Event-Triggered Entropy Dynamics in Human EEG Reveal a Robust Population-Scaling Phenomenon

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Abstract

Understanding how large-scale brain dynamics reorganize around internally generated events remains a central challenge in neuroscience. While neural events are often studied using local spectral or regional measures, less is known about how global information-theoretic quantities evolve following such events at the population level.

Here we report a robust, event-triggered entropy response in human EEG that appears consistently across meditation, tightly controlled meditation, and resting-state datasets. Using an entropy-based framework applied to thousands of subject pairs, we show that following detected emission events, the mean entropy change of target subjects exhibits a structured temporal profile. This profile remains stable under extensive subsampling of subject pairs, scales smoothly with population size, and is strongly separated from multiple null models.

Critically, the observed effect strengthens with increased data aggregation rather than diminishing, indicating that it reflects a collective dynamical phenomenon rather than idiosyncratic subject behavior or statistical artifact. While the underlying mechanism remains unknown, these results establish the existence of a population-level entropy response associated with neural events.

1 Introduction

Neural activity is commonly characterized through local measures such as oscillatory power, coherence, or event-related potentials. While these approaches have yielded valuable insights, they often emphasize region-specific or frequency-specific features. In contrast, global measures grounded in information theory provide a complementary perspective on how distributed brain activity reorganizes over time [1, 2].

Entropy-based metrics have been used to quantify neural complexity, state diversity, and transitions across sleep, anesthesia, neuropsychiatric conditions, and altered states of consciousness [3, 4]. However, most prior work treats entropy as a static or slowly varying quantity, rather than examining its temporal evolution following internally generated neural events.

A key open question is whether neural events trigger a consistent, population-level response in global entropy. If present, such a response would imply coordinated reorganization across distributed neural systems rather than purely local or stochastic dynamics.

In this work, we test whether event-triggered entropy responses exhibit reproducible temporal structure, whether they scale with population size, and whether they are separable from appropriate null models.

2 Data and Experimental Regimes

We analyzed three EEG regimes:

1. **Meditation:** EEG recordings from subjects engaged in meditation, representing a relatively stable but internally structured cognitive state.

2. **Tightly Controlled Meditation:** A subset of meditation data processed under stricter preprocessing and inclusion criteria.

3. **Resting-State EEG (EEGMMIDB):** Resting segments from the EEG Motor Movement Imagery Dataset, representing a task-free baseline [5].

EEG signals were segmented into fixed-length epochs. For each epoch, band-power fractions were computed across canonical frequency bands (theta, alpha, beta, gamma). These fractions were normalized and used to compute a Shannon entropy value [1], yielding a univariate entropy time series per subject.

All figures shown in the main text correspond to the tightly controlled meditation regime. Replication results for the broader meditation dataset and for resting-state EEG are provided in the Supplementary Information.

3 Event Detection and Pairwise Analysis

3.1 Emission Event Detection

Emission events were detected within each subject's entropy time series using a threshold-based rule based on entropy changes and state transitions. These events are defined operationally and make no assumptions about physiological origin or causal influence.

3.2 Pairwise Entropy Response

For each detected event in a source subject, we computed the change in entropy ΔH in a target subject over a fixed post-event lag window. This produced a lag-resolved entropy response curve for each ordered subject pair.

No temporal synchronization between subjects is assumed. Events act as abstract markers within individual time series, and responses are aggregated statistically across many pairs.

4 Scaling Analyses

4.1 Pair Scaling

We randomly subsampled fractions of available subject pairs and recomputed the mean entropy response curve for each subsample. Fractions ranged from 5% to 100%, with repeated resampling.

