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Binaural sensitivity of bilateral implanted patients to amplitude modulated stimulation presented on multiple electrodes

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1. INTRODUCTION

The localization and segregation of sound sources in an acoustically complex environment requires the binaural processing of interaural acoustical cues, such as the interaural time (ITD) and interaural level (ILD) differences in the sounds arriving between the ears. For bilateral cochlear implant (BiCI) users, ITD encoding in existing CI technology is poor, as only ITDs in the signal's envelope are represented because the temporal fine structure is replaced with constant, high-rate electrical pulse trains.

Previous work has shown that many adult BiCI users with post-lingual onset of deafness exhibit sensitivity to ITDs from pulse trains delivered through synchronized processors to single interaural electrode pairs at low stimulation rates (100 pulses per second or pps)[1,2]. Sensitivity progressively worsens as the pulse rate increases to 1000 pps[2]; however, it has also been demonstrated that BiCI users show sensitivity to ITDs contained in the envelopes of amplitude modulated, high-rate pulse trains[3,4,5,6]. This is important because CI speech encoding presently achieves good speech understanding by utilizing high pulse rate stimulation (~1000pps) delivered on *multiple electrodes*.

As a first step towards understanding how ITD cues on multiple electrodes are combined and utilized by BiCI users, there is a need to systematically investigate sensitivity to ITDs when multiple electrodes are stimulated.

QUESTIONS

- **Is there a region of the cochlea where combinations of multiple electrodes produce the best ITD sensitivity?**
- **Is there a particular combination of multiple electrodes that produces the best ITD sensitivity?**
- **Do BiCI users maintain ITD sensitivity with high rate, amplitude modulated stimulation on multiple electrodes?**
- **How does this sensitivity compare to that produced by low rate stimulation?**

2. SUBJECTS AND DESIGN

Listeners

- 11 post-lingually deafened BiCI Cochlear Nucleus 24, Freedom, or N5 users.
  - Participation in one of the two experiments listed below:
    1.) Low rate stimuli
    2.) High rate stimuli

Table 1. Listener profiles and etiology

Exp.	ID	Age	Sex	Years of CI Experience L/R	Etiology
Both	**IAJ**	65	F	14/7	Unknown
Both	**IBX**	70	F	2/1	Ototoxicity
Both	**ICB**	61	F	8/11	Hereditary
Low	**IBQ**	79	F	1/3	Otosclerosis
Low	**IBY**	48	F	8/8	Etiology unknown
Low	**ICA**	53	F	4/11	Progressive / High temp
Low	**ICG**	50	F	9/9	Etiology unknown
Low	**ICI**	54	F	19/19	Etiology unknown
High	**IBK**	71	M	7/1	Hereditary / Noise
High	**IBN**	65	M	3/13	Born deaf, etiology not listed
High	**ICM**	59	F	7/2	Progressive, nerve-damage

Procedure

1. Measure subjects' threshold, comfortable, and maximum comfortable levels.
2. Identify 5 pitch-matched pairs via bilateral pitch comparison (2I-5AFC), followed by loudness balancing and ILD centering for each electrode pair.
3. Test ITD discrimination for all single electrode pairs and all multi-electrode combinations (see Fig. 1).

Stimuli

- 300 ms biphasic (25 μs/phase) electrical pulse trains
  - Low rate (100pps) constant amplitude
  - High rate (1000pps) amplitude modulated (100%) at 100 Hz
- Presented at the level identified as "comfortable" using monopolar stimulation via a bilaterally-synchronized pair of Nucleus Implant Communicators (NICs).
- ITD = ±100, ±200, ±400, ±800 μs
- 20 reps @ each ITD

*For AM stimuli, the ITD was represented in both the fine structure and envelope of the signal.

3. METHODS

ITD Discrimination

- 2Interval-2Alternative Forced Choice Left/Right discrimination task.
- Subjects reported whether the auditory image in the second interval was perceived to the left or right of the first.
- Percent correct data for single electrode pairs were fit with a psychometric function to obtain a 71% correct threshold.
- Multi-electrode combos were selected from thresholds (Fig. 1, see color coding and grouping) for further testing.

