Cross-Frequency Coupling Increases Memory Capacity in Oscillatory Neural Networks

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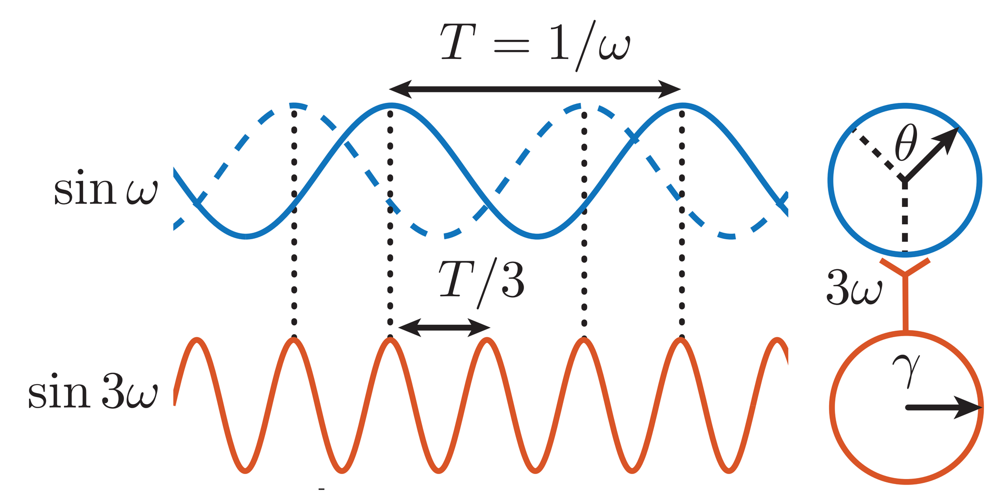
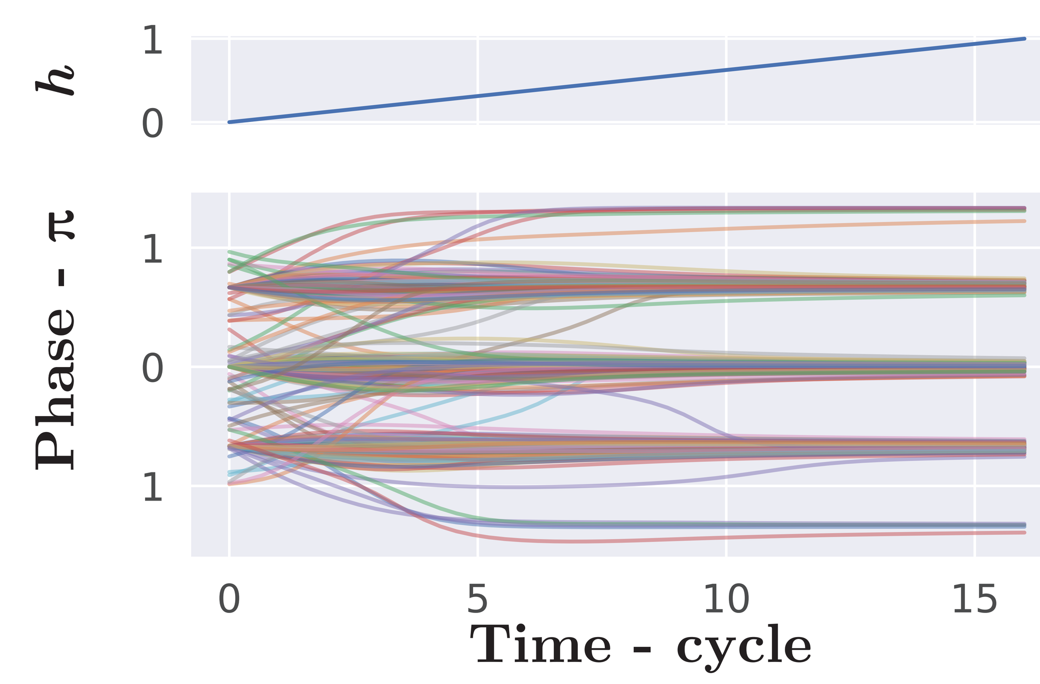
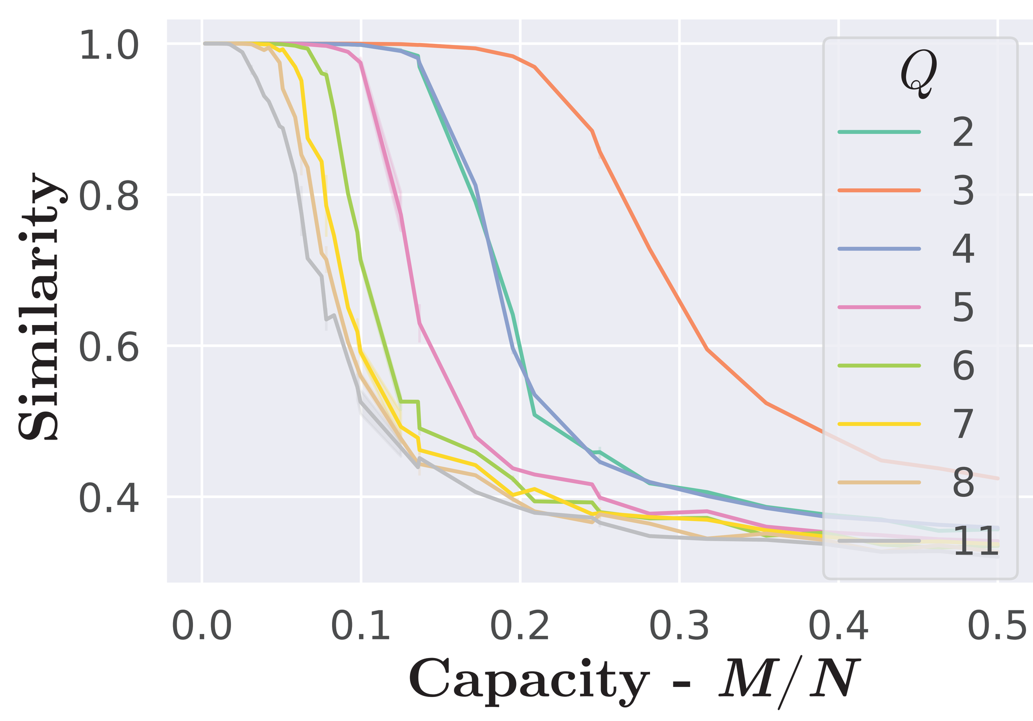
Introduction

