Phase-Locking Induced by tACS in a Balanced Network of AdEx Neurons

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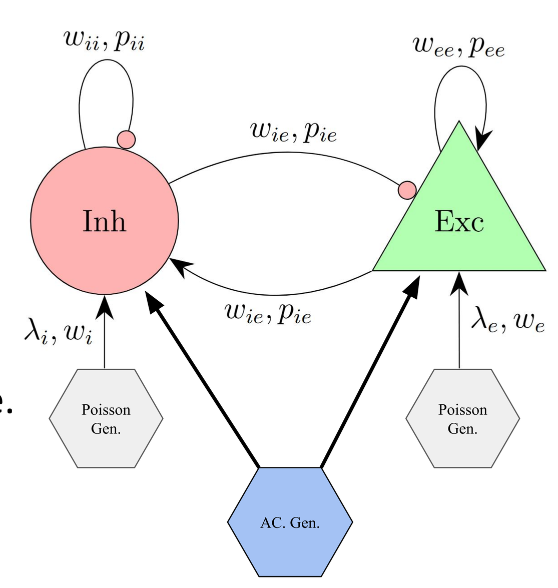
1 Introduction

Transcranial alternating current stimulation (tACS) is a non-invasive brain stimulation technique that delivers weak alternating electrical currents to the scalp. These currents aim to modulate the brain's electrical oscillations. It allows researchers to investigate the causal role of specific brain rhythms in cognitive processes and behavior. By influencing brain oscillations, tACS shows promise as a potential therapeutic tool for various neurological and psychiatric conditions, as well as for enhancing cognitive functions in healthy individuals.

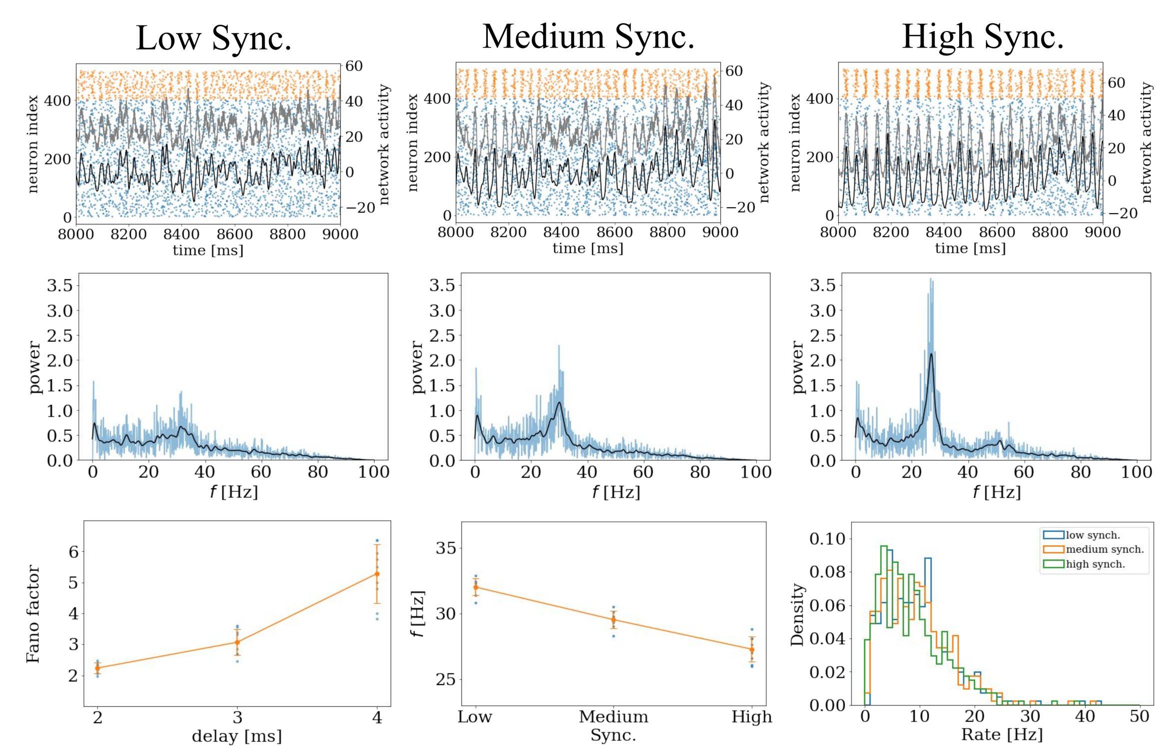
Investigating brain-state dependency in tACS is crucial because the effectiveness of tACS in modulating brain activity and behavior is not constant. Instead, entrainment by tACS depends on the endogenous oscillation of the neural network, which is based on the endogenous synchrony of the neurons' activity. This means that the brain's ongoing oscillatory state – whether it's highly synchronized or operating at a particular frequency – significantly influences how it responds to the externally applied current. Understanding this dependency allows for more targeted and effective tACS interventions, potentially leading to personalized and more consistently beneficial outcomes in both research and clinical applications.