Multi- Electrode Combinations

- (1) *basal:* three most basal pairs
- (2) *apical:* three most apical pairs
- (3) *spread:* base-mid-apex pairs
- (4) *best:* three pairs with the lowest individual ITD thresholds
- (5) All five electrode pairs

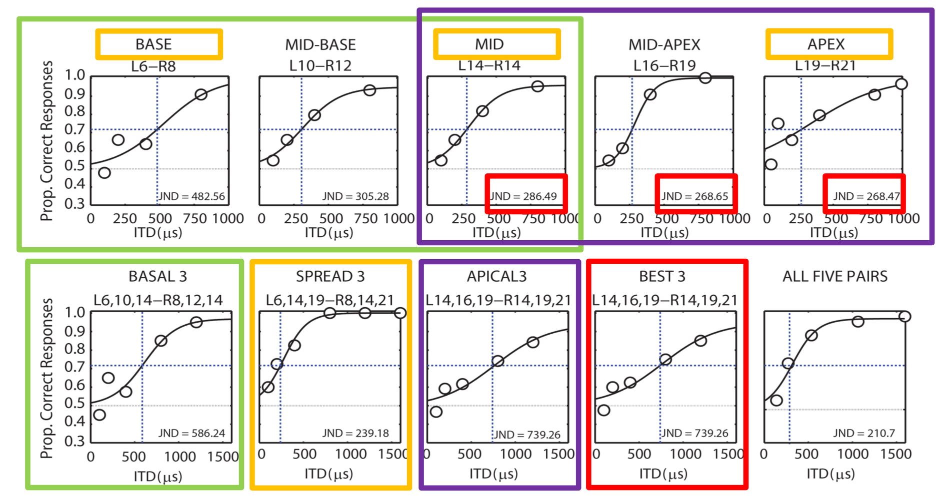
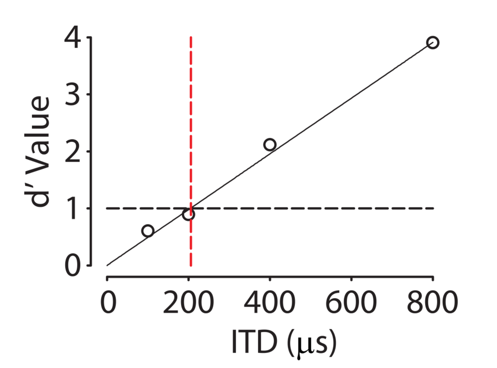


Fig. 1. Example of selecting all the multi-electrode combinations tested for subject IAJ. (Top) Single electrode pair percent correct scores for each ITD tested. (Bottom) All the multi-electrode combinations tested. The colored boxes indicate how the combinations were selected.

d' Analysis

- Percent correct scores were converted into d' values as a statistical measure of sensitivity.
- The d' values were plotted as a function of the ITDs tested and fit with a linear regression forced to pass through y=0 (Fig. 2).



*Total cue size presented was twice the ITD used in either interval, so the calculated ITD thresholds were doubled.

Fig. 2. Determination of ITD threshold based on calculated d' values.

4. ITD SENSITIVTY: LOW RATE

Results

Single Electrode Pairs

- ITD thresholds were highly variable across subject and place of stimulation (Fig. 3, straight lines).
- No place of stimulation produced the lowest ITD thresholds.

Three Electrode Pair Combinations

- ITD sensitivity was observed for multi-electrode stimulation (Fig. 3, stars).
- Across subjects, no place or electrode combination consistently produced the lowest ITD thresholds.

