



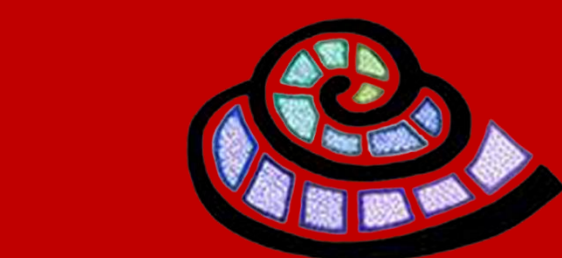
# Investigating Binaural Cue Processing in Individuals with Typical Hearing and Bilateral Cochlear Implants: Neural and Psychophysical Perspectives

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AAS 2026

Poster Session II, #110

## INTRODUCTION

- Sound localization depends on binaural cues: interaural time differences (ITDs) at low frequencies and interaural level differences (ILDs) at high frequencies<sup>1</sup>. Low-frequency ITDs are conveyed by temporal fine structure (TFS), while high-frequency ITDs can be transmitted through slow envelope (ENV) modulation<sup>2</sup>.
- Typically-hearing (TH) listeners exhibit high sensitivity to both TFS- and ENV-ITDs. In contrast, bilateral cochlear implant (BiCI) users show reduced ITD sensitivity due to limitations in temporal precision of CI processors<sup>3</sup>.
- Previous work has demonstrated that children with BiCIs can detect ENV-ITDs<sup>4</sup>, but only those with early acoustic hearing experience are sensitive to TFS-ITDs<sup>5</sup> (Figure 1).

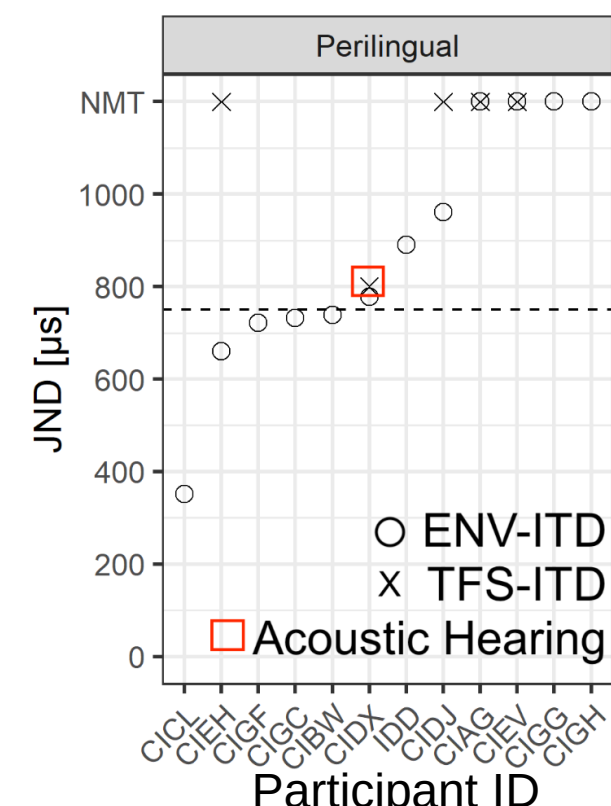


**Figure 1:** Just-noticeable-difference thresholds from children with BiCIs tested in our lab. Circle symbols denote ENV-ITD data (Peng et al., under review<sup>4</sup>) and X denote TFS-ITD data (Ehlers et al., 2017<sup>5</sup>) from the same children. Red square highlights 1 BiCI user with early acoustic hearing, showing measurable ITD sensitivity for TFS-ITD stimuli.

- However, neural encoding of TFS- and ENV-ITDs in TH individuals remains underexplored, especially that comparable to CI listening.
- In this phase of the study, we investigate neural processing of TFS- and ENV-ITD in few BiCI users, and in TH adults using novel stimuli intended to simulate CI-like single-electrode stimulation.

## OBJECTIVES

- Investigate how TFS- and ENV-ITD cues are differentially processed and whether attention enhances cortical representations of these cues.
- Evaluate relationship between behavioral measures (just-noticeable-differences, reaction time and accuracy) and active cortical discrimination responses.

## METHODS

### Participants:

- TH: N = 15 (mean age(SD): 20.81 years (1.79))
- BiCI: N = 3

| ID     | Age at testing | Age of onset | Etiology  | BiCI experience | Implant                | Electrode stimulated |
|--------|----------------|--------------|-----------|-----------------|------------------------|----------------------|
| BiCI-1 | 72 years       | 18 years     | Sudden HL | 15 years        | L: C1512<br>R: C124RE  | L12 – R12            |
| BiCI-2 | 67 years       | 32 years     | Unknown   | 32 years        | L: C124RE<br>R: C124RE | L10 – R10            |
| BiCI-3 | 61 years       | 25 years     | Sudden HL | 15 years        | L: C1512<br>R: C124RE  | L12 – R12            |

### Stimuli:

- To avoid CI-related artifact during EEG recordings, we used short duration (50ms) stimuli<sup>6</sup>.
- In BiCI users, we directly stimulated a single electrode in both ears at C (comfort) levels using research processors. Stimuli consisted of electrical pulse trains of 100pps (TFS) <sup>7,8</sup> or 4000pps, 125Hz modulated (ENV) <sup>9</sup>.
- In TH, we used 50ms acoustic click-trains of similar rates to mimic single-electrode CI stimulation. In order to restrict excitation on the basilar membrane, we embedded these stimuli in broad-band notched noise with a spectral notch at 500Hz (TFS) or 4000Hz (ENV).

