Effect of Noise on a Pulse-Coupled Neural Network with Phase-Amplitude Coupling

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Abstract

Recent literature has emphasized the importance of cross-frequency coupling (CFC) in neural communication. Like most communication, it is compromised when noise is introduced. We modeled a neural network with theta/gamma phase-amplitude coupling (PAC) to analyze the impact of increased random baseline activity ("noise") on the local field potential (LFP) and its power spectrum. Results were compared to past experiments and simulations.

Introduction

- Oscillations in neural networks are important for communication between neuronal ensembles and brain areas via CFC [1].
- **Theta/gamma PAC:** the amplitude of high-frequency gamma oscillations (80-150 Hz) is coupled with the phase of low-frequency theta oscillations (4-8 Hz) throughout the human brain [2].
- PAC is compromised by **background noise:** the increase in baseline neural activity [3].
    - Linear-nonlinear Poisson (LNP) model: background noise whitens the power spectrum by flattening power in the high gamma band [4].
        - This indicator is supported by studies on aging [4].
        - **Neural noise (NN):** slope of the power spectrum (80-150 Hz)
- Spiking neuron models are useful to test and develop hypotheses and to corroborate experimental findings
    - We observed how PAC and NN were affected by the injection of different amounts and variations of baseline neural activity

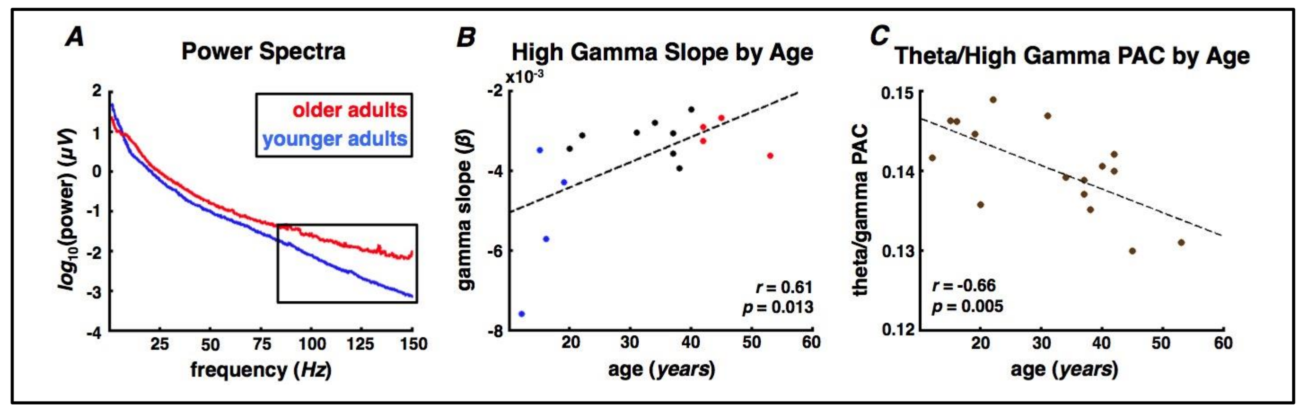


Figure 1. Aging leads to (A,B) increased NN and (C) decreased PAC, measured by electrocorticography in epilepsy patients (reprinted from [4]).

