Original rc'd 1/4/99

11th Quarterly Progress Report

July 1, 1998, through September 30, 1998

Speech Processors for Auditory Prostheses

NIH Contract N01-DC-6-2100

submitted by

Christopher J. Long
Donald K. Eddington
H. Steven Colburn
William M. Rabinowitz
Margaret E. Whearty
Nico Kadel-Garcia

Massachusetts Institute of Technology
Research Laboratory of Electronics
Cambridge, MA

1 Introduction

1.1 Background

Many cochlear implant users report having great difficulty understanding speech in noisy situations. It is known that binaural cues provide normal-hearing listeners advantages in understanding speech in a background of noise. When the signal and noise are optimally located, a monaural listener requires a 13dB higher signal to noise ratio than a binaural listener to attain the same level of speech discrimination (Carhart et al., 1967). An average across all possible signal and noise positions gives a binaural advantage of 5dB (Zurek, 1993).

Binaural advantages could translate to significant increases in speech intelligibility for cochlear implant users. For three high-performing cochlear implant users tested on HINT Sentences (Nilsson et al., 1994), Rabinowitz and colleagues (Eddington et al., 1997) found that a 5dB increase in SNR (from 0dB to 5dB Speech to Noise Ratio) resulted in a mean word score increase from approximately 43% to 76%. An increase to an 8-10dB Speech to Noise Ratio resulted in a mean word score of approximately 94%. Thus a binaural advantage, which could increase the effective signal to noise ratio, could produce significant increases in speech understanding in noisy situations for cochlear implant users. In addition, listeners using bilateral implants could receive other benefits such as information about the location of sound sources.

1.2 Report Overview

The overall objective of our bilateral stimulation research is to determine if and how binaural advantages can be realized with a pair of cochlear implants. A fundamental step toward this goal is the measurement of binaural sensitivity. This report contains the results of binaural psychophysical experiments conducted with a single bilaterally implanted subject. One question we address is whether there is binaural sensitivity at a pitch-matched electrode pair. A second question is whether binaural sensitivity is worse for an electrode pair that is pitch-*mis*matched.

Our primary assessment of binaural sensitivity comes from measurements of the subject's sensitivity to Interaural Time Differences (ITDs) in binaural psychophysical experiments. While we also measure Interaural Level Difference (ILD) sensitivity, the significant monaural sensitivity to level changes complicates the use of ILD sensitivity as a measure of binaural sensitivity. Because of the very poor monaural sensitivity to time delays, ITD sensitivity provides a straightforward assay of binaural sensitivity.

We found sensitivity to (perceptually-relevant) ITDs on a pitch-matched, interaural electrode pair. For a pair of electrodes which were pitch-mismatched, we were unable to observe any ITD sensitivity. This is consistent with data from normal hearing listeners that shows a limited interaural frequency offset for which ITD effects can be seen (Nuetzel and Hafter, 1981).

These results give evidence that it may be possible to exploit binaural sensitivity to provide binaural advantages to cochlear implant users. The results also indicate that the choice of electrode pair affects the binaural sensitivity and, therefore, this choice should be a consideration in attempts to provide binaural advantages.

2 Methods

2.1 Subject

The subject was a 72-year-old woman with an Ineraid implant (right cochlea) and a Clarion implant (left cochlea) who has been under the care of the Warren Otologic Group of Warren, Ohio. She apparently had normal hearing as a child, but at age 25 she noticed the onset of a bilateral hearing loss. Her hearing loss progressed bilaterally and she became deaf at age 44. At age 59, she received the Ineraid cochlear implant and used that system on a daily basis until age 70, when she received the Clarion implant in an effort to improve her hearing using new technology. Since then, she has been a full-time user of the Clarion implant alone. When she first received the Clarion implant, the subject attempted to use both Clarion and Ineraid implants simultaneously – with unmatched processors and electrode pairs – for a brief period, but found the sensations confusing.

