Processing of Binaural Envelope and Fine-Structure Interaural-Time-Difference Cues along the Auditory Pathway in Typical-Hearing Adults

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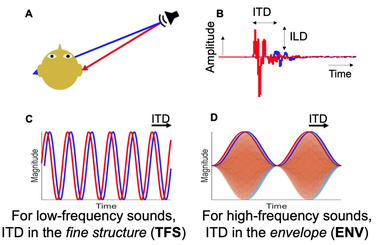
INTRODUCTION

- Sound localization depends on binaural cues: interaural time differences (ITDs) at low frequencies and interaural level differences (ILDs) at high frequencies[1]. Low-frequency ITDs are conveyed by temporal fine structure (TFS), while high-frequency ITDs can be transmitted through slow envelope (ENV) modulation[2].



For low-frequency sounds, ITD in the *fine structure* (**TFS**)

For high-frequency sounds, ITD in the *envelope* (**ENV**)

Figure 1: A. *Illustration of ITD* ***B.*** *Waveform representing ITD and ILD (red=right ear; blue=left ear)* ***C.*** *Representation of fine-structure ITD* ***D.*** *Representation of envelope ITD*

- 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[3].
- High-rate stimulation during CI processing preserves ILD and ENV-ITD sensitivity. TFS-ITD sensitivity requires access to low frequencies through low-rate stimulation.
- Previous work from our lab demonstrated that children with BiCIs can detect ENV-ITDs, but only those with early acoustic hearing experience are sensitive to TFS-ITDs[4–5]. However, neural encoding of TFS- and ENV-ITDs in TH children remains underexplored.
- This study investigates TFS- and ENV-ITD processing in TH adults by simulating a single-electrode stimulation in CIs, providing a foundation for future studies in children with TH and BiCIs.

OBJECTIVES

1. **Examine the effect of task on neural processing of binaural cues (active discrimination vs. passive listening).**
   - Investigate how active auditory attention influences binaural cue processing along the auditory pathway.
   - Assess variability in encoding and accessibility of binaural cues at different auditory processing stages.
   - ***Implication:*** Understand how task demands (active attention) modulate auditory encoding to better inform future CI-focused work.
2. **Investigate the effect of ITD cue type on neural processing (TFS vs. ENV cues).**
   - Delineate how TFS- and ENV-ITD cues are differentially processed.
   - Explore whether attention selectively enhances cortical representations of TFS- and/or ENV-ITD cues.
   - ***Implication:*** Gain insights that are translatable to cochlear implant users, who typically lack robust TFS encoding.

METHODS

Participants:

- N = 5; (mean age(SD): 21.8 years (1.64))

Stimuli:

- Short-duration click trains[6] (50 ms) for TFS (100 pps) and ENV (4000 pps, 125 Hz AM) ITDs to simulate restricted, CI-like excitation patterns; embedded in notched noise to limit excitation spread, addressing limitations of broader-excitation stimuli like Gaussian Envelope Tones (GETs)[7].

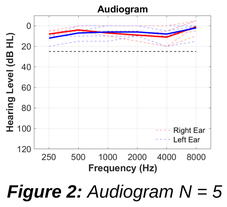


Figure 2: *Audiogram N = 5*

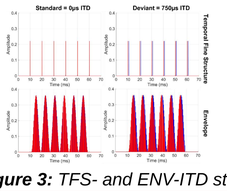


Figure 3: *TFS- and ENV-ITD stimuli*

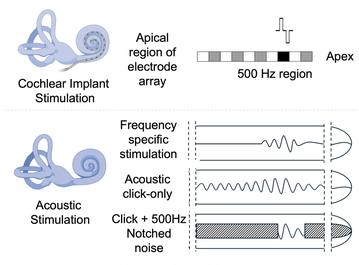


Figure 4: *Simulated CI-like spread of excitation from simultaneous click train and notched-noise.*

METHODS

Behavioral Just-Noticeable-Difference

- Behavioral ITD JNDs provide a measure of accuracy and threshold for binaural cue processing.
- ITD cue magnitudes (10, 20, 40, 80, 140, 200, 400, 750 µs) were tested 20x per ear, varied randomly.
- A logistic sigmoid was fit to the data using psignifit, and a threshold at 70.1% correct was considered as JND.

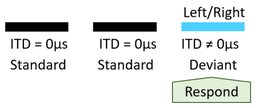


Figure 5: *Single trial of the 3-interval, 2AFC JND task. Target interval was always the 3rd.*

Electrophysiological experiments

- Obligatory (P1-N1-P2) and active cortical (P300) responses were recorded using a 64-channel EEG system (Compumedics Neuroscan Synamps II amplifier and Curry9 v9.0.2) while participants listened (passive control) or actively responded (active oddball) to changes between standard (ITD=0µs) and deviant (ITD=750µs) stimuli.