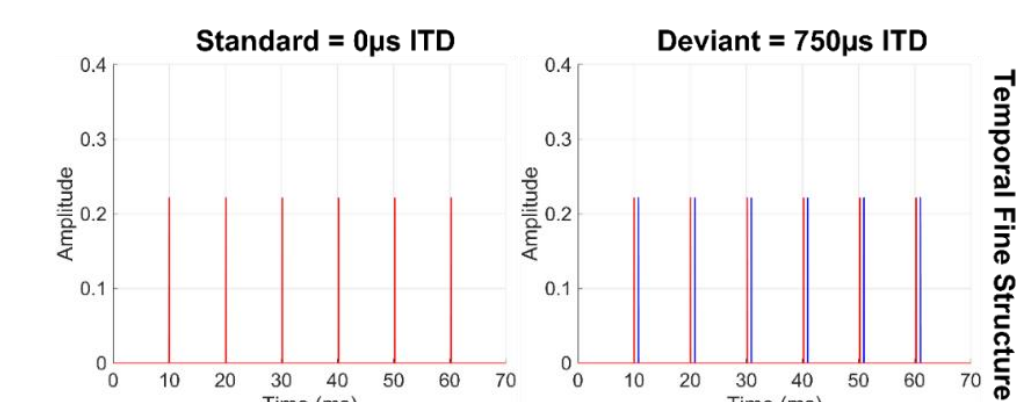


**Figure 2:** TFS- and ENV-ITD stimuli.

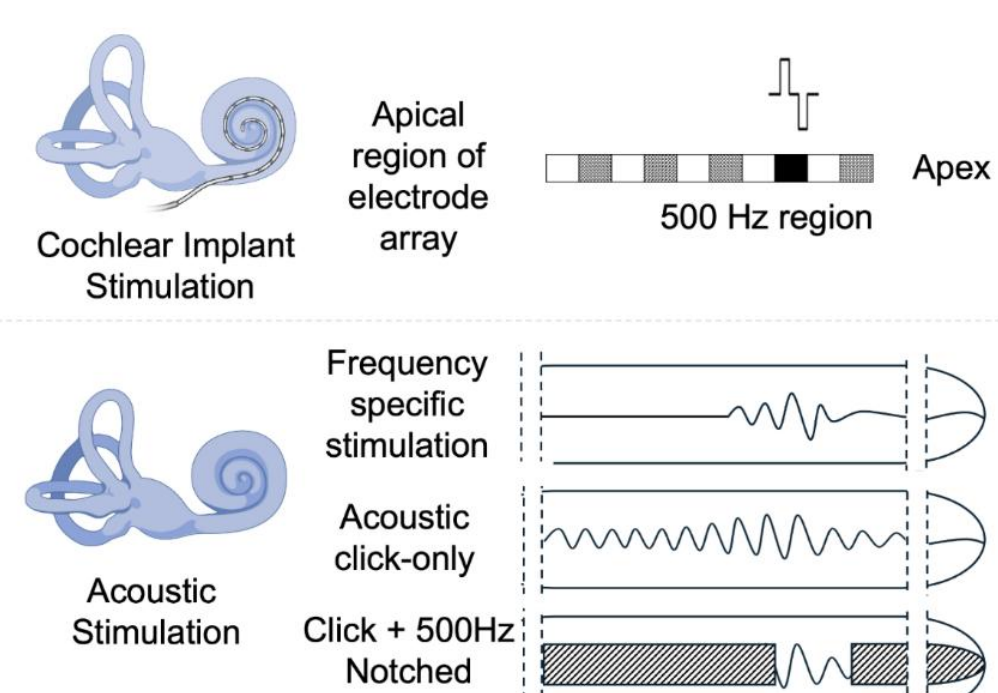


**Figure 3:** Simulating single electrode stimulation in TH.

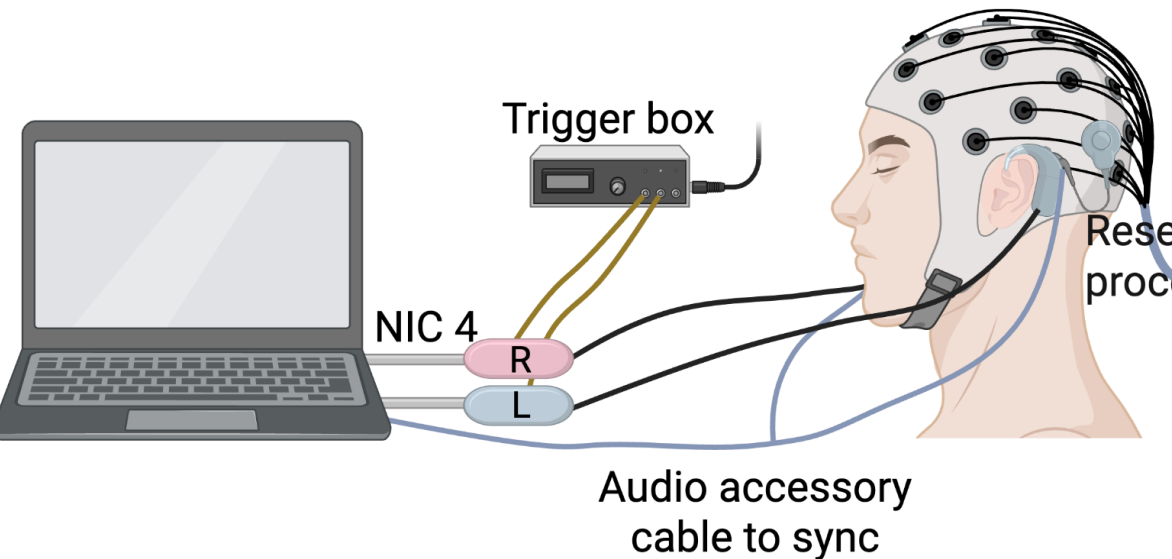


**Figure 4:** Direct stimulation set up for recording EEG in BiCI users using Cochlear Ltd. Nucleus Implant Communicator (NIC 4).