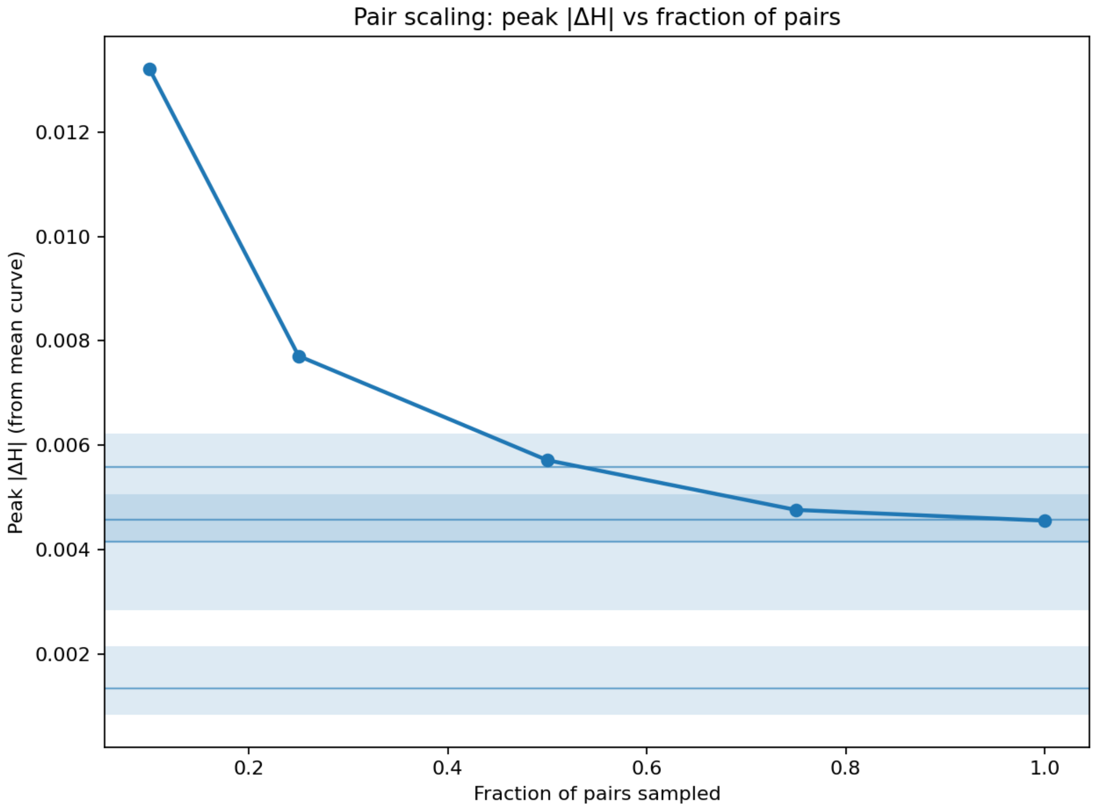

Figure 1: Pair scaling of the peak absolute entropy response. The peak magnitude of the mean ΔH curve remains stable and converges as the fraction of sampled subject pairs increases. Shaded regions indicate variability across resamples.