2.2 Stimulus Waveforms

Trains of fixed-amplitude, biphasic pulses were delivered to both the Clarion and the Ineraid electrodes. In the case of the Clarion implant, we report the requested current amplitude in quotes (i.e., "μApp") because the current actually delivered to the subject depends on a number of factors (including the electrode impedance) due to the nature of the implanted current source. A given "μApp" value will produce the same amplitude current (across a set load) as a given Clarion Clinical Unit (SCLIN 3.1 supplement) with half its value (e.g., 551.8"μApp" is equivalent to 275.8 Clinical Units). The amplitudes reported for the Ineraid implant are the levels actually delivered and, therefore, are not in quotes (i.e., μApp).

All electrodes were stimulated in a monopolar configuration. Stimulation of the 7th medial Clarion electrode and its far-field ground is indicated by "7MC." Stimulation of the 2nd Ineraid electrode with its far-field ground is indicated by "2I." For both devices, electrode 1 represents the most apical electrode.

All stimuli were trains of $300ms$ duration, biphasic, cathodic-first pulses ($76.9\mu sec$ phase duration). These waveform parameters differed across implant systems by less than 0.1%. During monolateral and non-simultaneous (alternating) bilateral stimulation, the pulse repetition rates were $100pps$ or $813pps$. During simultaneous stimulation, the repetition rate was always $100pps$.

ITDs were imparted by delaying the stimulation of the Ineraid electrode relative to the stimulation of the Clarion electrode (see Figure 1 on page 4). The total delay was a fixed hardware delay ($2.19\mu sec \pm 0.15\mu sec$) plus a programmable software delay, but in this report all ITDs will be given in terms of their software delay only.

The cochlear implant analog of Interaural Level Differences (ILDs) was produced by adjusting the Ineraid amplitude while holding the Clarion amplitude at a comfortable loudness level. The term ILD will refer to the Ineraid amplitude deviation from the Ineraid amplitude which produced a centered, fused (unitary) percept (with ITD equal to zero). In cases where a fused percept was not obtained, the ILD refers to a deviation from the Ineraid amplitude that produced a sensation equal in loudness to that of the Clarion comfortable stimulus level (with ITD equal to zero).