## RESULTS

### Differential Processing of TFS- and ENV-ITD in Typical-Hearing Adults

#### EXPERIMENT I: PSYCHOPHYSICS

**Smaller Just-Noticeable-Difference Thresholds (JNDs) indicating better binaural sensitivity to TFS- than ENV-ITD is the psychophysical task (Fig 6)**

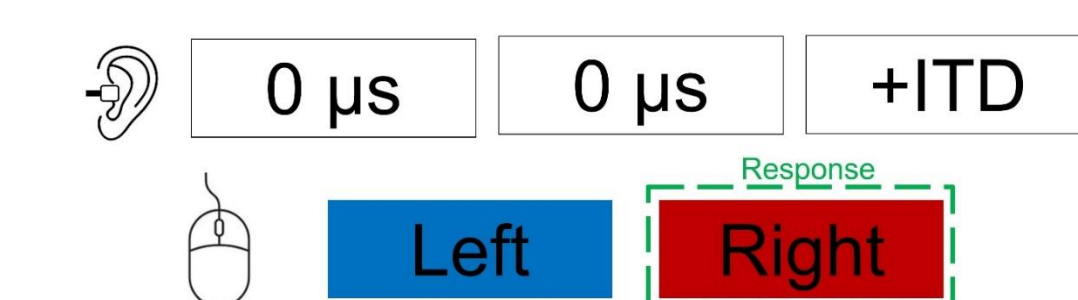


**Figure 5:** Example of a right-leading trial from the 3-interval 2-alternate forced choice task.

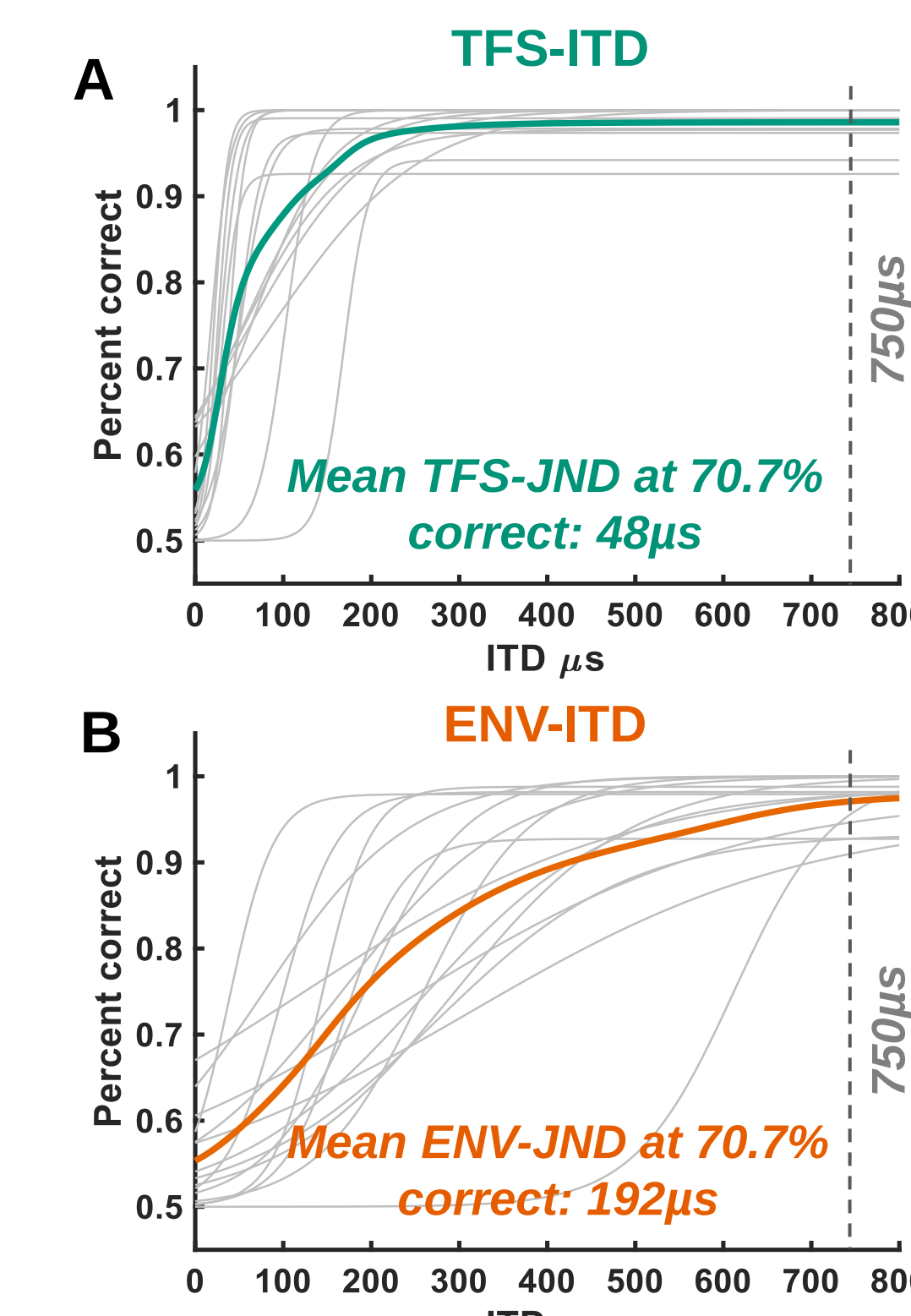


**Figure 6:** JND defined at 70.7% correct. Mean (N=15; A: TFS-ITD; B: ENV-ITD) and individual data (grey) showing smaller/better JNDs for TFS-ITD.

#### EXPERIMENT II: ELECTROPHYSIOLOGY

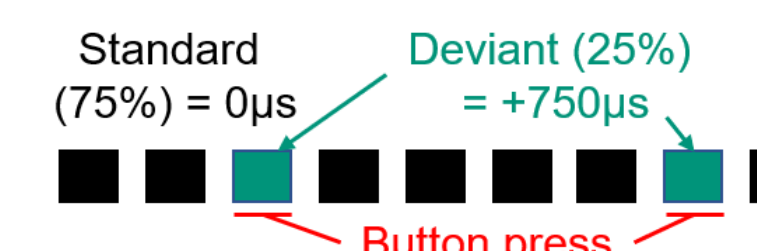