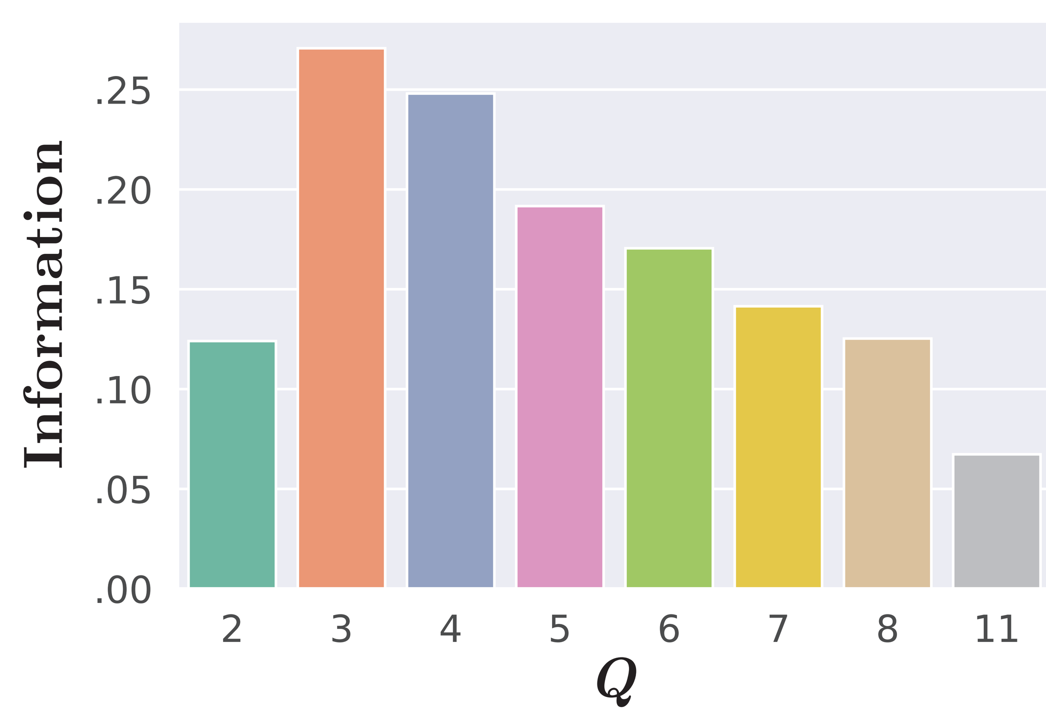
An open problem in neuroscience is to explain the functional role of oscillations in neural networks, contributing to perception, attention, and memory. Cross-frequency coupling (CFC) is associated with information integration across populations of neurons[1]. We construct a novel oscillator Q-state phasor associative memory (PAM)[2,3], a type of phasor neural network (PNN), that exhibits CFC via subharmonic injection locking (SHIL)[4] and predicts a computational role for observed theta-gamma oscillatory circuits in neural populations. We validate the capacity analysis of Q-state PAM networks[5] through simulation. We show that the presence of SHIL increases the memory capacity of a population of oscillatory neural networks (ONN), connected by plastic synapses. This work bridges gaps between information theory and dynamical systems theory to construct robust associative memories in neural networks.