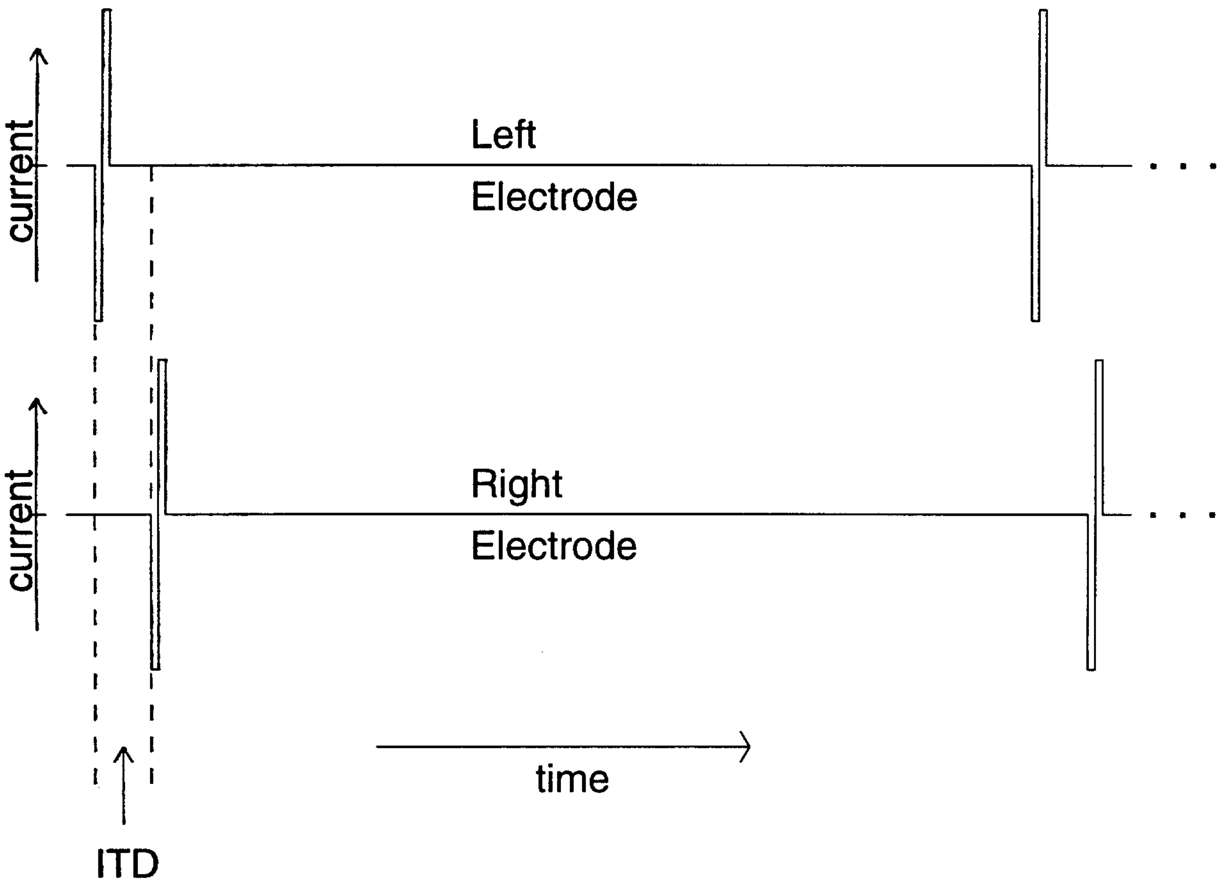

Figure 1: This schematic shows the first two pulse pairs in a bilateral train of pulses. Stimuli delivered to the right electrode (Ineraid) are always delayed relative to those delivered to the left electrode (Clarion). The time axis is to scale and the ITD shown is $600\mu sec$.

2.3 Preliminary Tests

The threshold and the uncomfortable loudness (UCL) levels were used to define the dynamic range for each test electrode. Absolute thresholds were measured using a three-interval, three-alternative, forced-choice task. A two-down, one-up, adaptive procedure was used to adjust the amplitude of the monolateral stimuli. Uncomfortable loudness (UCL) was assessed with a one-interval, two-alternative, forced-choice task (one-down, one-up, adaptive) designed to find the monolateral stimulus amplitude that resulted in a sensation level on the verge of being uncomfortable.

A centering test was conducted with simultaneous, bilateral stimulation (100*pps*; ITD = $0\mu sec$) for electrode pairs in which such stimuli resulted in a fused percept. The amplitude of the Clarion stimulus was held constant at a comfortable level and the Ineraid stimulation amplitude was adjusted in order to produce a centered sensation. A one-interval, two-alternative, forced-choice (one-up, one-down, adaptive) procedure was employed. The result was used to determine the center of the range of Ineraid stimulus amplitudes to be used in the lateralization test. For an electrode pair in which the stimuli were not perceptually fused, the stimulus presentation method described above was used, but the subject was instructed to balance the simultaneous loudnesses of the two sound sensations.

Additional informal tasks were used to gather anecdotal information about fusion and lateralization. These tasks included (1) asking the subject questions about the sound sensations; (2) having the subject draw the perceived location of the sound sensations on a schematic picture of a head; and (3) the interactive use of a lateralization scale.

2.4 Pitch Ordering Test

This test was used to rank order the electrodes by the pitch sensations they produced. We assumed that electrodes eliciting similar pitch sensations (across ears) were located at similar cochleotopic positions. Based on the results of this test, cochleotopically matched (or mismatched) electrode pairs could be selected for further study in binaural psychophysical experiments. Before performing the interaural pitch ordering test, the subject was trained and tested with monolateral stimuli.