Results: Simulated PAC and NN

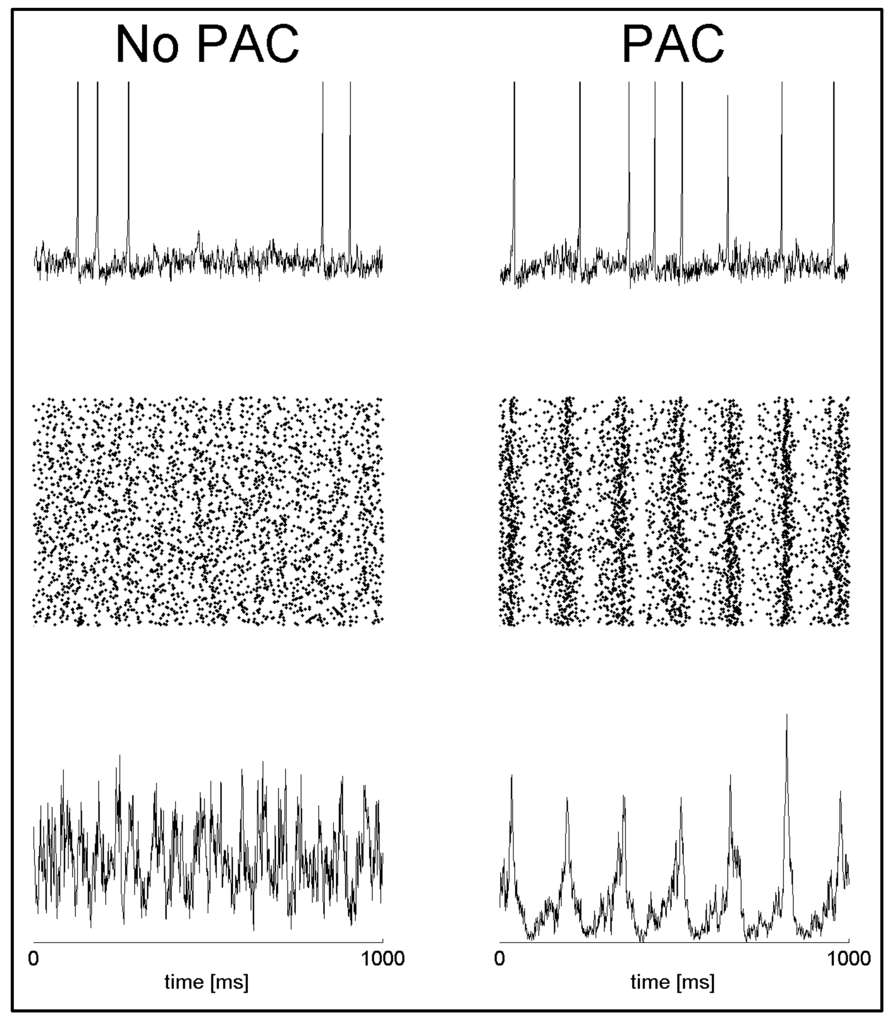


Figure 3. Networks with and without theta/gamma PAC. (Top) Representative excitatory neuron voltage trace. (Middle) Raster plots of spikes. (Bottom) LFPs.

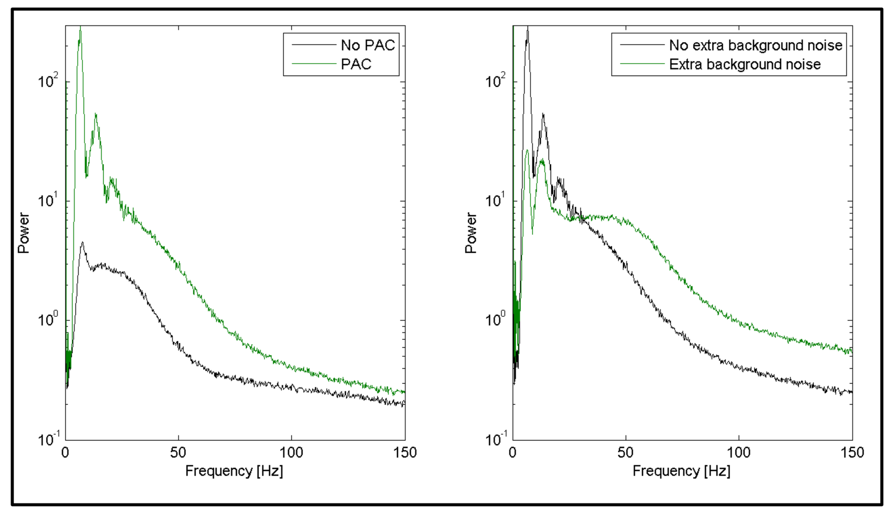


Figure 4. (Left) Increased theta-modulated current increased low frequency power. (Right) Increased background noise increased high frequency power. 1000 ensembles simulated.

