Top-Down Propagation of Neural State Boundaries During Movie Viewing

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Abstract

Our senses receive a continuous stream of complex information, which we segment into discrete events. Previous research has related such events to neural states: temporally and regionally specific stable patterns of brain activity. The aim of this study was to investigate whether there was evidence for top-down or bottom-up propagation of neural state boundaries. To do so, we used intracranial measurements with high temporal resolution while subjects were watching a movie. As this is the first study of neural states in intracranial data in the context of event segmentation, we also investigated whether known properties of neural states could be replicated. The neural state boundaries indeed aligned with stimulus features and between brain areas. Importantly, we found support for top-down propagation of neural state boundaries at the onsets and offsets of clauses. Interestingly, we did not observe a consistent top-down or bottom-up propagation in general across all timepoints, suggesting that neural state boundaries could propagate in both a top-down and bottom-up manner, with the direction depending on the stimulus input at that moment. Taken together, our findings provide new insights on how neural state boundaries are shared across brain regions and strengthen the foundation of studying neural states in electrophysiology.

Introduction

The continuous influx of sensory input in our daily lives encompasses a vast amount of information. Despite its complexity, we can effortlessly process and utilize this information. This is due, in part, to our ability to automatically segment information into meaningful units (Zacks, Speer, Swallow, Braver, & Reynolds, 2007). Recently, various studies have investigated neural states as a possible neural underpinning of event segmentation. Neural states are temporarily stable patterns of brain activity in a local brain area that are observed across the cortex and are usually studied while subjects experience a naturalistic stimulus (Sava-Segal, Richards, Leung, & Finn, 2023; Oetringer, Gözükara, Güçlü, & Geerligs, 2025).

Although it has been shown that transitions in neural states (i.e., neural state boundaries) in different brain regions co-occur forming a nested hierarchy (Geerligs et al., 2022; Baldassano et al., 2017), it is not known how neural states are propagated across the cortex and what the role of bottom-up versus top-down signalling is. Here, we investigate this by studying the timing differences between neural state boundaries in a high-level and a low-level language area, and how these timing differences relate to stimulus changes. To enable precise timing and spatial localization, we use electrocorticography data (ECoG), recorded while subjects process naturalistic language in a movie.

Materials and methods

Data

11 subjects (aged 19 to 52 years, 4 male, 7 female) watched a short audiovisual movie with ECoG electrodes in the language-dominant hemisphere. This data is part of an open iEEG dataset (Berezutskaya et al., 2022) . Only speech blocks (rather than music blocks) were used in our analyses, giving 3 minutes of ECoG data per subject. We additionally extracted the on- and offsets of clauses in the movie stimulus. We defined one high-level language ROI (Brodmann areas 38, 39, 40, 44, 45, 46, 47) and one low-level language ROI (Brodmann areas 20, 21, 22, 41, 42) per subject. One subject did not have any electrodes in the low-level ROI, and was thus excluded from any analysis that required this ROI. A preprocessing pipeline similar to Zada et al. (2024) and Goldstein et al. (2022) was applied.

Analysis[1]

Greedy State Boundary Search (GSBS; Geerligs, van Gerven, and Güçlü (2021)) was applied on single-subject data per speech block and per ROI to extract the timings of neural state boundaries, and in particular the state-GSBS algorithm (Geerligs et al., 2022). Because of the lower signal-to-noise ratio in single-subject data, the t-distance metric to determine the optimal number of states was adjusted by taking the number of states that gave the highest average t-distances across blocks within each subject. Per block we subsequently fine-tuned the number of states by identifying the nearest t-distance peak.

The match between two boundary timelines was computed as the Gaussian match, a measure that consists of projecting a Gaussian (SD = 332 ms, mean of 0) with an amplitude scaled between 0 and 1, onto each boundary in one timeline. Then, per boundary, the closest boundary in the other timeline was selected and the match was determined using the amplitude of the projected Gaussian at the timepoint of this closest boundary. The average match across all boundaries is the Gaussian match. By computing the match over various delays, the optimal delay was defined as the delay that gave the maximum Gaussian match. The relative Gaussian match was defined as the increase in match as compared to chance-level. Group-level statistics were computed using the Wilcoxon signed-rank test.

Results

We first set out to replicate the findings of previous fMRI studies. We indeed found a significant match between neural states and the on- and offsets of clauses (Figure 1A; one-tailed; low-level ROI: $p < 0.001$; high-level ROI: $p = 0.034$), showing an alignment to stimulus features similar to Oetringer et al. (2025). Additionally, we found that the maximum Gaussian match between the neural state boundaries of the two ROIs within subjects was significantly above zero

[1] Code is openly available at: `https://anonymous.4open.science/r/temporal_propagation-466C/`

