Neural coding of binaural cues between acoustic and electrical stimulation in an animal model of single-sided deafness

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INTRODUCTION

Cochlear implant (CI) users increasingly have significant acoustic hearing in the non-implanted ear and continue to use a hearing aid (HA) in the non-implanted ear. In addition, CIs are becoming a treatment option for people with single-sided deafness (SSD). These populations of CI users can potentially enjoy the benefits of binaural hearing such as improved sound localization and speech reception in noise by utilizing binaural cues present between the two different modes of stimulation. Here, we investigated the sensitivity of midbrain auditory neurons to interaural time differences (ITD) with bimodal stimulation to understand how the binaural cues are represented in the central auditory pathway and identify the most effective stimulation parameters for delivering these cues.

The results show that neurons in the auditory midbrain can be sensitive to binaural cues in combined acoustic and electric stimulation and suggests binaural benefits with bimodal hearing could be improved by providing better access to binaural cues in SSD/CI users and HA-CI users.

METHODS

Awake rabbit preparation

- Dutch-belted rabbits
- Unilateral deafening and implantation in one adult rabbit. Deafening by distilled water injection during CI surgery
- Cochlear implant: 8-contact array (HL-8, Cochlear Corp.)
- Unanesthetized, two-hour recordings per session
- Recording: Well isolated single units using linear microelectrode array (LMA) with 4 contacts (MicroProbes).

Stimuli

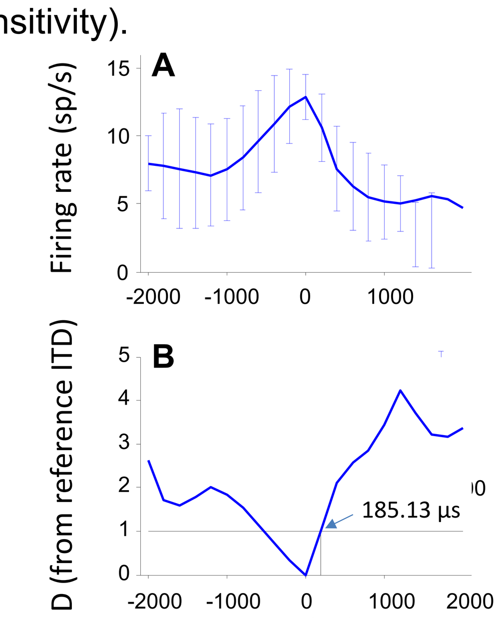
- Combined acoustic clicks and electric pulse trains at low rates (20 - 80Hz). Bimodal CI users are sensitive to ITDs in acoustic clicks and electric pulses in this frequency range (Francart et al., 2009; 2011).
- **Mismatch between acoustic and electric delays (De)**
  - Electric stimulation: directly stimulates the auditory nerve.
  - Acoustic stimulation: frequency dependent delay of 1-5 ms primariliy due to cochlear traveling wave delay.
  - Estimated from latencies of neural responses to both acoustic and electric stimulation when possible.
- ITDs: first tested over a wide range (-10ms to 10ms), then tested over De±2000 μs in 200 μs steps.

Analysis

- ANOVA based metric, “signal-to-total-variance ratio” (STVR).
  - Compares the variations in firing rate due to changes in ITD to the intrinsic variability in rate over multiple repetitions of the same stimulus (Hancock et al. 2010).
  - STVR varies from 0 (no sensitivity) to 1 (perfectly reliable sensitivity).
- ITD just-noticeable difference (JND)
  - Neural standard separation based on signal detection theory (Shackleton et al., 2003)

$$D_{ITD,ITD+\Delta ITD} = \frac{|\mu_{ITD} - \mu_{ITD+\Delta ITD}|}{\sqrt{(\sigma^2_{ITD} + \sigma^2_{ITD+\Delta ITD})/2}}$$

  - Analogous to d’
  - ITD JND: ΔITD needed for $D_{ITD,ITD+\Delta ITD}$ to reach 1.
- ITD tuning shape
  - Peak: excitatory binaural interaction near De.
  - Trough: inhibitory binaural interaction near De.