Each run of the test consisted of 25 presentations of the stimulus pairs. In the interaural test, two electrodes (at loudness-balanced amplitudes) were selected, one from each ear. In the monolateral test, two electrodes (at loudness-balanced amplitudes) were selected from the same ear. In the test, two boxes were drawn on the subject's display screen. Each presentation consisted of two stimuli presented in sequence. In the interaural test, the left box was lit during the presentation of the first (left ear) stimulus and the right box was lit during the presentation of the second (right ear) stimulus. In the monolateral test, all stimuli were presented to a single ear and the order of the two stimuli was randomized. For each, the subject's task was to type the number of the box (1 or 2) that was lit during the sound sensation that was higher in pitch. The test was a two-interval, two-alternative forced-choice task with stimuli that were fixed during each run. The stimulus waveforms were 813*pps* biphasic pulse trains presented non-simultaneously.

The results of the interaural pitch ordering test were expressed in terms of the percent of the presentations in which the subject judged the Clarion electrode as higher in pitch than the Ineraid electrode, $P(C > I)$. We classified the Clarion electrode as discriminably higher in pitch than the Ineraid electrode (i.e., pitch-mismatched) if $P(C > I) \geq 76\%$ and as discriminably lower in pitch (i.e., pitch-mismatched) if $P(C > I) \leq 24\%$ for 25 presentations. For results between these bounds, the electrodes were classified as indiscriminable (i.e., pitch-matched). At the bounds, the sensitivity index, d', equals 1.0 and for 25 presentations the probability in the upper or lower tail of the binomial distribution with $P = 0.5$ is 0.0073. For 50 presentations, the upper and lower bounds of discriminability are 68% and 32%, respectively, and the probability in the upper or lower tail of the binomial distribution with $P = 0.5$ (at the bounds) is 0.0077.

2.5 Lateralization Test

This test was designed to measure perceived locations (lateral positions) for a set of ILDs and ITDs on a given electrode pair. For each presentation, the subject assigned a number from a lateralization scale that represented the lateral position of that sound sensation. The scale range was from 1 to 7 where 1 represented a sound sensation at her left ear, 4 represented a centered sound sensation, and 7 represented a sound sensation at her right ear. The numbers in between allowed her to indicate intermediate positions. The subject was also instructed to indicate "None of the Above" (NA) if she could not assign a (single) number to the perceived location (e.g., if she heard more than one sound sensation during a single presentation). Thus, this was a one-interval, eight alternative (1, 2, 3, 4, 5, 6, 7, NA) test. A stimulus set was made up of 15 bilateral stimuli (5 ILDs and 3 ITDs). The ILDs were selected to elicit sensations at locations covering the range from the far left to the far right and were determined from the informal tests. The ITDs ($0\mu sec$, $300\mu sec$, and $600\mu sec$) were chosen to span the range of ITDs relevant in real-world situations. On two days of testing with electrode pair 7MC/2I, a total of 33 of the randomized stimulus sets were presented.

2.6 Relative Loudness Test

This test was designed to determine if ITD had any effect when bilateral stimulation produced two separate (unfused) sensations and the lateralization test was, therefore, inappropriate. In this test, the subject was asked to assign a number to indicate the relative loudness of the two simultaneous sound sensations. The number 1 indicated that the sound sensation in the left ear was considerably louder than the sound sensation in the right ear. The number 4 indicated that the sound sensations were loudness balanced across the ears. The number 7 indicated that the sound sensation in the left ear was considerably softer than the sound sensation in the right ear. The numbers in between allowed her to indicate intermediate relative loudnesses. This one-interval, eight-alternative (1, 2, 3, 4, 5, 6, 7, NA) test used a stimulus set of 15 stimuli (5 ILDs and 3 ITDs). On one day of testing with electrode pair 3MC/2I, a total of 10 of the randomized stimulus sets were presented.