**Figure 7:** Active oddball paradigm to elicit cortical discrimination responses with a single suprathreshold ITD of +750μs as the deviant stimuli.

**TFS-ITD elicited more robust early cortical (N1) and later discrimination (P300) responses than ENV-ITD (Fig 8), along with higher accuracy and faster reaction times (Fig 9)**

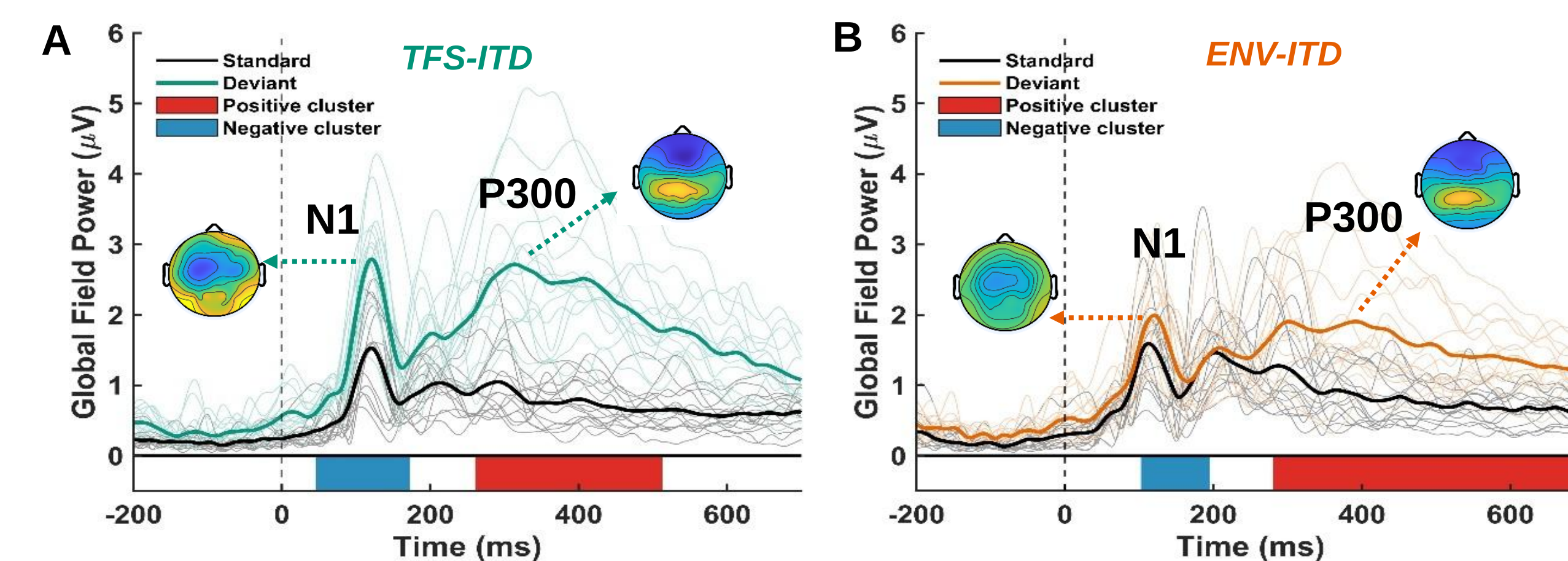


**Figure 8:** A: Grand averaged Global Field Power (GFP) for both standard (0μs) and deviant (+750μs) trials along with individual data (grey) for TFS-ITD stimuli. B: Similarly for ENV-ITD stimuli. Time windows of interest shown in blue and red derived based on significant spatio-temporal clusters through cluster-based permutation analysis<sup>10</sup>. Area under the curve during these time windows considered for further correlation shown in Figure 10.