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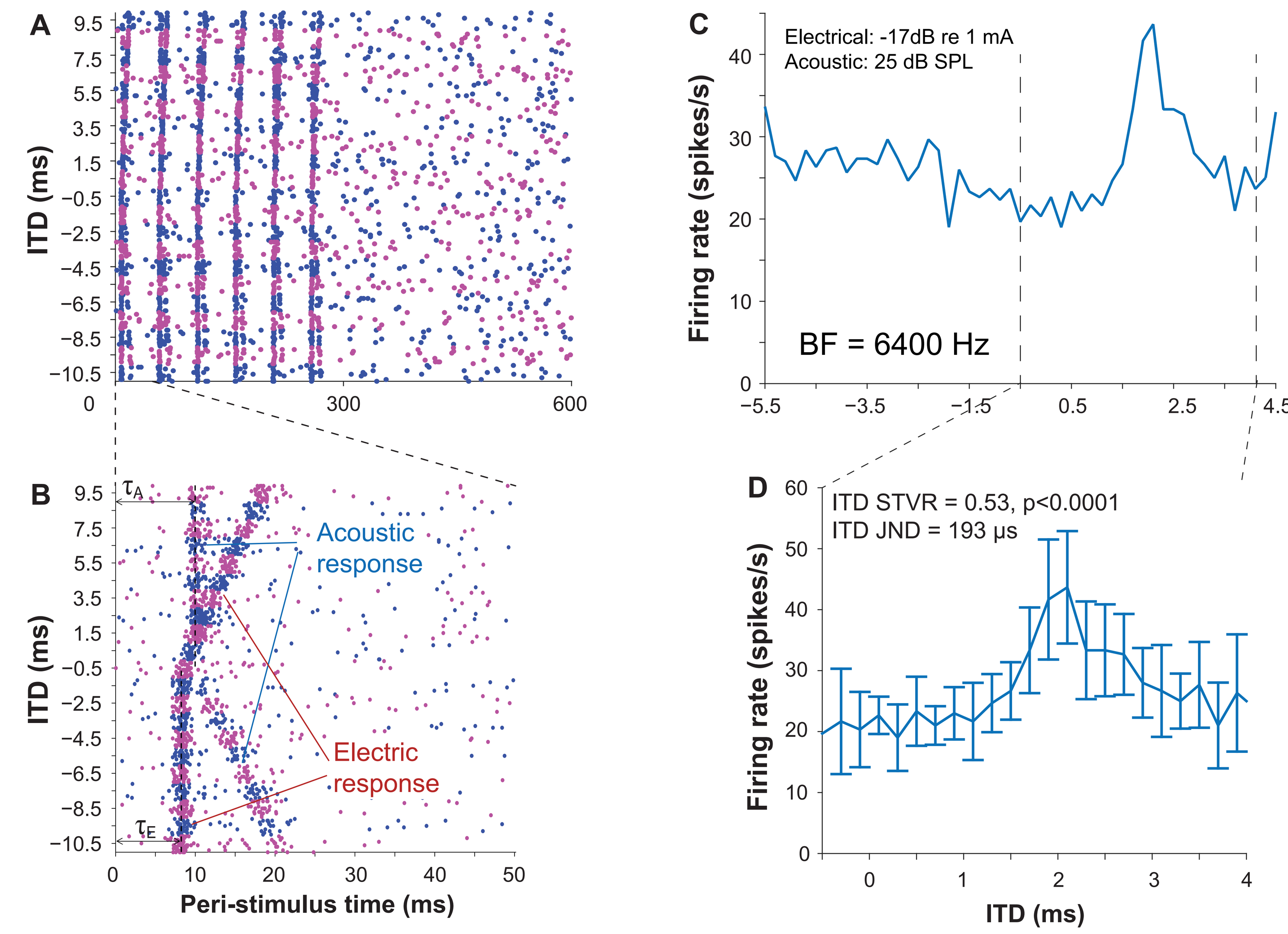
Example 1: Peak-shape ITD tuning