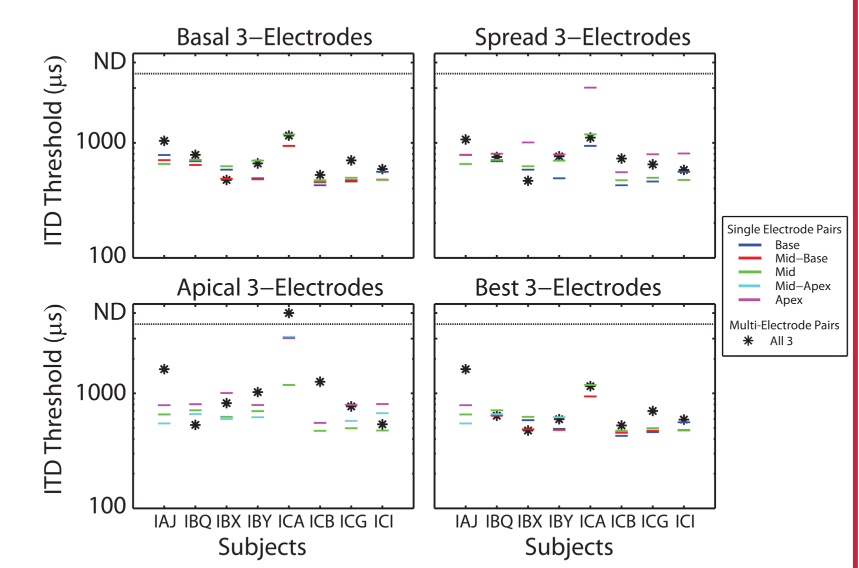


Fig. 3. ITDs thresholds for all single and three electrode combinations.

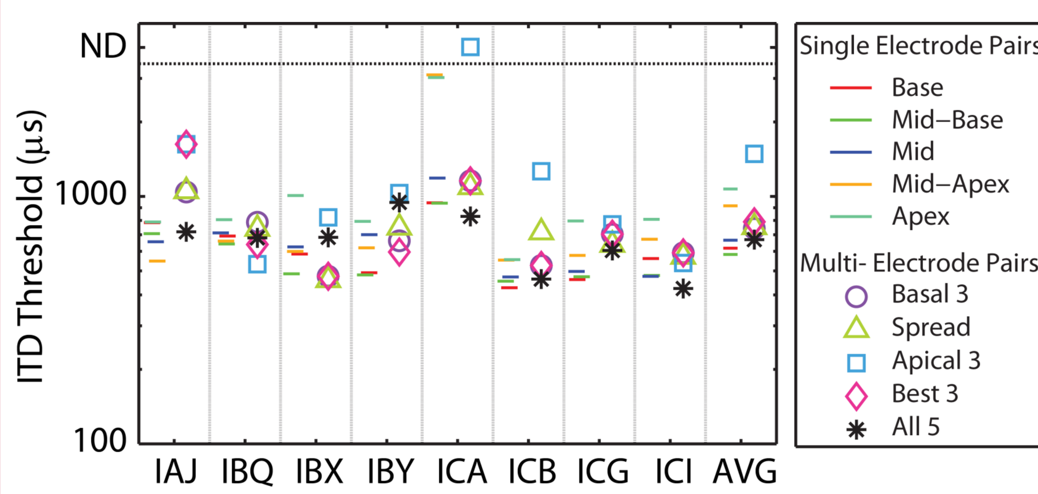


Fig. 4. ITD thresholds for all electrode conditions tested.

Five Electrode Pair Combination

- Stimulation of all 5 electrodes resulted in the best performance in 5 out of 8 subjects (Fig. 4, stars).
- For the other 3 subjects, thresholds typically fell within the range of single electrode thresholds.
- Poor ITD sensitivity on a single electrode pair does not greatly affect overall sensitivity when all 5 electrodes were stimulated.

5. ITD SENSITIVTY: HIGH RATE w/ AM

Results

Single Electrode Pairs

- ITD thresholds of high rate stimuli exhibited a similar amount of high variability as observed for the low rate stimuli (Fig. 5, straight lines).

Three Electrode Pair Combinations

- In almost all cases, stimulation on 3 electrodes resulted in better (or comparable) ITD thresholds than the lowest single electrode pair in the combination (Fig. 5, asterisks).