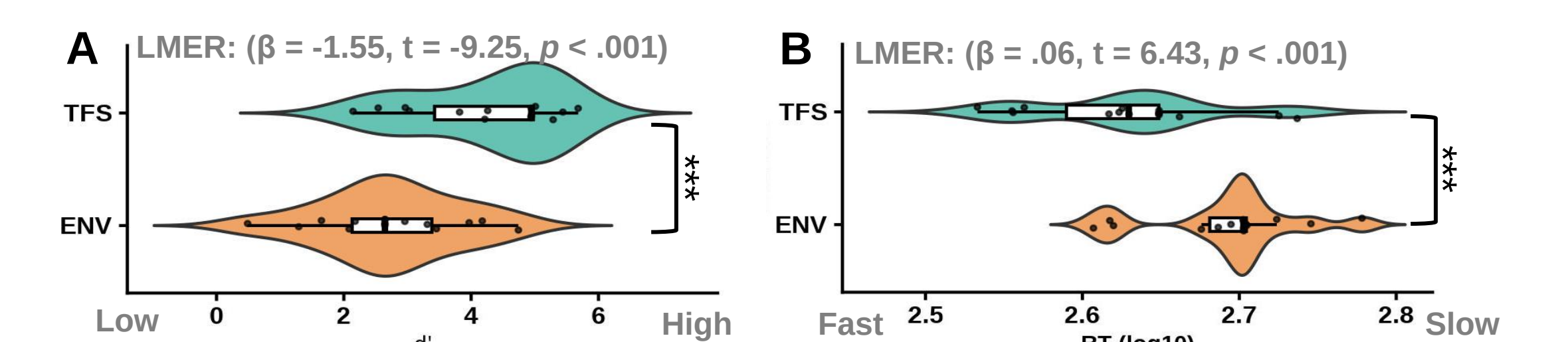


**Figure 9:** A: Violin plots showing significantly higher/better  $d'$  (measure of accuracy) for TFS- than ENV-ITD during the active oddball EEG task for a suprathreshold ITD of +750μs. B: Similarly, significantly faster reaction times for TFS-ITD.

#### CORRELATIONS

**Higher accuracy and faster reaction times for ENV-ITD significantly correlated with P300 AUC**

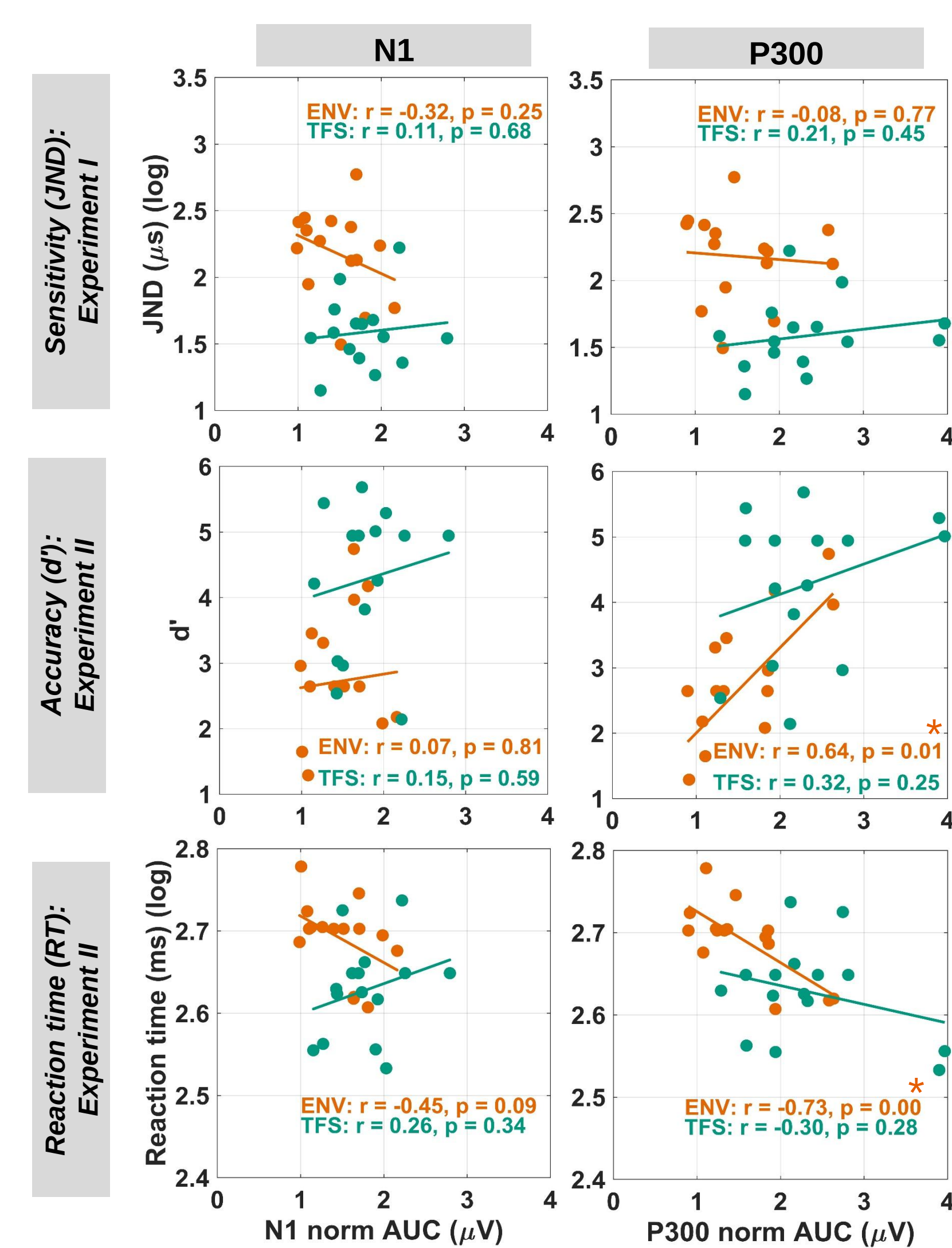


**Figure 10:** Left column: Pearson's correlation results for N1 normalized area under the curve (AUC). Right column: Similarly, P300 normalized AUC. Top: JND (log) from 3I-2AFC psychophysics task. Middle:  $d'$  (accuracy) during the active oddball task. Bottom: Reaction times from the active oddball task.