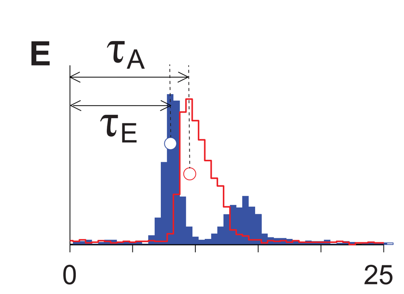
1) Responses of an IC neuron that shows excitatory binaural interaction to combined electric and acoustic stimulation



- Stimulation rate = 20 Hz
- BF = 6400 Hz
- IC unit contralateral to acoustic stimulation

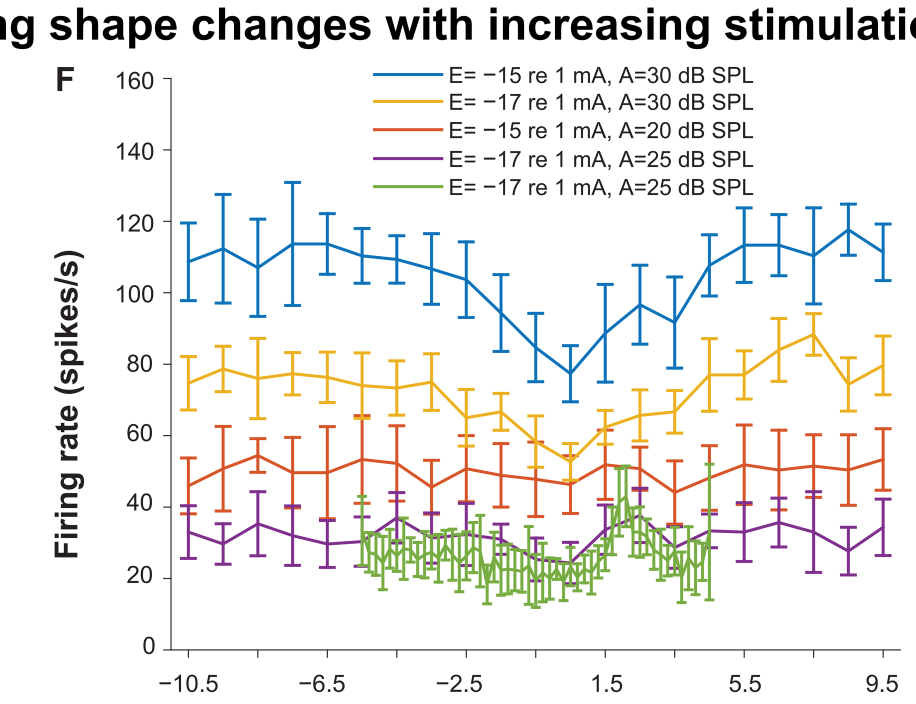
A, B: Dot rasters show response patterns as a function of ITD. Alternating colors indicate blocks of stimulus trials at different ITDs. Temporal discharge pattern shows strong response to both stimuli for large positive (acoustic leading, >4 ms) and negative (electric leading, <0ms) ITDs (Fig B). The acoustic response latency is longer than the electric response latency as expected.
C: ITD tuning cuve measured over -5.5 ms to 4.5 ms. For ITDs between 0 and 4 ms, this neuron shows clear binaural interaction to the bimodal stimuli with increase in firing rate relative to the firing rate to larger ITDs.
D: ITD tuning curve from the same neuron measured over a smaller ITD range with 200 μs steps. ITD tuning curve shows a peak at 2100 μs (best ITD).

2) Latency difference between the acoustic and electric response reflects the additional biological delay of the sound traveling through the external, middle and inner ear.



- The acoustic response delay is longer than the electric delay (τ_A = 9.5 ms, τ_E = 8.0 ms, estimated based on the spike latency in response to each stimulus), yielding a 1.5 ms estimated De.
- This neuron shows a peak at 2100 μs close to the estimated De (Fig B).