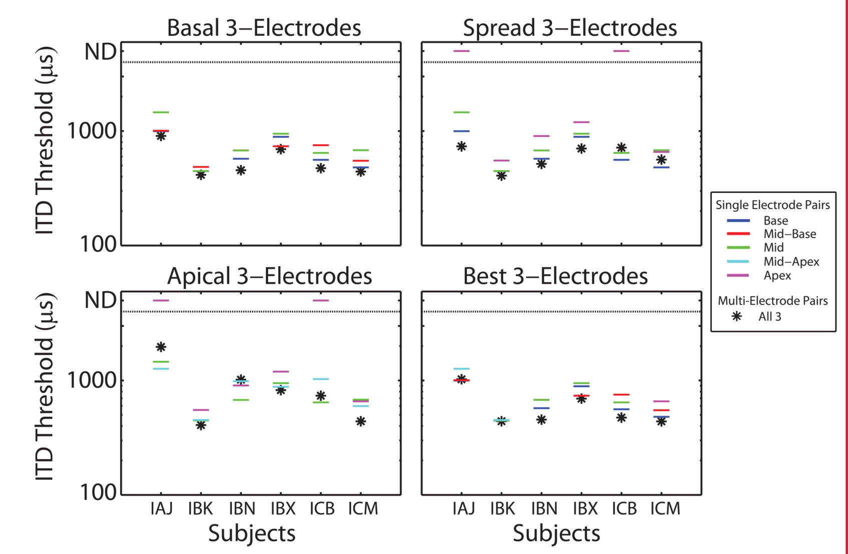


Fig. 5. ITDs thresholds for all single and three electrode combinations.

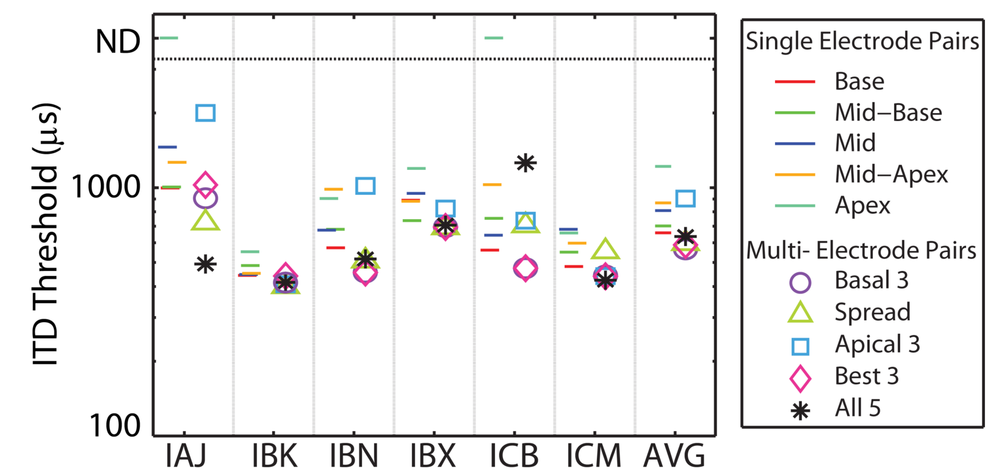


Fig. 6. ITD thresholds for all electrode conditions tested.

Five Electrode Pair Combination

- Multi-electrode stimulation with high rate-AM stimuli generally produced lower ITD thresholds than the single electrode pairs tested at the same rate.
- Amplitude modulation appears to produce ITD sensitivity of multi-electrode stimuli to ranges observed for low rate stimuli presented on single electrode pairs.

6. RATE AND PLACE COMPARISONS

Which place produces best ITD sensitivity?

Single Electrode Pairs

- A repeated-measures ANOVA revealed <u>no significant effect of place</u> across group single electrode ITD thresholds for either the low or high rate stimuli (p=0.48 and 0.89, respectively).

Multi-Electrode Pairs

- A repeated-measures ANOVA revealed <u>no significant effect of place</u> on ITD thresholds for either the low or high rate stimuli (p=0.84 and 0.41, respectively).

- The basal, spread and all 5 combinations typically achieved the lowest multi-electrode ITD thresholds (Fig. 7).
- For both rates, the Apical 3 multi-electrode combination typically had the highest ITD thresholds.