### Individual Differences in Processing of TFS- and ENV-ITD in Three Adults with Bilateral Cochlear Implants

#### EXPERIMENT I: Left-Right discrimination task for BiCI users

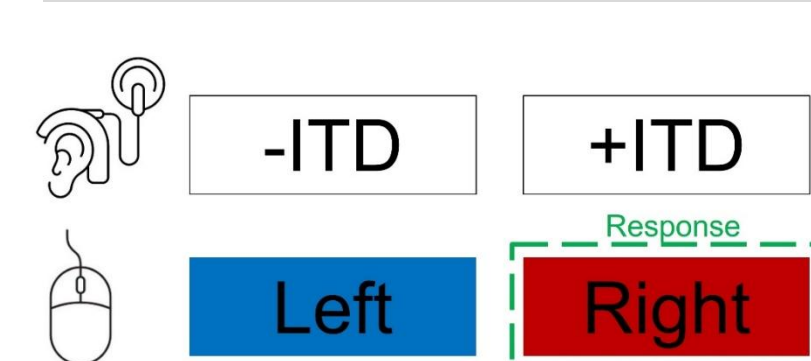


**Figure 11:** Example of a right-leading trial from the Left-Right discrimination (2-interval 2-alternate forced choice) task. Given the nature of the task, we consider 2\*ITD change.

#### EXPERIMENT II: Active oddball EEG task for BiCI users

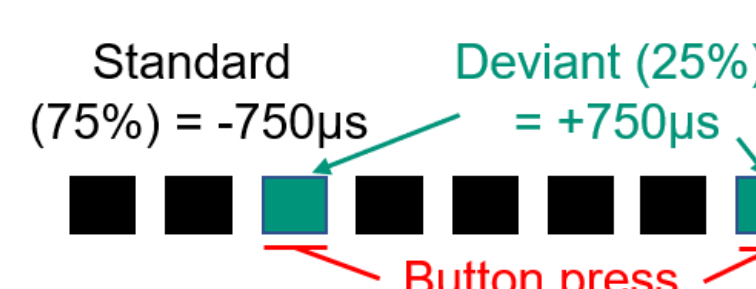


**Figure 12:** Active oddball paradigm to elicit cortical discrimination responses. Standard: left-leading (-750μs); Deviant: right-leading (+750μs).

**Better sensitivity (JND) for ENV-ITD in 2 BiCI users; poorer accuracy and slower reaction times for ENV than TFS-ITD at a large magnitude (+/-750μs; total=1500μs)**