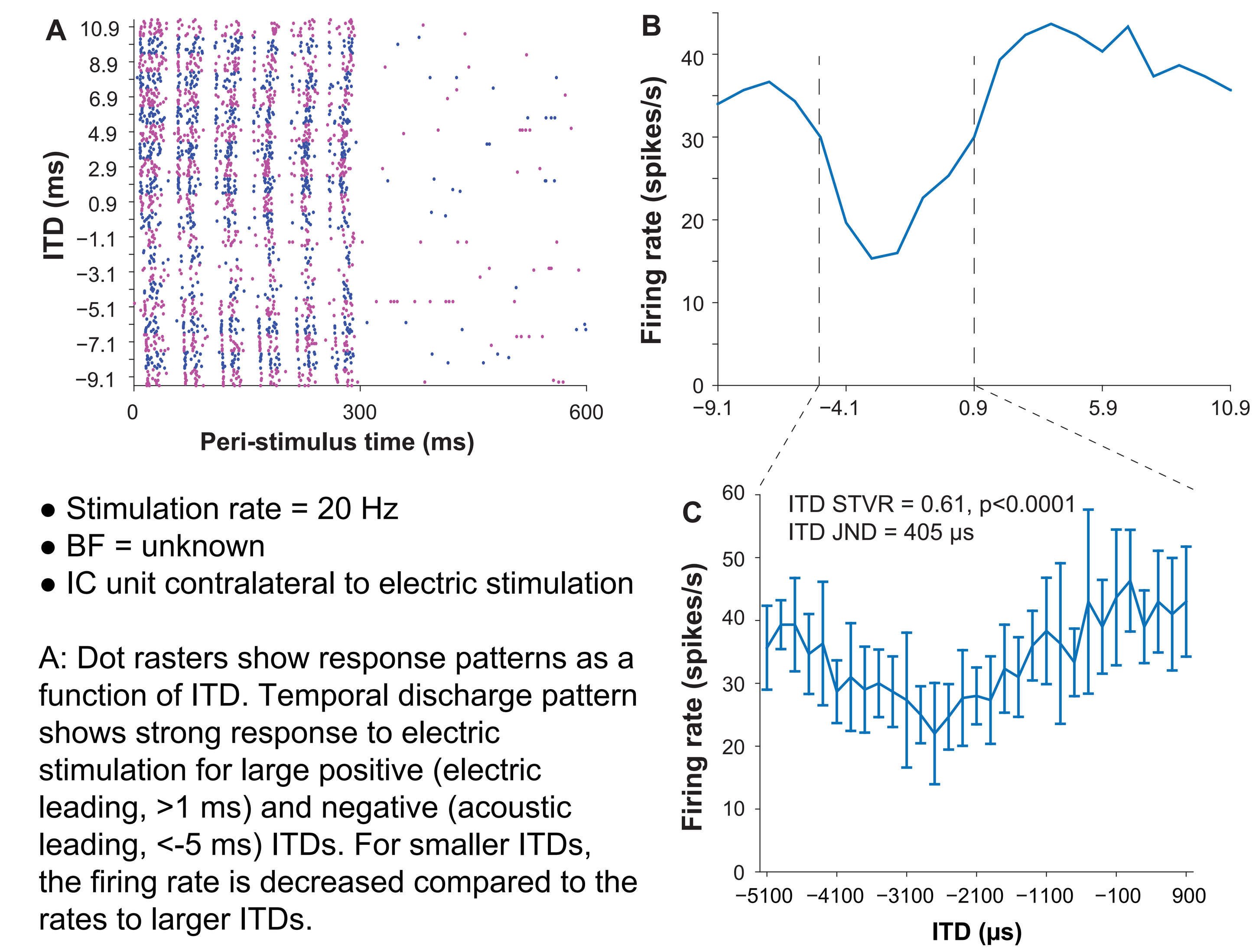
3) ITD tuning shape changes with increasing stimulation level



- The shape of the ITD tuning curve depends on the stimulation level. This neuron shows trough shape ITD tuning to a combination of higher current and sound level.