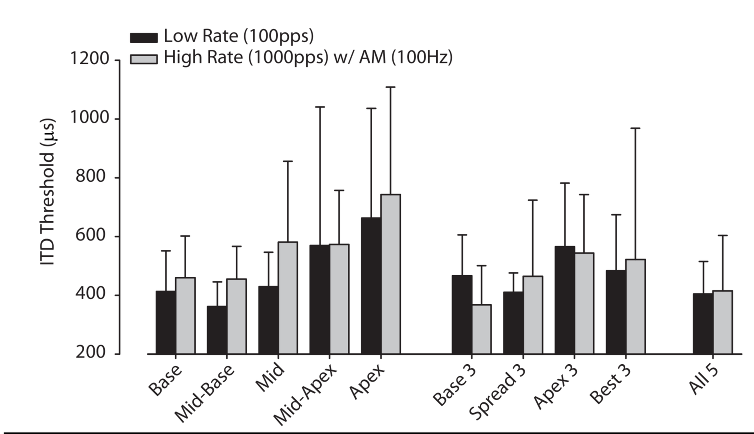


Fig. 7. Across subject average ITD threshold (bars) and standard deviation (error bars) for both rate and electrode condition tested.

Which rate is better? (low vs. high w/AM)

Single Electrode Pairs

- A one-way ANOVA revealed <u>no significant effect of rate</u> on single electrode ITD thresholds (p=0.08).

Multi-Electrode Pairs

- A one-way ANOVA revealed <u>no significant effect of rate</u> on ITD thresholds (p=0.84).

Within-Subject Rate Comparison

- For single electrode pairs, low rate stimuli produced lower ITD thresholds compared to the high rate stimuli (Fig. 8, triangles above the line).
- For 3 subjects, on the All 5 condition, one did better with the low rate stimuli, one did better with high rate stimuli and one did the same with both (Fig. 8, stars).

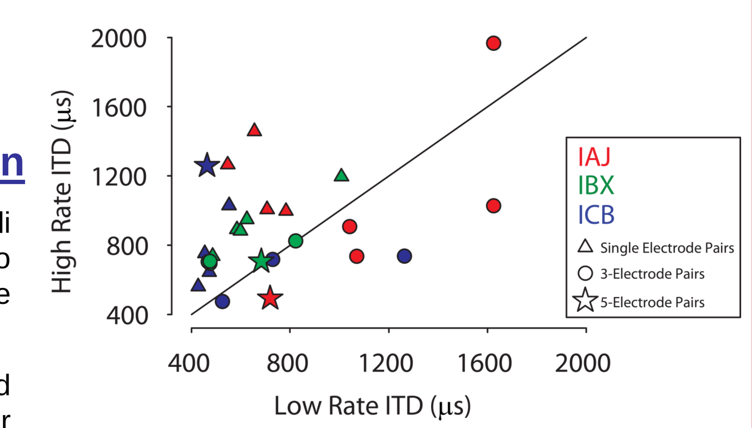


Fig. 8. Three subjects tested on both conditions. Similar trends to the group data were observed.

7. MULTI-ELECTRODE INTEGRATION

Which multi-electrode combination?

Multi-Electrode Pairs (3 vs. 5 pairs)

- A repeated-measures ANOVA revealed <u>no significant effect of electrode combination</u> on ITD sensitivity in either the low or high rate conditions (p = 0.31 and 0.64, respectively).

Optimal listener model

- Based on the d' values for each single electrode pair, theoretical performance was modeled (see optimal eq.) for all the multi-electrode combinations[6]. The modeled ITD thresholds were once again taken as the ITD at d' =1.

Optimal $|d_c'=(\Sigma d_i'^2)^{1/2}|$
Highest Single Electrode d'
Lowest Single Electrode d'