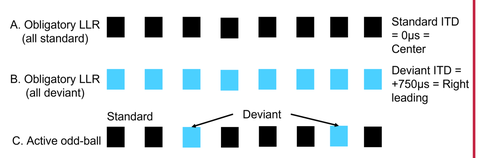


Figure 6: *Different recording paradigms of obligatory and active oddball tasks.*

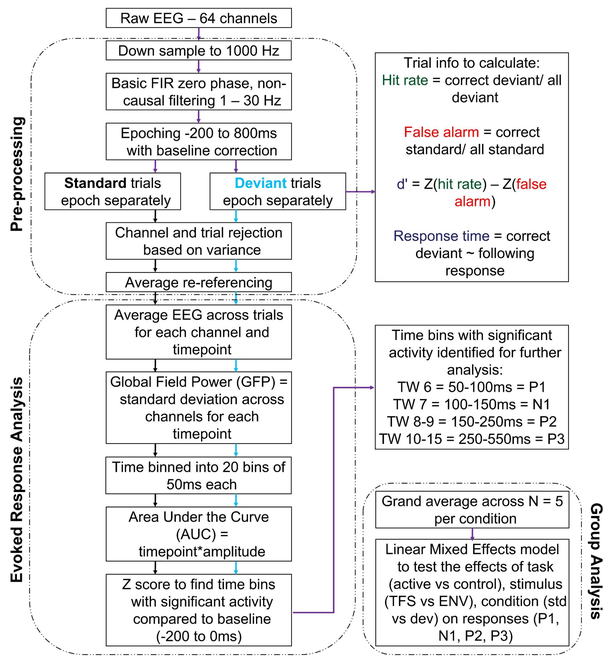
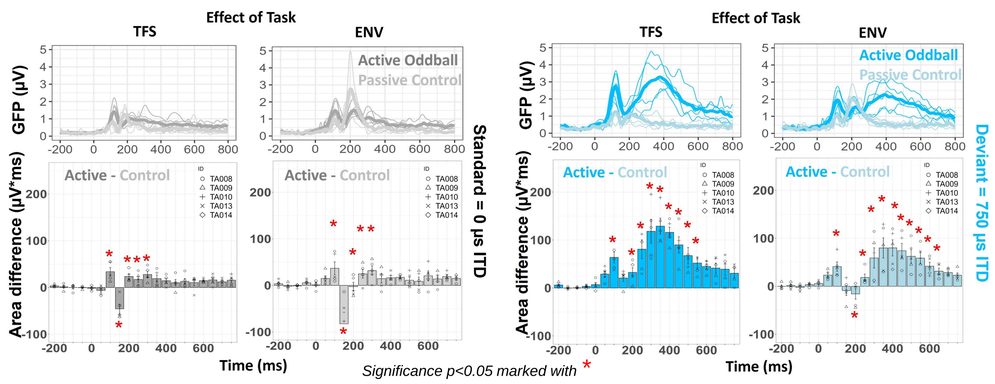


Figure 7: *EEG preprocessing and evoked response analysis pipeline.*

RESULTS

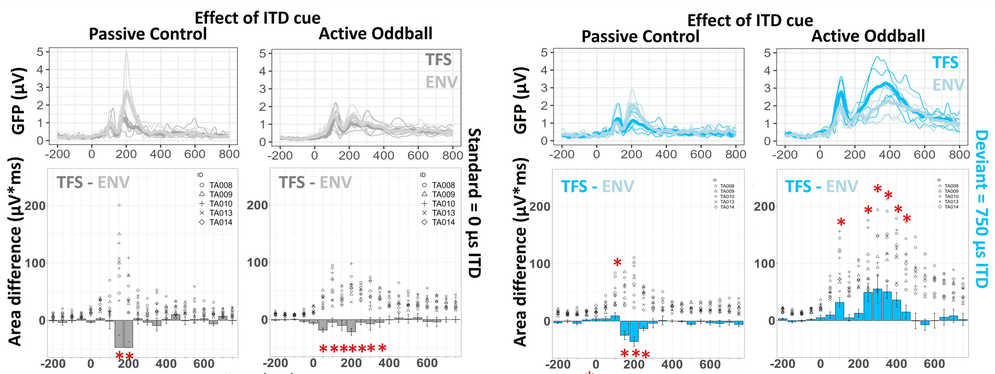
Effect of Task: Active Oddball vs Passive Listening



Significance p<0.05 marked with *

- P2 suppression in active oddball compared to passive control for standards.
- Larger N1 and P300 response for deviants in active oddball than passive control.