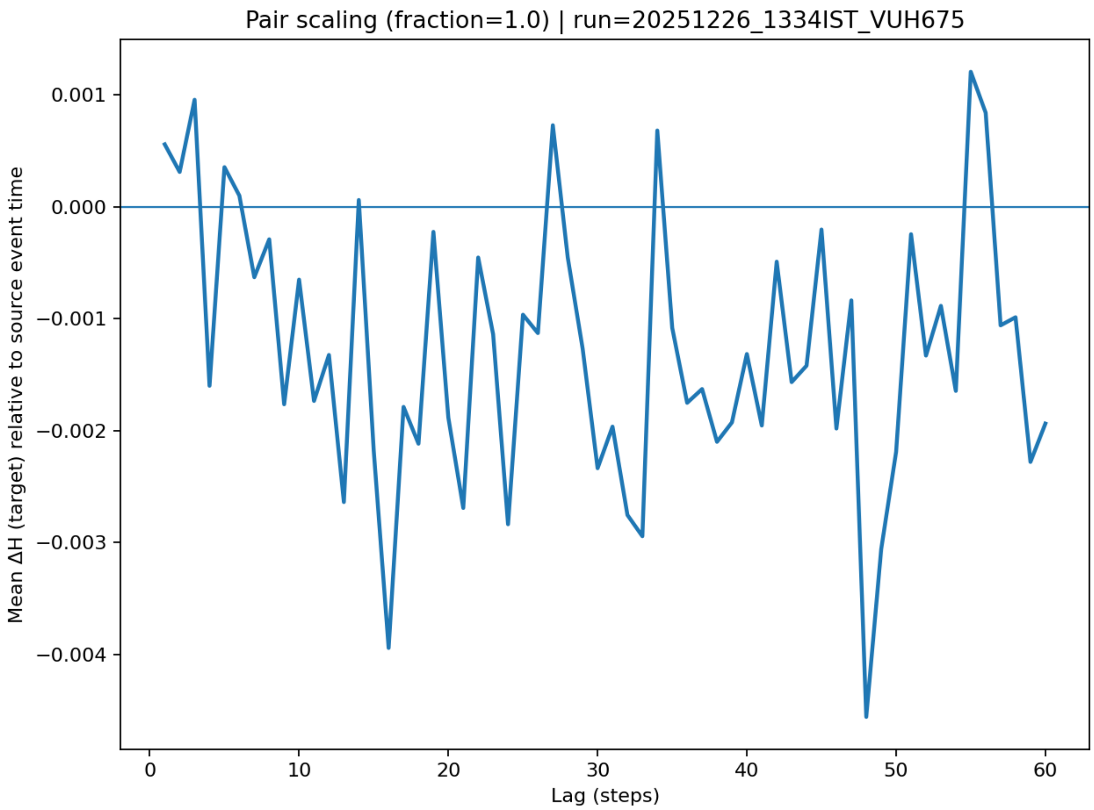

Figure 2: Mean event-triggered entropy response at full pair sampling. The structured temporal profile persists under maximal aggregation, indicating a population-level effect rather than pair-specific noise.

4.2 Subject Scaling

We independently subsampled the number of subjects, recomputed all valid pairwise responses within each subset, and examined how the aggregate entropy response scales with population size.

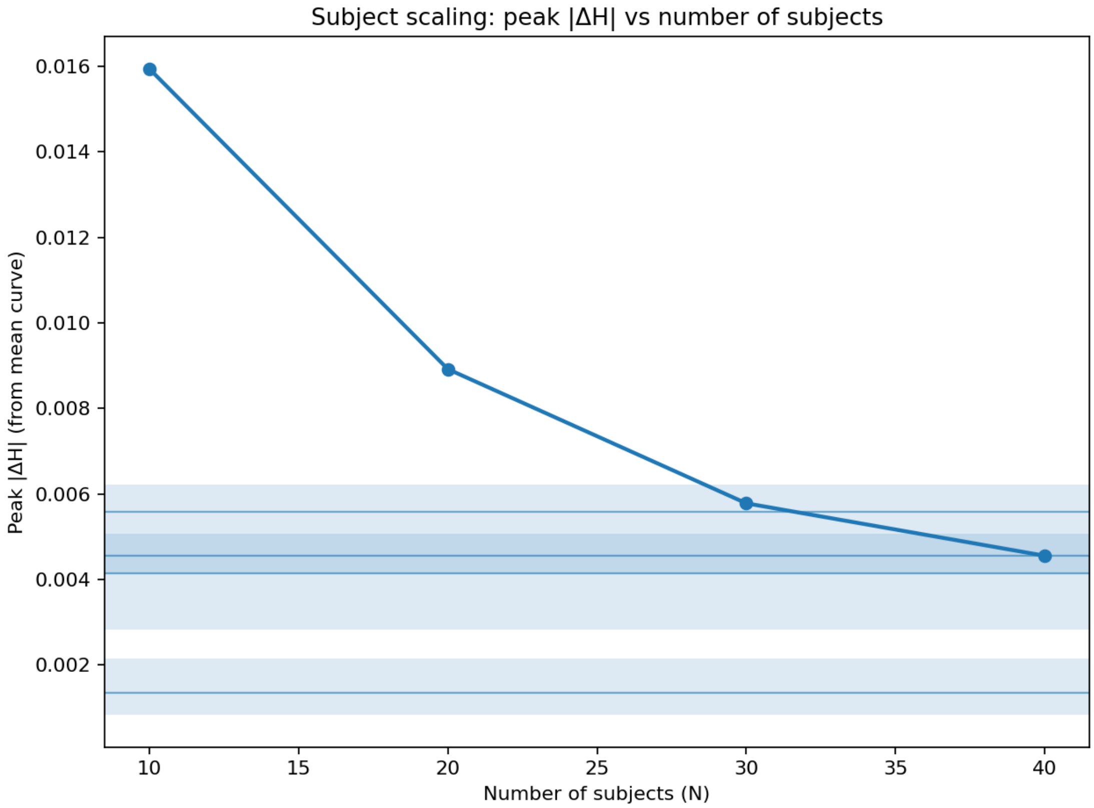

Figure 3: Subject scaling of the peak absolute entropy response. The signal strengthens and stabilizes as the number of subjects increases, demonstrating that the effect does not wash out under aggregation.

