodulated, high-rate (above 800 pps) pulse trains on a single, interaural electrode pair, but they are sensitive to ongoing ITDs in the modulation of high-rate (1450pps) pulse trains in the through-processor case. Also, neural data from Smith (2006) suggest that some neurons in the inferior colliculus that were not sensitive to ITD in the unmodulated pulse train at high rate became sensitive to the ITD of the same pulse trains when the train is sinusoidally modulated. Testing should be done with sinusoidal-amplitude-modulated pulse trains on single, interaural electrode pairs as a function of modulation frequency. Sensitivity to modulation (envelope) ITDs should be compared using 0 μs ITD in the carrier pulses and with the same ITD in both carrier and modulator. Sensitivity to carrier ITD should also be measured with fixed (e.g. 0 μs) ITD in the modulation. These data would be a valuable addition to the limited reports on ITD sensitivity using amplitude-modulated pulse trains on single, interaural electrode pairs in the literature (van Hoesel et al., 2002; Nam and Eddington, 2003; van Hoesel and Tyler, 2003).

Finally, to better understand ITD sensitivity through sound processors, the impact of multiple-electrode stimulation should be studied. It is uncertain how bilateral CI users' ITD sensitivity with multiple-electrode stimulation through the processors may depend on the number of ITD-sensitive, interaural electrode pairs. Another unknown is how stimulation of both ITD-sensitive and ITD-insensitive, interaural electrode pairs affects listeners' through-processor ITD sensitivity. To address these issues, different combinations of ITD-sensitive and ITD-insensitive electrode pairs should be tested with custom-made hardware/software that can stimulate multiple electrode pairs, bypassing the processors to eliminate the effect of CI processing.

VIII. Summary

Many performance-limiting factors must be identified and understood in order to be able to maximize binaural benefits with bilateral cochlear implants. This thesis took the initial steps to examine how ITD sensitivity depends on two stimulation parameters of unmodulated pulse trains, the basic stimulation waveform used in most cochlear implants. Sound-localization performance with two independent cochlear implants was also examined. The extent to which ITD was used in bilateral CI localization was investigated. This work has implications for further understanding of bilateral electric stimulation and improving the design of bilateral cochlear implants for the hearing-impaired users.

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