2 Methods

- **Model:**
  - 500 neurons (80% E, 20% I), randomly connected.
  - Baseline synchronization controlled via synaptic delay (2–4 ms ⟶ low/medium/high).
  - Balanced state of Exc./Inh.
- **Stimulation:**
  - Sinusoidal input (5–60 Hz; 3–10 pA) mimicking tACS.
- **Metrics:**
  - **Population:** PLV (stimulus-network activity), Arnold tongue.
  - **Single Neuron:** Spike-Field Coherence (SFC).
- **Simulation:**
  - NEST/PyNEST, 9 noise realizations per condition.

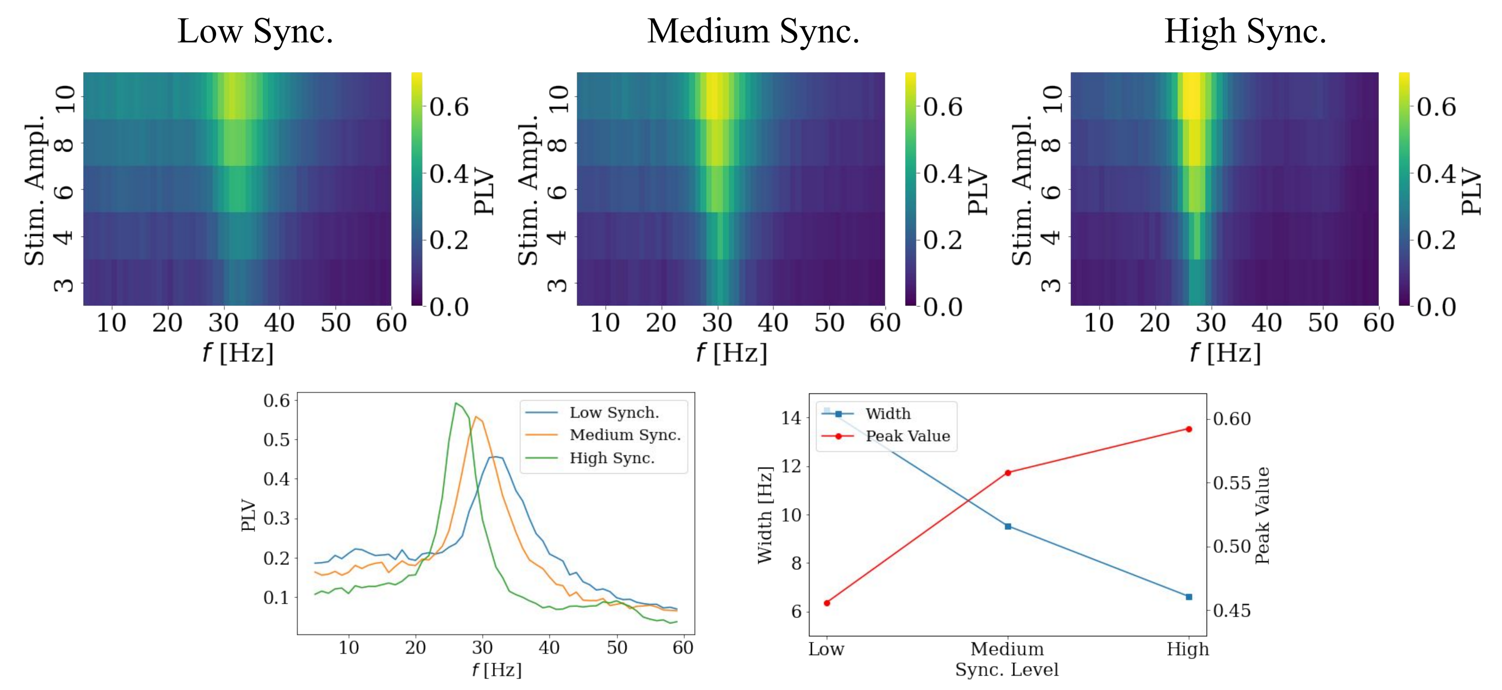


3 Baseline States



Increasing synaptic delay increased network synchrony and reduced oscillation frequency.

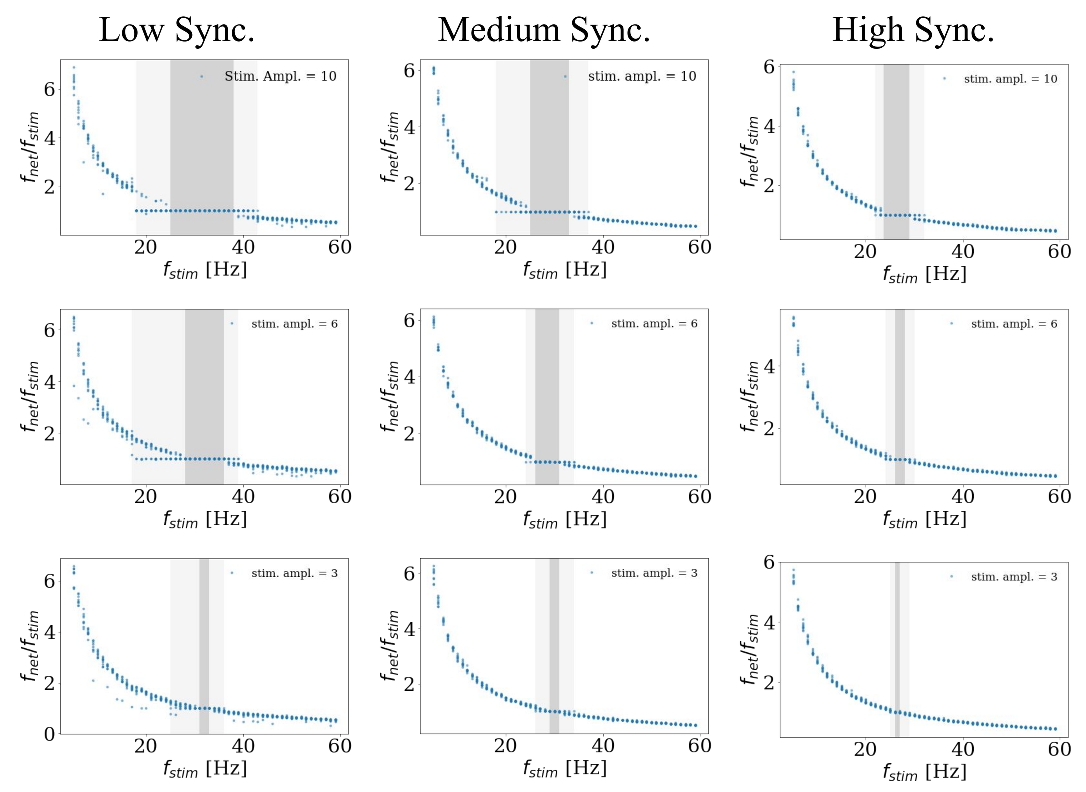
4 Network Entrainment



Low-synchrony networks exhibited broader Arnold tongues.