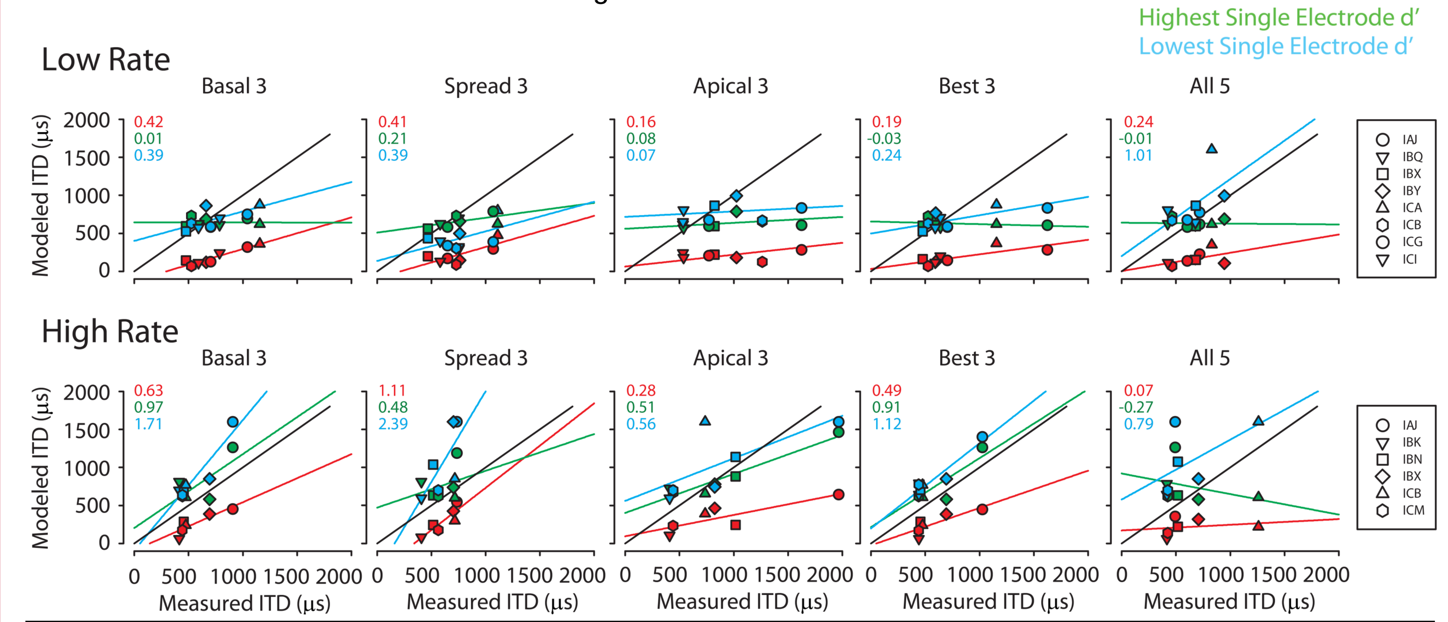


Fig. 9. Modeling multi-electrode ITD sensitivity based on single electrode measurements. (Top row) Low rate stimulation. (Bottom row). High rate stimulation w/100Hz at 100% AM. For each subject, the ITD threshold measured for a particular multi-electrode combination is plotted as a function of the ITD threshold computed from the single electrode d' values in that multi-electrode combination. The d' values were either optimally combined (eq. above), or calculated for the single electrode pair in the combination with the highest or the lowest d' value. The <u>slopes</u> of the fits are indicated at the top left of each subplot.

How does ITD sensitivity on the single electrode pairs contribute to the overall ITD sensitivity of multi-electrode stimulation?

- Results suggest that for low rate stimuli, BiCI users do not seem to be **optimally** combining ITD sensitivity across electrodes (Fig. 9, top panels). Depending on the subject, sensitivity seems to be determined either by the single electrode pair with the **highest** or **lowest** sensitivity.
- For the high rate stimuli, modeled ITD thresholds based on either the **highest** or **lowest** single electrode d' value tended to be higher than what was measured (Fig. 9, bottom panels) suggesting that information may be integrated in some way across electrodes.

8. CONCLUSIONS

- In general, ITD sensitivity is maintained (or better) when multiple, pitch-matched electrodes are stimulated compared to stimulating single pitch-matched electrode pairs individually.
- BiCI users demonstrate the ability to discriminate ITDs of amplitude modulated, high rate (1000pps) signals delivered across multiple electrodes at 100% modulation depth and ITD sensitivity is comparable to that observed for low rate stimuli.
- On average, stimulation of apical single or multi-electrode combination produced higher ITD thresholds. Results suggest that ITD information may be the most useful when delivered to either (1.) more basal locations, (2.) spread along the array, or (3.) more electrodes on the array.
- Temporally coordinating clinical BiCI speech processors and bilaterally mapping each patient individually to deliver stimulation on pitch-matched electrode pairs across the ears may help better provide crucial ITD information not currently available in present day cochlear implants.

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