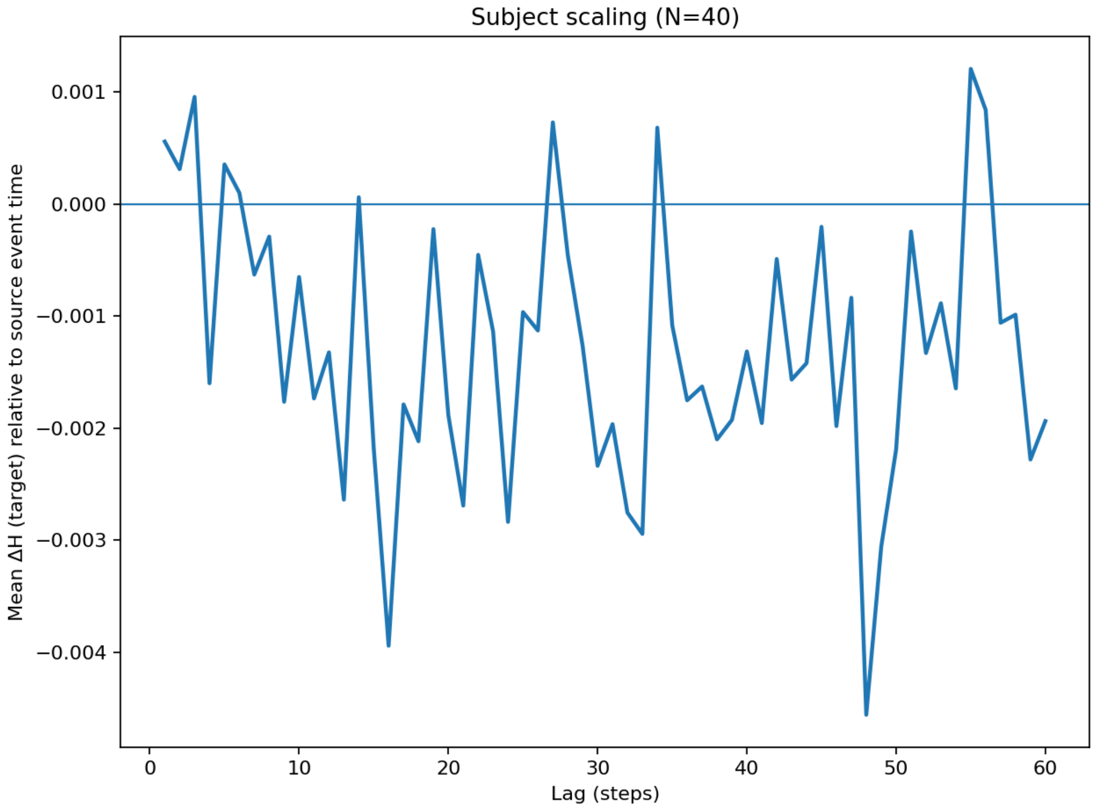

Figure 4: Mean entropy response curve at the largest subject count. Variance decreases while the mean response remains finite, consistent with a collective phenomenon.

5 Null Models and Statistical Controls

To test whether the observed dynamics could arise from trivial statistical structure, we evaluated multiple null models, including time-shuffled entropy series, phase-randomized surrogates, time-reversed controls, and randomized event timings.