Example 2: Trough-shape ITD tuning

4) Responses of an IC neuron that shows inhibitory binaural interaction to combined electric and acoustic stimulation

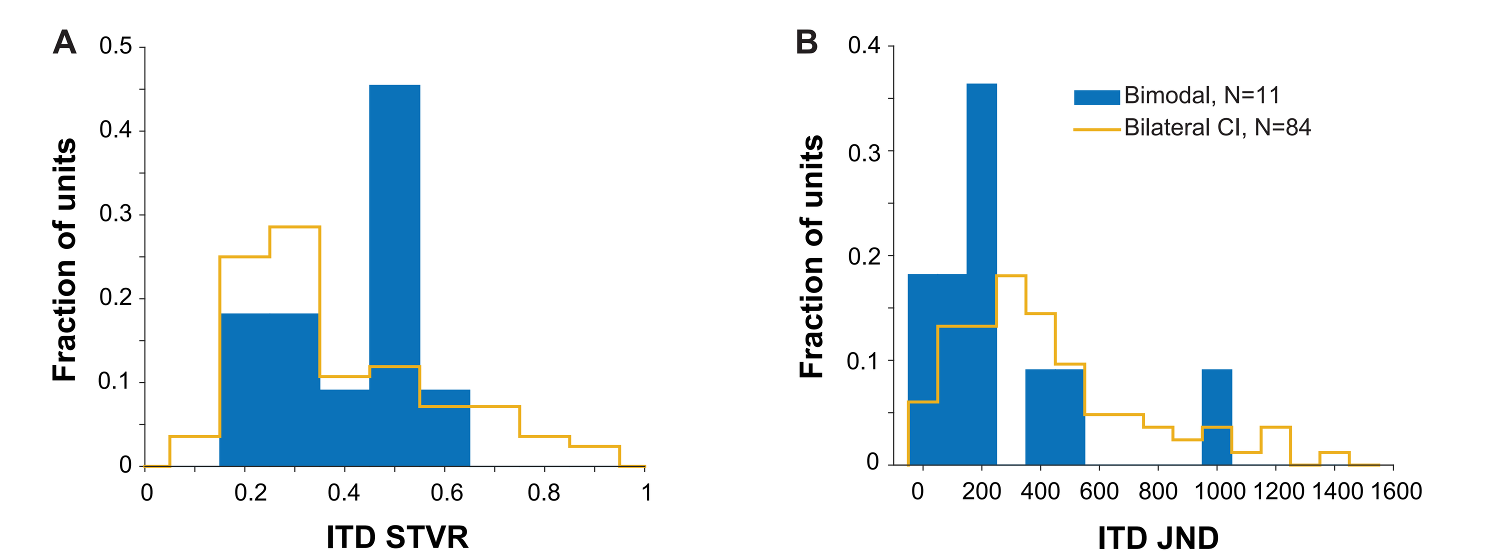


- Stimulation rate = 20 Hz
- BF = unknown
- IC unit contralateral to electric stimulation

A: Dot rasters show response patterns as a function of ITD. Temporal discharge pattern shows strong response to electric stimulation for large positive (electric leading, >1 ms) and negative (acoustic leading, <-5 ms) ITDs. For smaller ITDs, the firing rate is decreased compared to the rates to larger ITDs.

B: ITD tuning curve measured over -9.1 ms to 10.9 ms.
C: ITD tuning curve from the same neuron measured over a smaller ITD range with 200 μs steps. ITD tuning curve shows a minimum at -2100 μs. De could not be measured for this neuron due to the lack of excitatory response to acoustic clicks.

ITD sensitivity to bimodal vs. bilateral CIs



- 11/16 neurons that were tested for more than two ITD conditions showed significant ITD senstivity based on ANOVA. Trough shape was the most comment (5) followed by peak shape (3).
- A: Distribution of ITD STVRs.
- B: Distribution of ITD JNDs.

Overall, neural ITD discrimination thresholds were in the similar range as thresholds observed in IC neurons of bilaterally deafened and implanted animals (Chung et al. 2016).

SUMMARY

▶ Neurons in the auditory midbrain can be sensitive to binaural cues in combined acoustic and electric stimulation adjusted for acoustic and electric delay mismatch.

▶ Similar shapes of ITD tuning curves such as peak and trough shapes as previously observed in response to pairs of acoustic clicks or electrical pulses (Carney and Yin 1989, Chung et al. 2016).

▶ The results suggest binaural benefits with bimodal hearing could be improved by providing better access to binaural cues in SSD/CI users and HA-CI users.