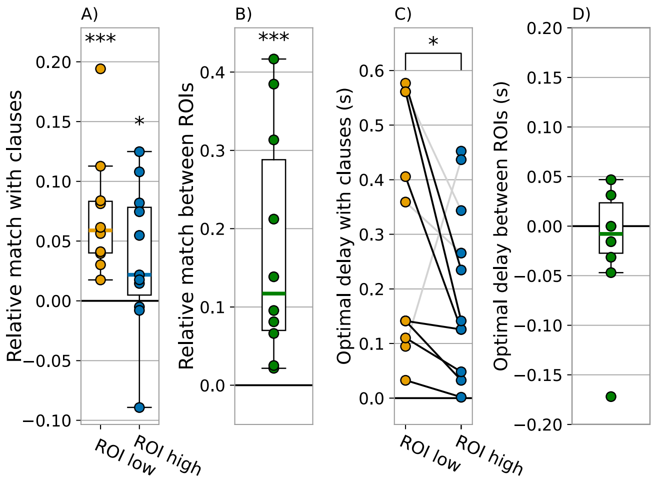

Figure 1: A) Maximum relative Gaussian match between the onsets and offsets of clauses and neural state boundaries in each ROI. B) Maximum relative Gaussian match between the neural state boundaries of the two ROIs. C) Optimal delay with clauses comparison between the two ROIs. D) Optimal delay with neural states in the other ROI. ABD: Each dot is one subject. C: Each line is one subject; gray lines are subjects without an above-chance match with clauses in at least one ROI. ABC: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

(one-tailed; $p < 0.001$; Figure 1B). This indicates that boundaries showed significant overlap between the two ROIs, similar to Baldassano et al. (2017) and Geerligs et al. (2022).

To investigate the presence of top-down and bottom-up propagation, we investigated whether the optimal delay between the stimulus and the neural state boundaries would be different for the two ROIs, by subtracting the optimal delays from each other within each subject, and applying a two-tailed test, only including subjects with a clause-match above chance (N = 7). If the timing of neural state boundaries purely reflect a simple bottom-up flow of information, neural state boundaries would occur in the low-level ROI before the high-level ROI. If the timing is instead in the opposite direction, it would be indicative of the presence of a top-down flow of information, particularly at the onsets of offsets of clauses. We indeed found that the optimal delay is significantly longer in the low-level ROI relative to the high-level ROI (Figure 1C; $p = 0.016$). Given that all included subjects have a shorter optimal delay with clauses in the high-level ROI than in the low-level ROI, we can conclude that neural state boundaries related to the start and/or end of clauses occur in the high-level ROI before occurring in the low-level ROI, and thus that the alignment with clauses indicates a top-down flow of information.

When we investigated the timing delays across all neural state boundaries (irrespective of the stimulus), we did not observe evidence for a consistent delay in the boundary timing across the ROIs (Figure 1D). These results suggest that some boundaries might be the result of a top-down flow of information, while other boundaries follow from a bottom-up flow.

Discussion

Utilizing the high temporal resolution of ECoG, we studied precise timing differences in neural state boundaries to investigate the presence of top-down and bottom-up processes. Indeed, we found that the optimal delay with the onsets and offsets of clauses is shorter in the high-level than in the low-level area, consistently across subjects. This indicates that clause-relevant neural state boundaries occur in high-level areas before low-level areas. This does not necessarily mean that boundaries in our high-level ROI cause boundaries in our low-level ROI. Instead, top-down propagation of information could be coming from other areas as well.

The exact timing differences we observed between stimulus features and neural states, suggest that the higher-level brain areas may be able to predict the onset and offset of clauses. Previous research has shown that predictability makes neural state boundaries occur earlier in time, and boundaries in higher-level areas are affected more than those in lower-level areas (Lee, Aly, & Baldassano, 2021). Additionally, many subjects had an optimal delay of under 180 ms in the high-level language area, while Goldstein et al. (2023) found a bottom-up optimal delay of 292 ms in the IFG, indicating that the clause-related boundaries in our study occur before the IFG has actually received the bottom-up end/start-of-clause information. In the low-level language ROI however, all but one subject had an optimal delay that was longer than that found by previous literature of 55 ms (Goldstein et al., 2023) and 34 ms (Flinker et al., 2015), indicating that the clause-related neural state boundaries occur some time after receiving the relevant bottom-up information.

This top-down propagation of neural states does not appear to be continuous as we did not find a consistent delay between the high- and low-level ROI when we looked at all neural state boundaries, irrespective of the stimulus. Together, our results imply that top-down processes happen at or around the onsets and offsets of clauses, but not all the time. When generalizing this observation beyond our specific stimulus, these results suggest that boundaries might propagate in a top-down manner when there are relevant changes in context that could affect the processing of information in lower-level areas, strengthening information separation in lower-level areas.

We were additionally able to replicate multiple fMRI findings, indicating that neural states are present and relevant in ECoG data as well despite the difference in temporal resolution. In particular, this is the first study to our knowledge that shows a neural state boundary alignment between multiple brain areas in electrophysiological data. Showing this alignment in ECoG is of particular importance, as it cannot be studied in MEG and EEG due to their lower spatial specificity. This study therefore provides a stronger foundation for studying neural states in existing and future electrophysiological studies, including more accessible methods such as EEG and MEG.

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