3 Results and Discussion

3.1 Preliminary Tests

Table 1 on page 7 shows the threshold and UCL test results and the dynamic range calculations for electrodes 2I and 7MC with a repetition rate of $100pps$. These test were not performed on electrode 3MC.

Results from Preliminary Tests

Test	2I	7MC
Threshold	$296.3\mu App$	247.2"μApp"
Uncomfortable Loudness Level	$826.3\mu App$	650.4"μApp"
Dynamic Range	$8.9dB$	8.4"dB"

Table 1: Results of threshold and UCL tests and the dynamic range calculations for electrodes 2I and 7MC.

% Clarion Judged Higher in Pitch (Number of Presentations)

	Clarion el:	1MC	2MC	3MC	4MC	5MC	6MC	7MC	8MC
Ineraid el:									
1I					8(25)	68(50)	84(25)		
2I						20(25)	56(25)	48(25)	76(25)
3I					0(10)				
4I									
5I					0(10)				

Table 2: Summary of Interaural Pitch Comparisons. This table shows the percent of the presentations in which the subject judged that the Clarion electrode was higher in pitch than the Ineraid electrode. The numbers in parentheses are the numbers of presentations for each electrode pair tested. For both devices, electrode 1 indicates the most apical electrode.

The centering test with 7MC fixed at 551.8"μApp" gave a centered percept when the electrode 2I amplitude was $605.4\mu App$. The simultaneous loudness balancing test with 3MC fixed at 408.8"μApp" gave a loudness balanced percept when the electrode 2I amplitude was $555.7\mu App$.

3.2 Pitch Ordering Test

The results of the pitch ordering test (Table 2, page 7) are expressed in terms of the percent of the presentations in which the Clarion electrode was judged higher in pitch than the Ineraid electrode, $P(C > I)$. When scanning from left to right across the table in a given row, this percentage generally increases. For example, the subject answered that 4MC was higher in pitch than 1I on only 8% of the presentations while she judged the more basal 6MC higher in pitch than 1I on 84% of the presentations. This trend is consistent with cochleotopic order.

Electrode pairs 7MC/2I and 6MC/2I, were classified as pitch indiscriminable. These pitch indiscriminable (i.e., pitch-matched) electrodes were taken as potentially good pairs for examining ITD sensitivity. Electrode pairs 5MC/1I and 8MC/2I were classified as bordering on discriminable. The other five electrode pairs tested were classified as discriminable (i.e., pitch-mismatched).

3.3 Electrode Pair 7MC/2I

Measurements of perceived lateral position as a function of ILD and ITD for electrode pair 7MC/2I are shown in Figure 2 on page 9. Consider first the results with ITD = $0\mu sec$. As might be expected, increases in the right electrode stimulus amplitude cause the mean lateral position of the sensation to move clearly toward the right. That is, lateral position is sensitive to ILD.

The results of Figure 2 also show lateral position sensitivity to ITD. For electrode 2I stimulated at $616\mu App$, the mean lateral position of the elicited sensations shifts left as the right electrode stimulus is delayed. Similarly, the sensations produced by stimulating electrode 2I at $605\mu App$ (centered amplitude), tend to shift left as the right electrode stimulus is delayed. These shifts are significant ($\alpha < 0.01$ on a t-test) and demonstrate ITD sensitivity for these amplitudes. These results are consistent with normal hearing ITD effects on lateralization and are evidence of binaural sensitivity.

At some Ineraid amplitudes a significant ITD effect is not observed; these results can be understood in light of research with normal hearing listeners. For electrode 2I at $580\mu App$, the ILD alone causes the percept to be lateralized to the left ear, leaving no room for an additional leftward shift with non-zero ITD. For electrode 2I stimulated at $627\mu App$ and $650\mu App$, the lack of a significant ITD effect is consistent with results in normal hearing (for click stimuli) where large ILDs can greatly reduce the effect of ITDs on lateral position (Durlach and Colburn, 1978; Blauert, 1997).