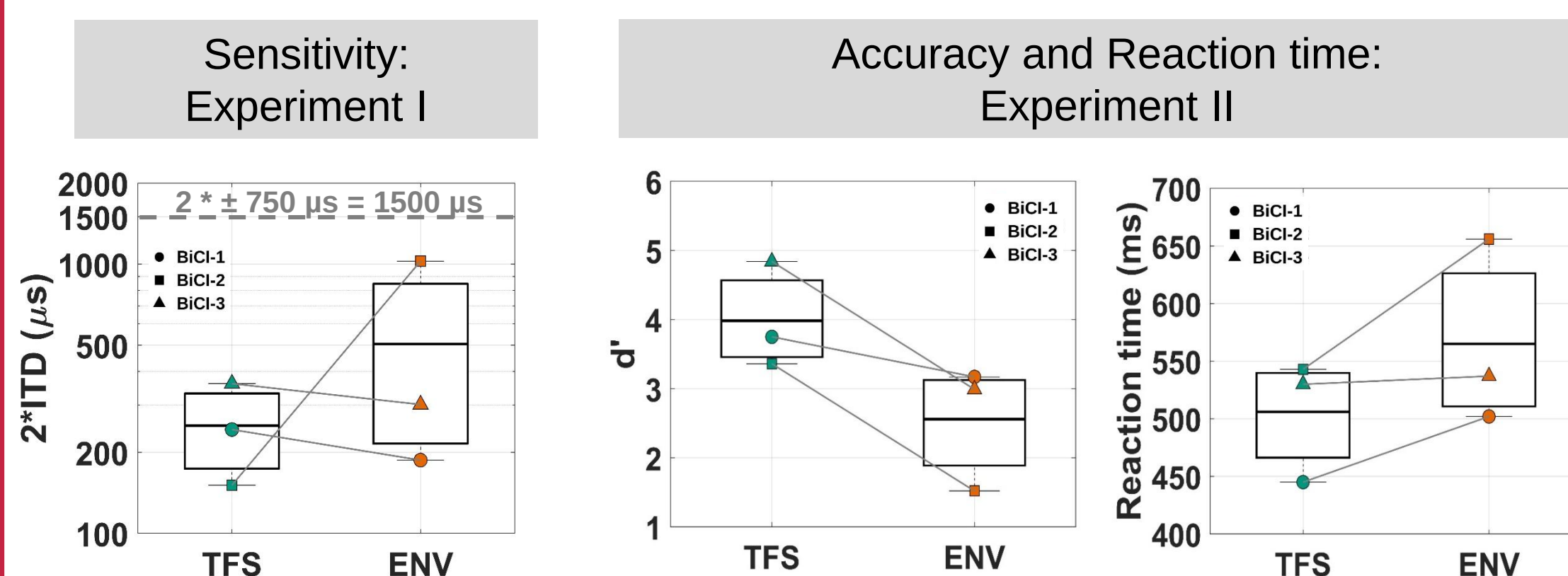


**Figure 13:** Boxplots showing JND (psychophysics task),  $d'$  and RT (active oddball task) data for BiCI users (N=3). Left: Slightly poorer JNDs for TFS-ITD in 2 BiCI users. However, BiCI-2 showed significantly poorer ENV-ITD. Middle: Higher  $d'$  (accuracy) for TFS-ITD during suprathreshold active oddball EEG task. Right: Faster reaction times for TFS-ITD during the active oddball task.

#### Individual variability in active cortical discrimination of TFS- and ENV-ITDs in an active oddball EEG task

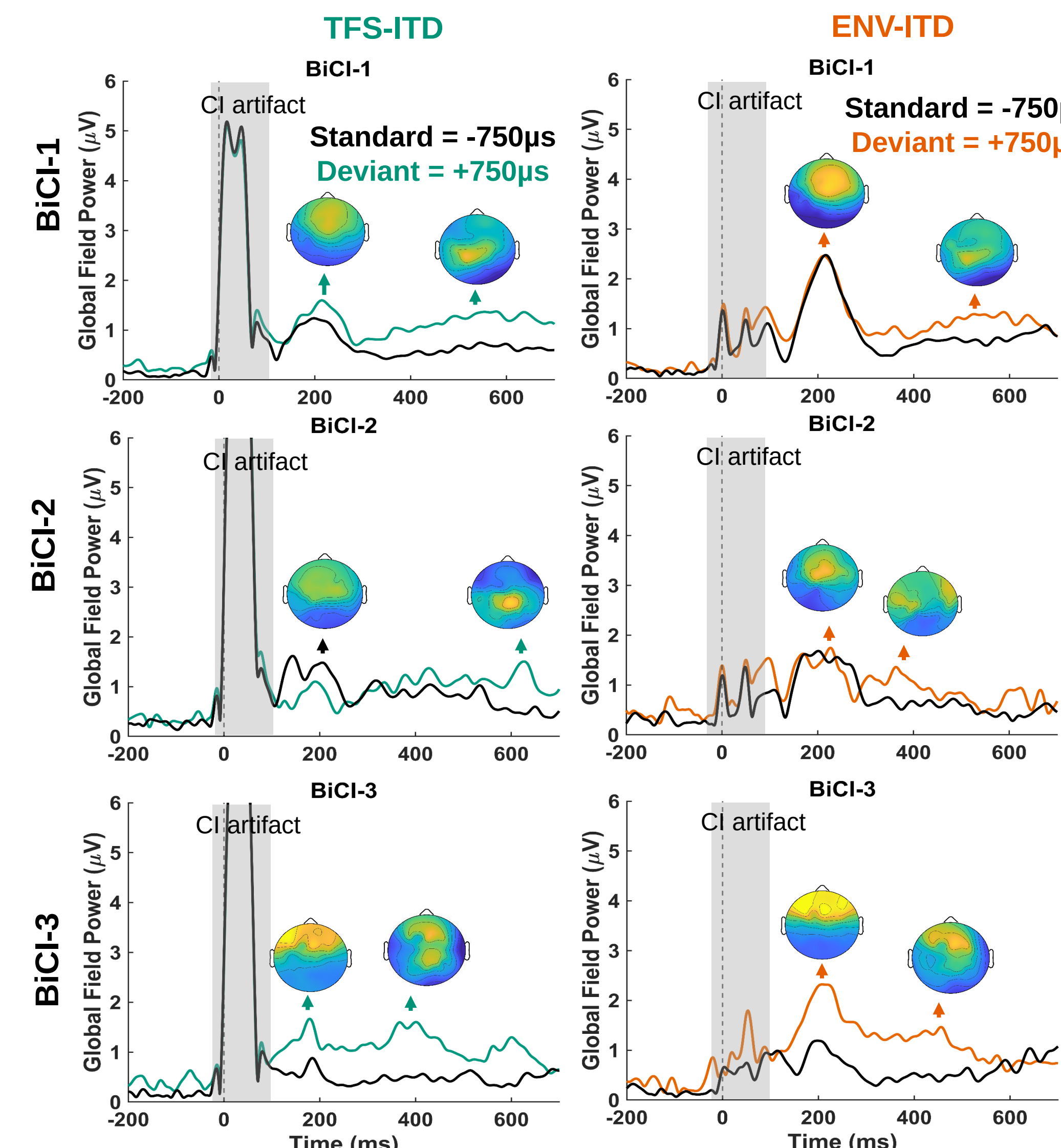


**Figure 14:** Left column: Global Field Power (GFP) for both standard (-750μs) and deviant (+750μs) trials for TFS-ITD stimuli for BiCI-1. Right column: Similarly for ENV-ITD. Top: BiCI-1 Middle: BiCI-2. Bottom: BiCI-3. Scalp topographies at marked timepoints shown as insets.