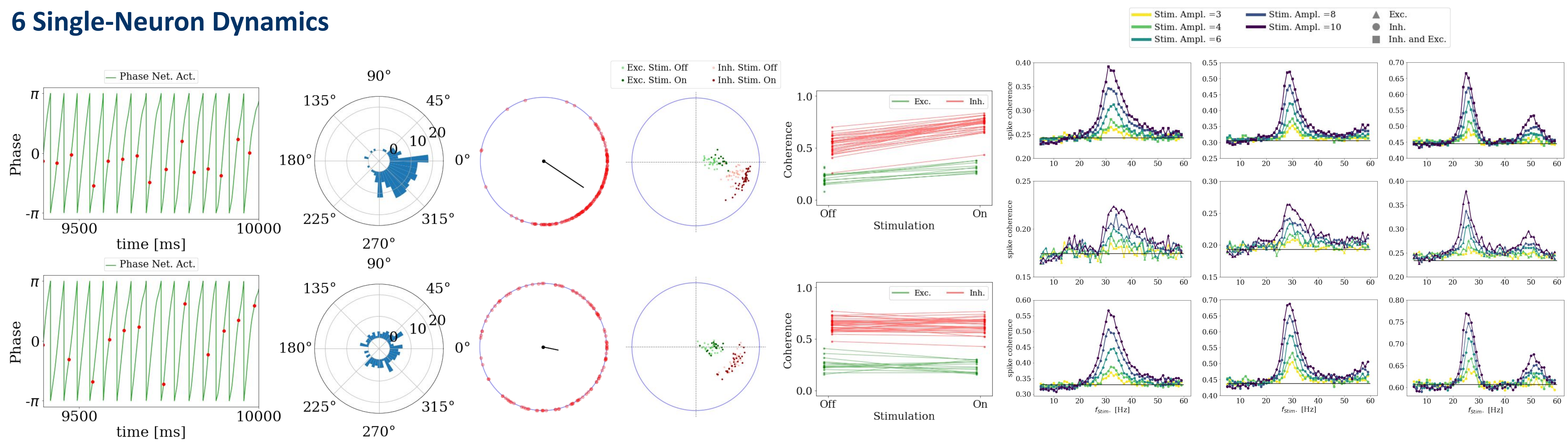
High-synchrony networks entrained only near resonance.

5 Bistability



Near locking boundaries, some trials entrain while others don't.

6 Single-Neuron Dynamics



Inhibitory neurons consistently displayed higher SFC values compared to excitatory neurons. This observation held both before and after the application of the simulated tACS stimulation.

The changes in locking values – the increase in SFC due to stimulation – were more pronounced in the inhibitory population.

No significant change in mean firing rates. External input modulates temporal coordination, not overall excitability.

Key Takeaways

- **Synaptic delay tunes baseline synchrony;**
- **Weak rhythms broaden tACS locking range;**
- **State-dependent Arnold tongues;**
- **Bistability suggests dynamical flexibility;**
- **Inhibitory neurons are key phase-lockers.**

References

- Roohi, N., & Valizadeh, A. (2022). Role of interaction delays in the synchronization of inhibitory networks. *Neural Computation*, 34(6), 1425-1447.
- Asl, M. M., & Valizadeh, A. (2025). Entrainment by transcranial alternating current stimulation: Insights from models of cortical oscillations and dynamical systems theory. *Physics of Life Reviews*.
- Trotter, D., Pariz, A., Hutt, A., & Lefebvre, J. (2023). Morphological variability may limit single-cell specificity to electric field stimulation. *bioRxiv*, 2023-06.
- Mahmud, M., & Vassanelli, S. (2016). Differential modulation of excitatory and inhibitory neurons during periodic stimulation. *Frontiers in neuroscience*, *10*, 62.
- Gewaltig, M. O., & Diesmann, M. (2007). Nest (neural simulation tool). *Scholarpedia*, *2*(4), 1430.
- Eppler, J. M., Helias, M., Muller, E., Diesmann, M., & Gewaltig, M. O. (2009). PyNEST: a convenient interface to the NEST simulator. *Frontiers in neuroinformatics*, *2*, 363.

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