The subject answered "None of the Above" (NA) in 12.2% of her responses. While we did not routinely ask for detailed descriptions of the sensations eliciting NA responses, it is our impression that a significant number of the NA responses indicated the presence of two images.

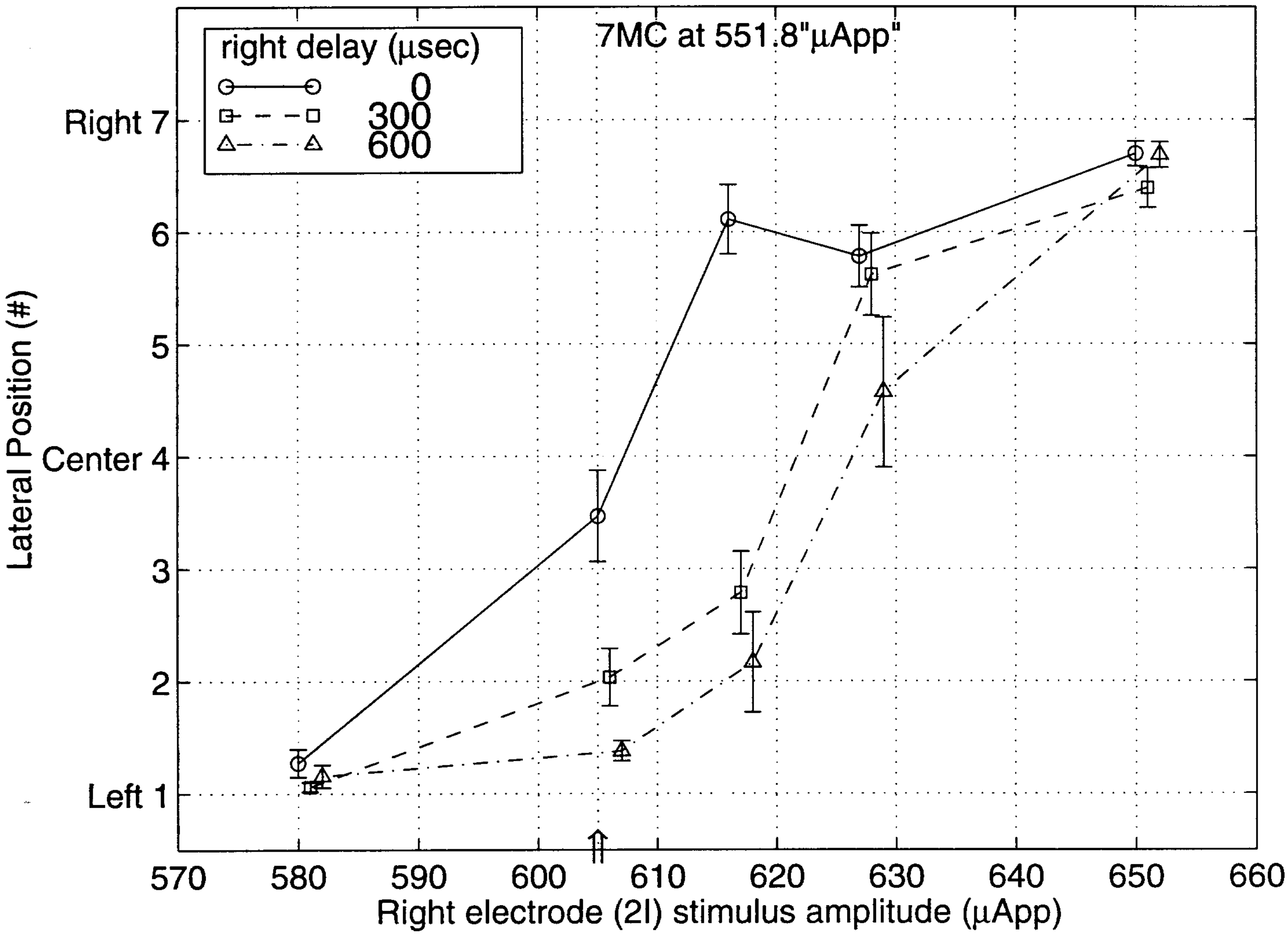

Figure 2: Lateral position as a function of ITD and ILD. This figure shows the mean (± standard error) lateral position for the indicated ILD and ITD combinations. Electrode 7MC was held at 551.8"μApp" while the amplitude of 2I was varied. The arrow indicates the 2I stimulus amplitude measured during the centering test (see section 3.1). Non-zero ITD data are shown slightly offset in amplitude for easier visual comparison, although their stimuli were presented at the same amplitudes as the zero ITD stimuli.

3.4 Electrode Pair 3MC/2I

Electrode pair 3MC/2I was chosen as a pair that was cochleotopically mismatched based on the pitch ordering test. We hypothesized that if the ITD sensitivity observed with 7MC/2I were truly based on binaural mechanisms, this pair (3MC/2I) should not show a sensitivity to ITD. Qualitatively, the sensations produced by bilateral stimulation of this electrode pair were very different than those produced with 7MC/2I. Rather than a single, fused sensation, she heard two separate sound sensations with different pitches. She could not perform the lateralization test with this electrode pair, so we used the relative loudness procedure (see section 2.6) to test for the presence of an ITD effect. The results of these tests are shown in Figure 3 on page 11.

There is a clear trend with ILD: as the right electrode amplitude increased, the right ear stimulus was judged as louder than the left on average.

There is no significant, nor consistent, ITD effect. This is consistent with results from normal hearing subjects in which ITD sensitivity disappears when the cochleotopic positions of excitation are significantly mismatched (Nuetzel and Hafter, 1981). This result indicates that the choice of electrode pair affects the binaural sensitivity and, therefore, this choice should be a consideration in attempts to provide binaural advantages.

