Single-Neuron Evidence for Attention and Prediction Error to Nested Auditory Regularities in the Human Auditory Cortex

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Abstract

The primary auditory cortex has traditionally been viewed as a feature detector rather than a processor of complex statistical regularities. We present rare single-neuron recordings from the human transverse temporal gyrus (TTG) during a Global-Local paradigm with nested temporal regularities. Time-resolved modeling of neural responses revealed that TTG neurons are sensitive to local deviance and its interaction with global task context, with this activity strongly modulated by attention. Notably, we observed super-additive responses to combined local-global deviants and relatively late response latencies (~200ms), suggesting complex integration of predictive signals rather than simple feature detection. These findings provide direct neuronal evidence for hierarchical processing at the earliest cortical stage of auditory processing, consistent with theoretical models that emphasize context integration and prediction in perception.

Introduction

Detecting unexpected environmental changes is a fundamental cognitive ability that has been extensively studied using oddball paradigms, revealing hierarchical processing from simple feature detection to complex pattern recognition. The Global-Local (GL) paradigm (Bekinschtein et al., 2009) extends this approach by embedding both local (within-sequence) and global (across-sequence) event regularities, allowing researchers to distinguish between different levels of deviance detection. While EEG and fMRI studies have mapped cortical networks involved in processing these hierarchical prediction violations, evidence from the single-neuron level in humans remains rare (Gabhart et al., 2025).

The transverse temporal gyrus (TTG, or Heschl's Gyrus) contains the primary auditory cortex (A1), the first cortical processing stage for auditory information. TTG has been traditionally characterized as primarily responsive to basic acoustic features, with more complex pattern detection emerging in higher cortical areas (Berger et al., 2023). However, recent findings suggest that even primary sensory regions may participate in predictive processing and integrate information across multiple timescales (Parras et al., 2017).

Here, we report single-neuron recordings from the human TTG during a GL paradigm. Our main aims were to elucidate whether neurons in the primary auditory cortex respond to statistical violations at different hierarchical levels, and how attention modulates these responses. Using time-resolved statistical modeling, we demonstrate single-unit activity in human TTG that integrates local and global regularities, with responses significantly modulated by attentional state. Our findings provide rare direct evidence for hierarchical processing at the earliest cortical stage of auditory processing.

Methods

Participant and recordings. Invasive recordings were obtained from a patient with drug-resistant epilepsy undergoing presurgical evaluation (ethics approval and informed consent were obtained). One Behnke-Fried electrode was implanted in the TTG. Neural activity was recorded at 30 kHz, and spike-sorted with Wave_clus (Chaure et al., 2018).

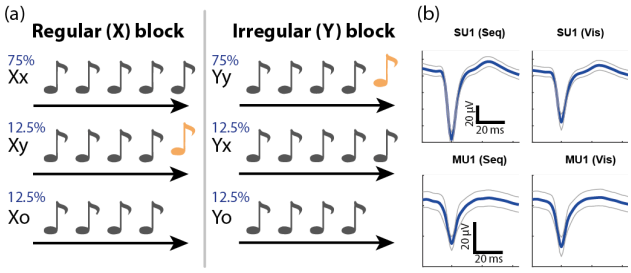

Figure 1: (a) Task stimuli, block structure, and sequence probability (182 trials per block, first 20 establishing the global task rule). (b) Average spike waveforms for each session.

Oddball task. We employed a modified GL paradigm with five-tone sequences (50ms tones, 150ms SOA). Three sequence types were presented: Standard (x), local deviant (y), and omission (o), with different blocks establishing global context for each of these sequences (Figure 1). We report results for blocks X and Y only. We manipulated attention across two sessions: One where the participant counted irregular sequences

and another where a distracting visual counting task was performed while sounds were played.

Data Analysis. Spike density functions (SDFs) were computed using a 50ms Gaussian kernel. We applied time-resolved GLMs to analyze how neurons encoded local/global regularities and attention, fitting nested models from null to three-way interactions. Models were compared using Bayesian Information Criterion (BIC), and statistical significance was assessed via FDR-corrected p-values.

Results

Neural Recordings. Both tasks were run in succession, resulting in the extraction of one single-unit (SU1: less than 1% ISI within 3ms) and three multi-units (MU1-3) in the TTG (Figure 1). Time-resolved GLM analysis revealed distinct temporal patterns of sensitivity to local and global regularities, as well as attentional modulation, as shown in Figure 2.

Local Deviance Processing. We observed significant local deviant positive responses ~200 ms after the last tone, followed by a negative deflection at ~400ms for all units.

Global Deviance Processing. No significant results were found for the main global effects.

Attention and interaction effects. In SU1, a three-way interaction term (AttendSeq:LocalDev: GlobalDev) captured temporal dynamics not explained by the main effects alone. While local deviance sensitivity appeared in simpler models, the complex interaction model revealed that this sensitivity was modulated by both global context and attention state, highlighting the integrative nature of TTG processing. The interaction term in MU1 indicated an enhanced response to pure global (Yx) deviants that was modulated by attention.

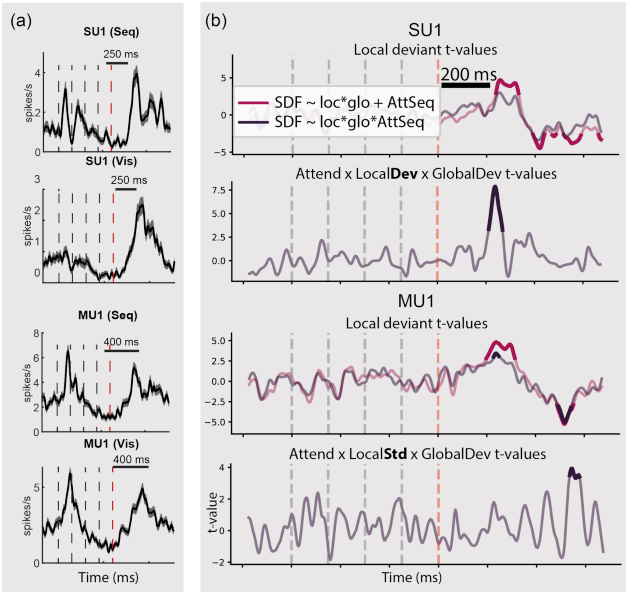

Figure 2:(a) Mean SDFs across all trials for SU1 and MU1, in both sessions.(b) T-values for local deviance and interaction factors from GLM models. Dashed lines indicate tone onsets.

Discussion and Conclusion

Our study provides rare single-neuron evidence that TTG neurons integrate statistical regularities across multiple timescales. The relatively late response (~200ms) to local deviants contrasts with simple feature detection models of A1 but aligns well with predictive coding frameworks and MMN responses. The super-additive responses to double deviants further suggest that TTG neurons specifically signal prediction violations across hierarchical levels. Additionally, we found that top-down attentional modulation significantly altered TTG processing, with prominent effects on global context that were reduced during the visual task.

Although our single-case results limit generalizability, the unique human TTG recordings offer valuable constraints for computational models. The distinct temporal profiles of local, global, and interactive deviance effects imply a processing sequence from simple feature detection toward complex predictive integration. These findings challenge traditional feedforward views of the primary sensory cortex and emphasize the importance of models with recurrent connectivity between hierarchical processing stages.

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