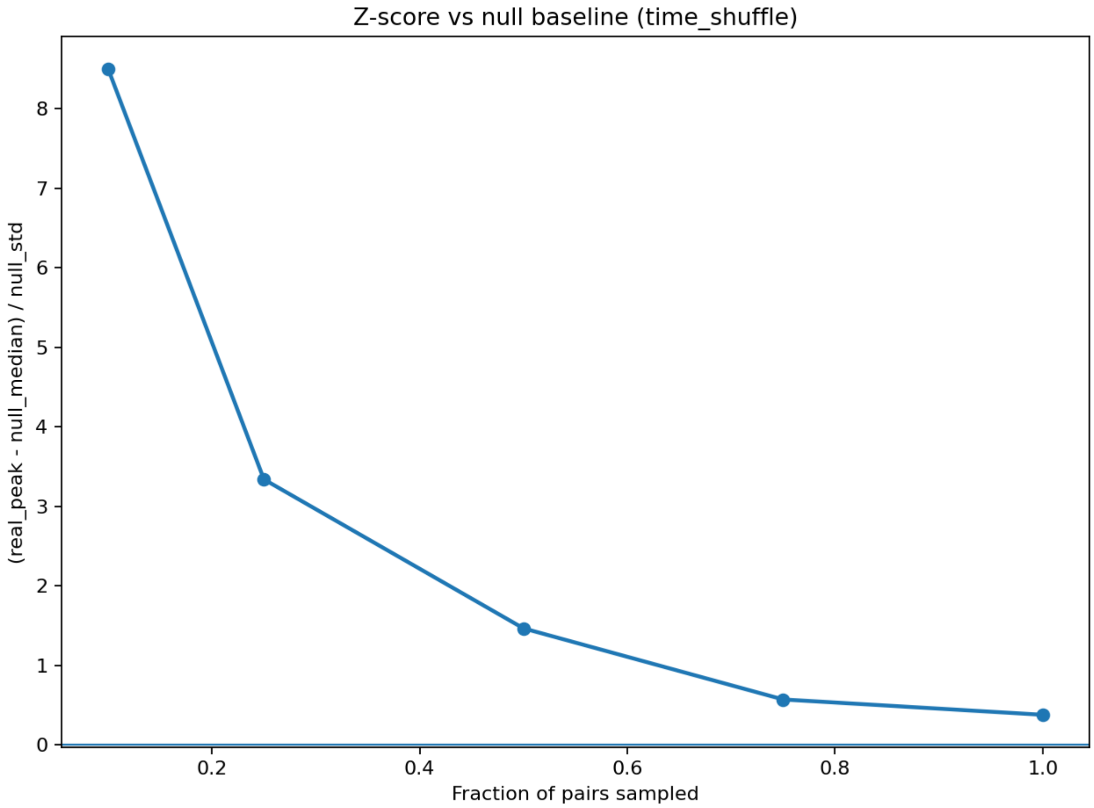

Figure 5: Z-score separation of real pair-scaling results from null models. Separation increases with sample size, inconsistent with finite-sample or autocorrelation artifacts.