**Preliminary data shows higher accuracy and faster reaction times for TFS- than ENV-ITD in BiCI users, along with more variability in sensitivity to ENV-ITDs, similar to TH adults**

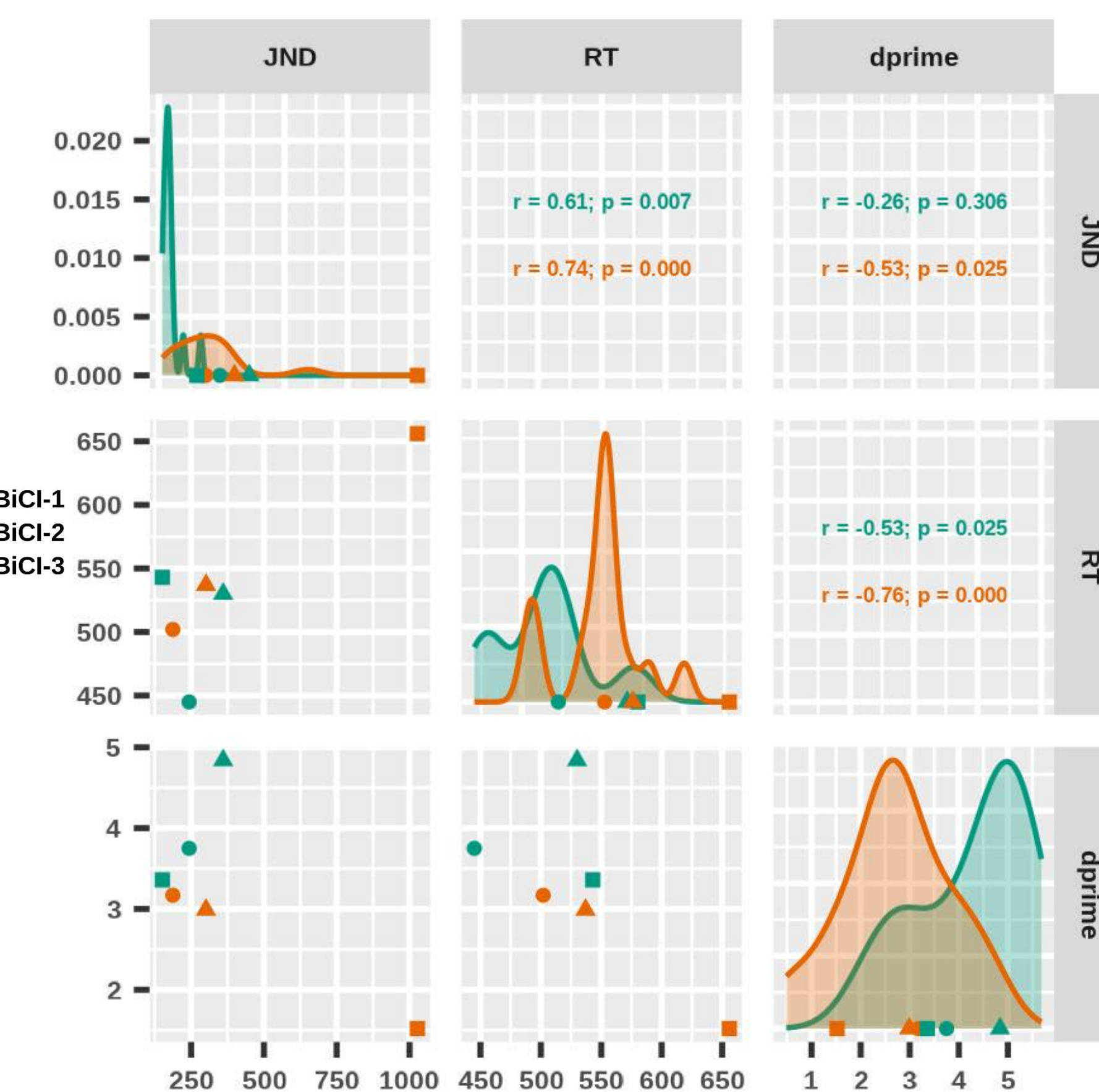


**Figure 15:** Matrix plot showing JND (psychophysics task), RT and  $d'$  (active oddball task) data along with correlations. Diagonal plots: Density plot depicts the distribution of TH data with BiCI data points overlaid. Upper plots: Correlation results of BiCI data only. Lower plots: Scatter plots of BiCI data only. Note that BiCI N=3.

## CONCLUSIONS

- In typical-hearing listeners, TFS-ITD cues lead to larger cortical responses (N1, P300) with attentional engagement, while ENV-ITD cues show weaker responses.
  - Despite good JND thresholds, differential processing of suprathreshold TFS- and ENV-ITD at the cortical level
- In bilateral CI listeners, binaural synchronized stimuli (a) lead to better performance overall with TFS- than ENV-ITD cues, and (b) can provide access to TFS- and ENV-ITDs at the cortical level.
- Findings highlight the importance of understanding distinct neural pathways for TFS-ITD and ENV-ITD in BiCI users, informing CI processing strategy optimization and future interventions.

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## ACKNOWLEDGEMENTS

This study was supported by NIH-NIDCD (R01DC020355 to R.Y. Litovsky) and in part by a core grant to the Waisman Center from the NIH-NIDCD (P50HD105353). Thank you to undergraduate researchers Lillian Williams and Mary Kristjanson for helping collect the data.