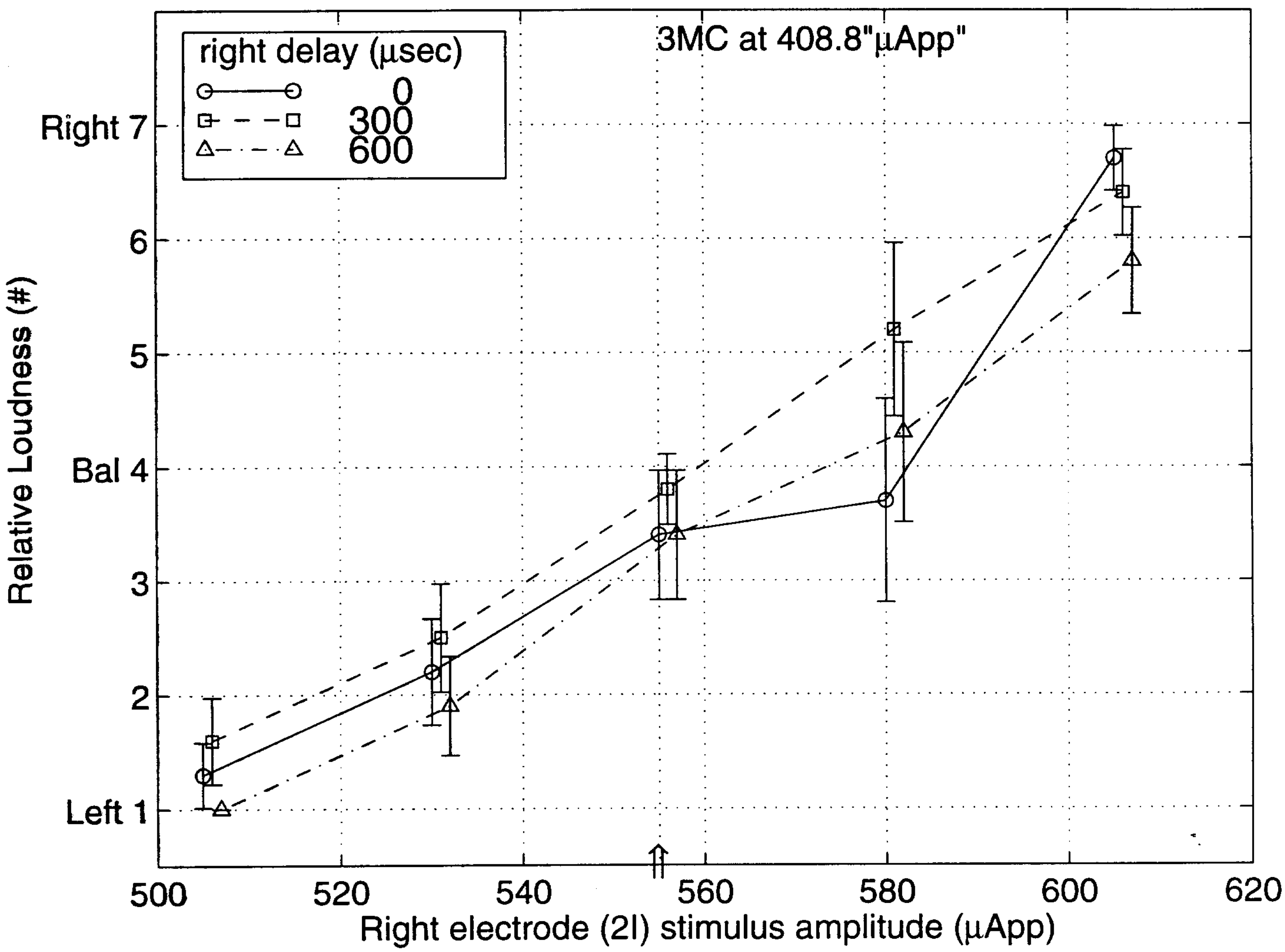

Figure 3: Relative Loudness as a function of ITD and ILD. The figure shows the mean (± standard error) relative loudness for 5 ILDs and 3 ITDs. The electrode 3MC amplitude was held at 408.8"*µApp*" while the stimulus amplitude of electrode 2I was varied. The arrow indicates the balanced 2I stimulus amplitude measured during the simultaneous loudness balancing test (see section 3.1). Non-zero ITD data are shown slightly offset in amplitude for easier visual comparison although their stimuli were presented at the same amplitudes as the zero ITD stimuli.

3.5 Summary

The subject demonstrated a sensitivity to ILD and ITD for trains of pulses (100*pps*) presented to a pair of electrodes judged to be in similar cochleotopic positions (based on across-ear pitch comparisons). The subject showed sensitivity to ITDs of $300\mu sec$ and $600\mu sec$. No ITD sensitivity was found for an interaural electrode pair that was mismatched cochleotopically. These results are evidence that it may be possible to exploit binaural sensitivity to make binaural advantages available to cochlear implant users. The results also indicate that the choice of electrode pair affects the binaural sensitivity and, therefore, electrode/channel matching across ears should be a consideration in attempts to provide binaural advantages.

4 Future Work

In the future, we plan to perform additional psychophysical experiments with this subject, related acoustic simulations in subjects with normal hearing, speech tests in quiet and noise with coordinated processors, and to develop related neural models.

5 Acknowledgments

We thank this subject for her participation in these studies. We also thank Dr. Franklin Rizer, M.D., and Mr. Peter Arkis of the Warren Otologic Group for facilitating our work with this subject.

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