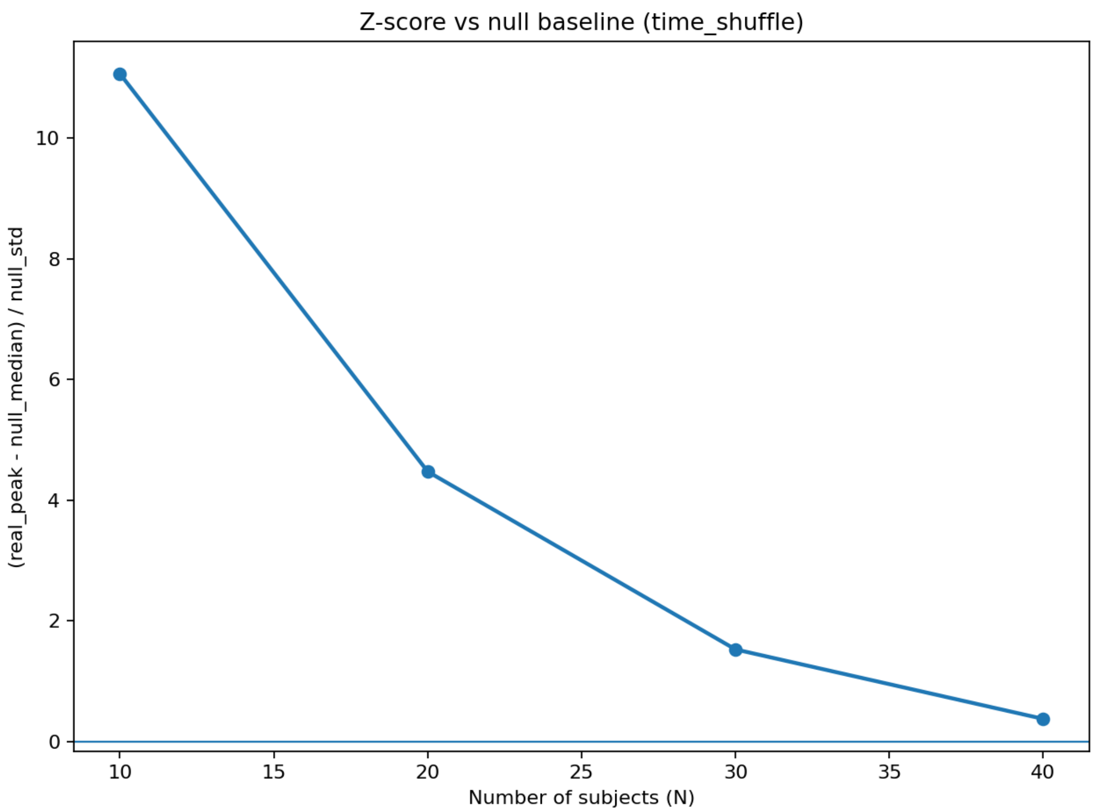

Figure 6: Z-score separation for subject scaling. The real data increasingly diverges from null distributions as population size grows.

Across all regimes, real data shows strong and growing separation from null models.

6 Results

Across meditation, tightly controlled meditation, and resting-state EEG, we observe:

- A reproducible, time-structured entropy response following emission events
- Stability of the response under extensive pair subsampling
- Strengthening and convergence of the signal with increasing subject count
- Clear separation from all tested null models

Meditation datasets exhibit the strongest responses, with resting-state EEG showing a weaker but still statistically separable effect.

7 Discussion

The results demonstrate a robust population-level entropy response associated with neural events. The fact that the signal strengthens rather than vanishes with aggregation strongly argues against explanations based on idiosyncratic subject behavior or statistical coincidence.

At present, no specific mechanistic explanation is proposed. Possible interpretations include large-scale network relaxation following state transitions, redistribution of informational load across distributed circuits, or emergent constraints in high-dimensional neural dynamics [6, 7]. Determining the precise mechanism requires targeted experiments and modeling beyond the scope of this study.

Importantly, the absence of a mechanism does not weaken the present findings. The role of this work is to establish that the phenomenon exists, scales correctly, and survives stringent null testing.

8 Limitations and Future Work

This study relies on coarse-grained entropy measures and does not incorporate spatial information. Event detection is operational rather than physiological, and causal influence between subjects is not implied.

Future work will explore mechanistic drivers, extend the analysis to other neural modalities, and test whether similar scaling behavior appears in non-neural complex systems.

9 Conclusion

We report a previously uncharacterized, event-triggered entropy response in human EEG that exhibits robust population scaling and strong separation from null models. These findings suggest that neural events are associated with coordinated, large-scale reorganization of brain dynamics observable through information-theoretic measures.

While the underlying mechanism remains unknown, the phenomenon itself is clear, reproducible, and scalable. This work establishes a foundation for future theoretical and experimental investigations of collective neural dynamics.

References

[1] Claude E. Shannon. A mathematical theory of communication. *Bell System Technical Journal*, 27(3):379–423, 1948.

[2] Giulio Tononi and Gerald M. Edelman. Complexity and coherency: integrating information in the brain. *Trends in Cognitive Sciences*, 2(12):474–484, 1998.

[3] Adenauer G. Casali, Olivia Gosseries, Mario Rosanova, Melanie Boly, Simone Sarasso, Krish D. Casali, Silvia Casarotto, Marie-Aurélie Bruno, Steven Laureys, Giulio Tononi, and Marcello Massimini. A theoretically based index of consciousness independent of sensory processing and behavior. *Science Translational Medicine*, 5(198):198ra105, 2013.

[4] Michael M. Schartner, Robin L. Carhart-Harris, Adam B. Barrett, Anil K. Seth, and Suresh D. Muthukumaraswamy. Increased spontaneous meg signal diversity for psychoactive doses of ketamine, lsd and psilocybin. *Scientific Reports*, 5:17069, 2015.

[5] Gerwin Schalk, Dennis J. McFarland, Thilo Hinterberger, Niels Birbaumer, and Jonathan R. Wolpaw. Bci2000: A general-purpose brain-computer interface (bci) system. *IEEE Transactions on Biomedical Engineering*, 51(6):1034–1043, 2004.

[6] John M. Beggs and Dietmar Plenz. Neuronal avalanches in neocortical circuits. *Journal of Neuroscience*, 23(35):11167–11177, 2003.

[7] Karl J. Friston. Transients, metastability, and neuronal dynamics. *NeuroImage*, 5(2):164–171, 1997.