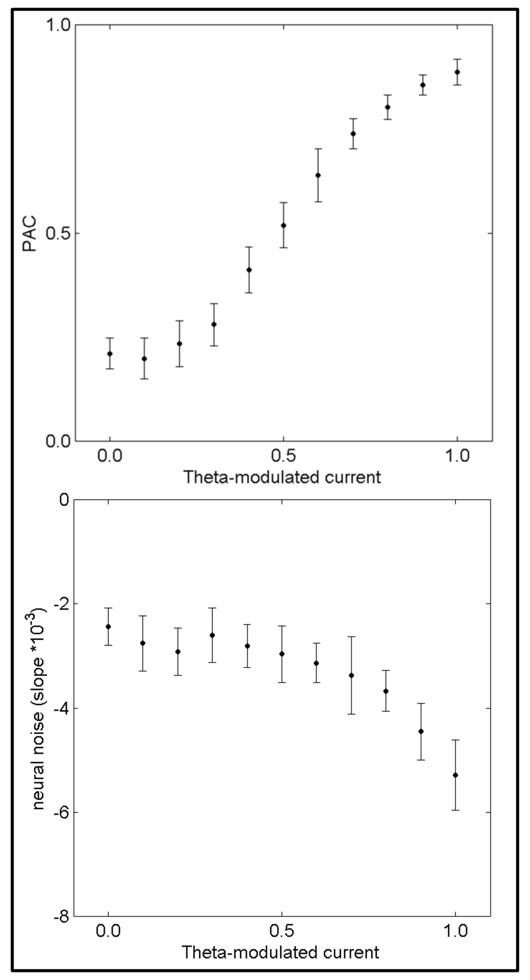


Figure 5. (Top) Increased theta-modulated current increased theta/gamma PAC. (Bottom) Increased theta-modulated current decreased NN. 10 runs of 10 ensembles simulated.

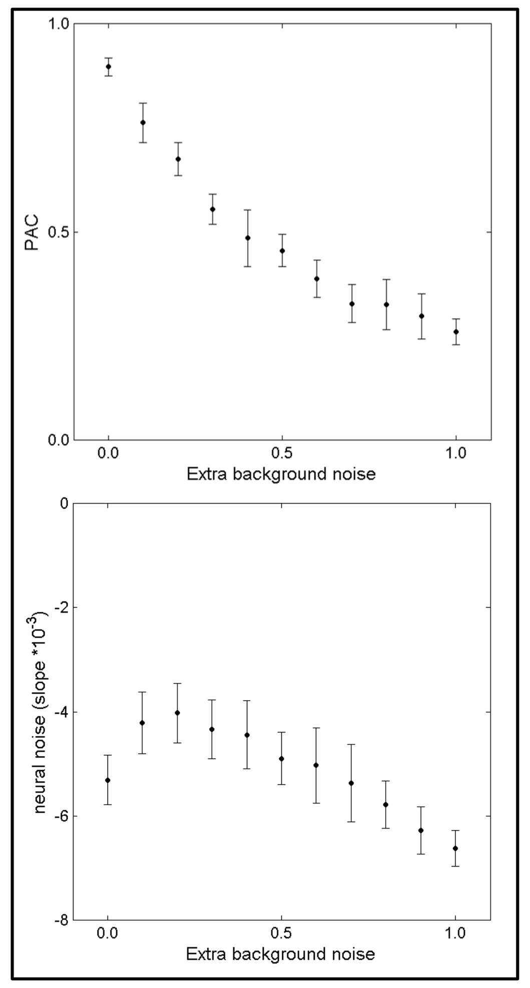


Figure 6. (Top) Increased background noise decreased theta/gamma PAC. (Bottom) Increased background noise inconsistently changed NN. 10 runs of 10 ensembles simulated. Theta-modulated current = 1.

Results: Variable theta-modulated current

Variations of postsynaptic current modulation by theta phase

1. Modulate magnitude or probability of postsynaptic current
2. Randomness of postsynaptic currents. Currents can be constant (nonrandom), uniformly distributed, or normally distributed