Effect of ITD cue: Temporal Fine Structure vs Envelope

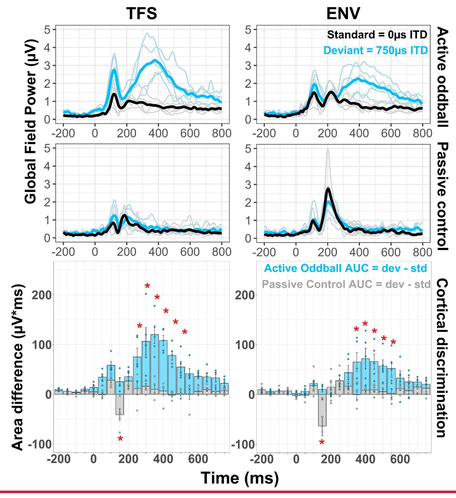


Significance p<0.05 marked with *

- Larger P2 response for standards for ENV- than TFS-ITD stimuli
- Larger N1 and P300 response for TFS-ITD deviants in active oddball than ENV-ITD.

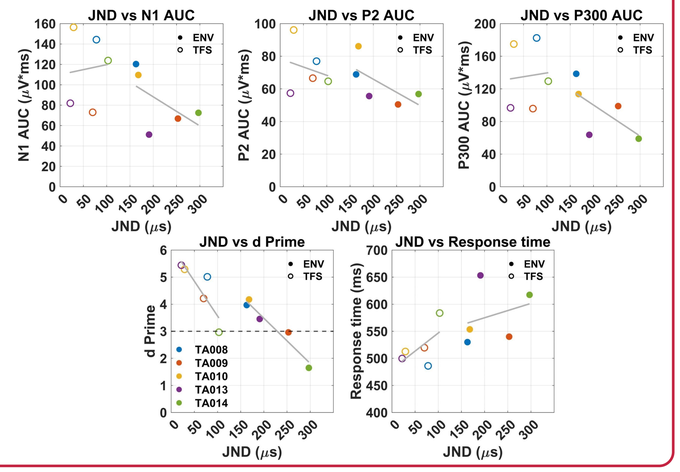
Active Cortical Discrimination

- Active attention enhances cortical discrimination of binaural cues, with stronger effects for TFS- than ENV-ITD, as shown by greater deviant-standard differences in GFP and AUC.

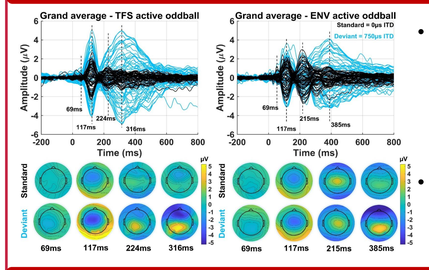


Correlations

- Emerging trends suggest correlations between JND thresholds and ERP components (N1, P2, P300) for deviant (750µs ITD) trials, as well as between behavioral measures (d′, response time), highlighting links between neural responses and perceptual accuracy for both TFS and ENV-ITD.

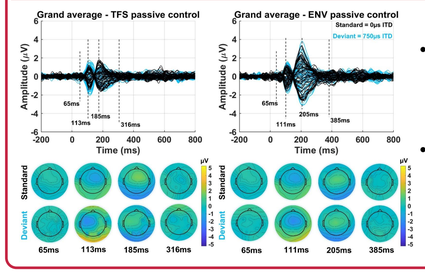


Active Oddball



- TFS and ENV-ITD deviants (750µs ITD) evoked larger ERPs than standards (0µs ITD).
- TFS-ITD elicited stronger N1 and earlier, larger P300s.

Passive listening



- Robust N1-P2 responses noted for both TFS- and ENV-ITD.
- Larger P2 response, especially for the standard ENV-ITD noted.

CONCLUSIONS

- Cortical processing of auditory cues is strongly shaped by both the acoustic salience of the stimulus and attention.
- TFS-ITD cues show enhanced cortical responses - from early detection responses (N1) to decision-related evaluation (P300) - particularly when attention is engaged.
- In contrast, ENV-ITD cues, elicit weaker and less robust responses, despite being perceptually louder; and even with attentional enhancement (e.g., P2 modulation), access to and utilization of these cues remains limited.
- Robust early encoding of binaural cues is essential for effective attentional modulation and behavioral performance, as attention alone cannot overcome poor cortical access to these binaural cues.
- Importantly, these findings have important implications for CI users, who lack access to TFS-ITD cues. Understanding the distinct neural processing pathways for TFS- and ENV-ITD is critical for optimizing CI strategies and guiding future interventions.

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