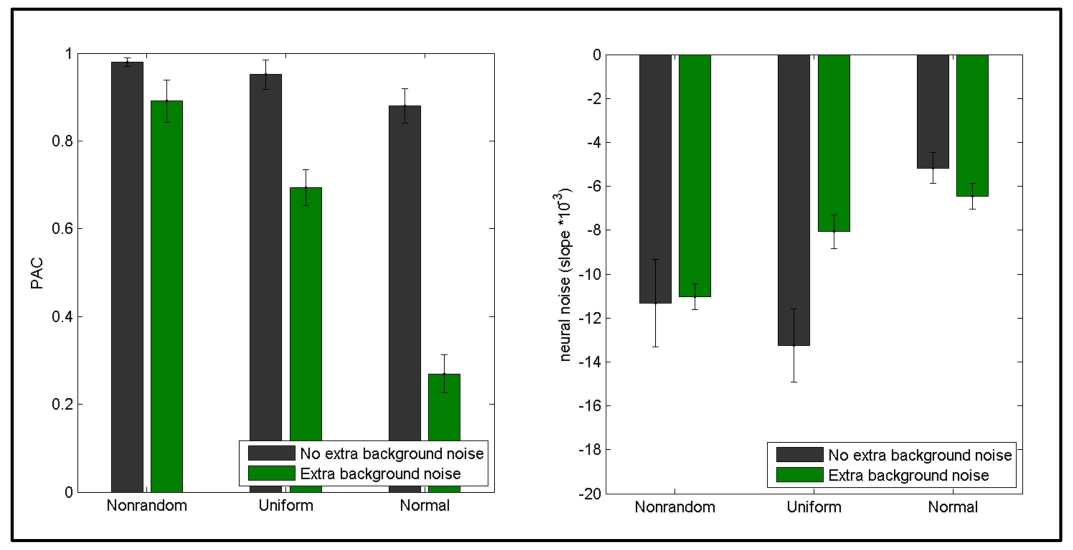


Figure 7. Background noise (Left) decreased PAC for all types of theta-modulated currents, but (Right) changes in NN varied for different strategies. Results for phase-weighted current *magnitude* shown only.

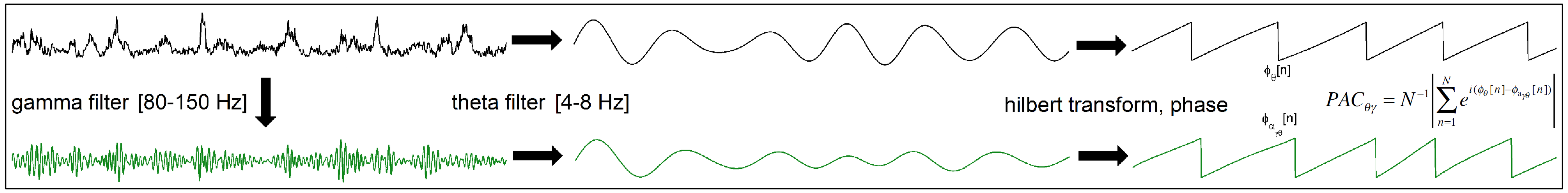
Discussion

- This simulation of a network of biologically plausible yet computationally efficient neurons [5] accurately produces a neural network with theta/gamma PAC.
- Increased background activity decreases PAC.
    - In accordance with LNP model [4]
- **Injected background firing does not increase NN.**
    - In contrast with LNP model [4]
    - May be due to specific network parameters (see "Future work")
- Different strategies of biasing the neurons to simulate theta/gamma PAC can change the properties of the network.
    - Biasing neurons with maximal excitatory input leads to maximal PAC, and uniformly random input leads to minimum NN.
- **Future work:** further investigation of attributes of the simulation and their effects on PAC, NN, synchrony, and other properties:
    - Connectivity between neurons [6]
    - Network size
    - Distribution of currents
    - Overall firing rate
    - Properties and heterogeneity of the neurons in the network

Methods

- Pulse-coupled neural network (PCNN) [5]
    - Each ensemble: 400 excitatory and 100 inhibitory neurons; 5 seconds
    - Neurons were randomly connected with uniformly distributed synaptic strengths
    - Synaptic input: excitatory and inhibitory postsynaptic currents (EPSCs, IPSCs)
        - Thalamic input: "background noise"
        - Theta-modulated current: input weighted by the theta phase
- Spike analysis
    - LFP: spike train convolved with an alpha function
    - PAC: Correlation between theta phase and gamma power (see **Figure 2**, below)
    - NN: Least-square fit to LFP power spectrum (80-150 Hz)

Figure 2. Illustration of phase-amplitude coupling calculation.



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