Capacity Analysis









(**Top-left**) Illustration of SHIL between theta and gamma neurons, corresponding to Q=3. Theta oscillator received input from gamma, resulting in 3 discrete phase states. (**Top-right**) Convergence of oscillators to discrete phase states with increasing harmonic coupling, h (Q=3). (**Bottom-left**) Similarity of retrieved memory as a function of capacity for varying Q-states (N=1,024). (**Bottom-right**) Information capacity (bits/synapse) as a function of Q. Q=3 has maximum storage capacity.

Q-State Associative Memory

Given M memories with discrete phases

$$\xi^k = e^{\frac{2\pi i}{Q}\mathbf{q}^k} \in \mathbb{C}^N, \forall k \in \{1,\ldots,M\}$$

Energy function contains stable fixed-points

$$E = -\frac{1}{2}\mathbf{z}^{*T}\mathbf{W}\mathbf{z} - \frac{h}{Q}\sum_i (z_i^Q + z_i^{*Q})$$

Iterative decent of energy function achieved via

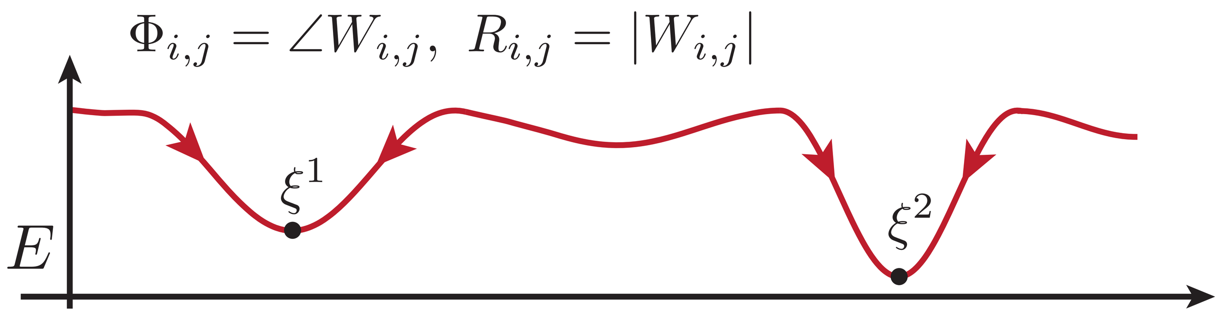
$$z_i(t+1) = f(\sum_j W_{ij} z_j(t))$$

$$f(u_i) = \exp(\frac{2\pi i}{Q} \arg\min_q |\phi_i^u - \frac{2\pi q}{Q}|)$$

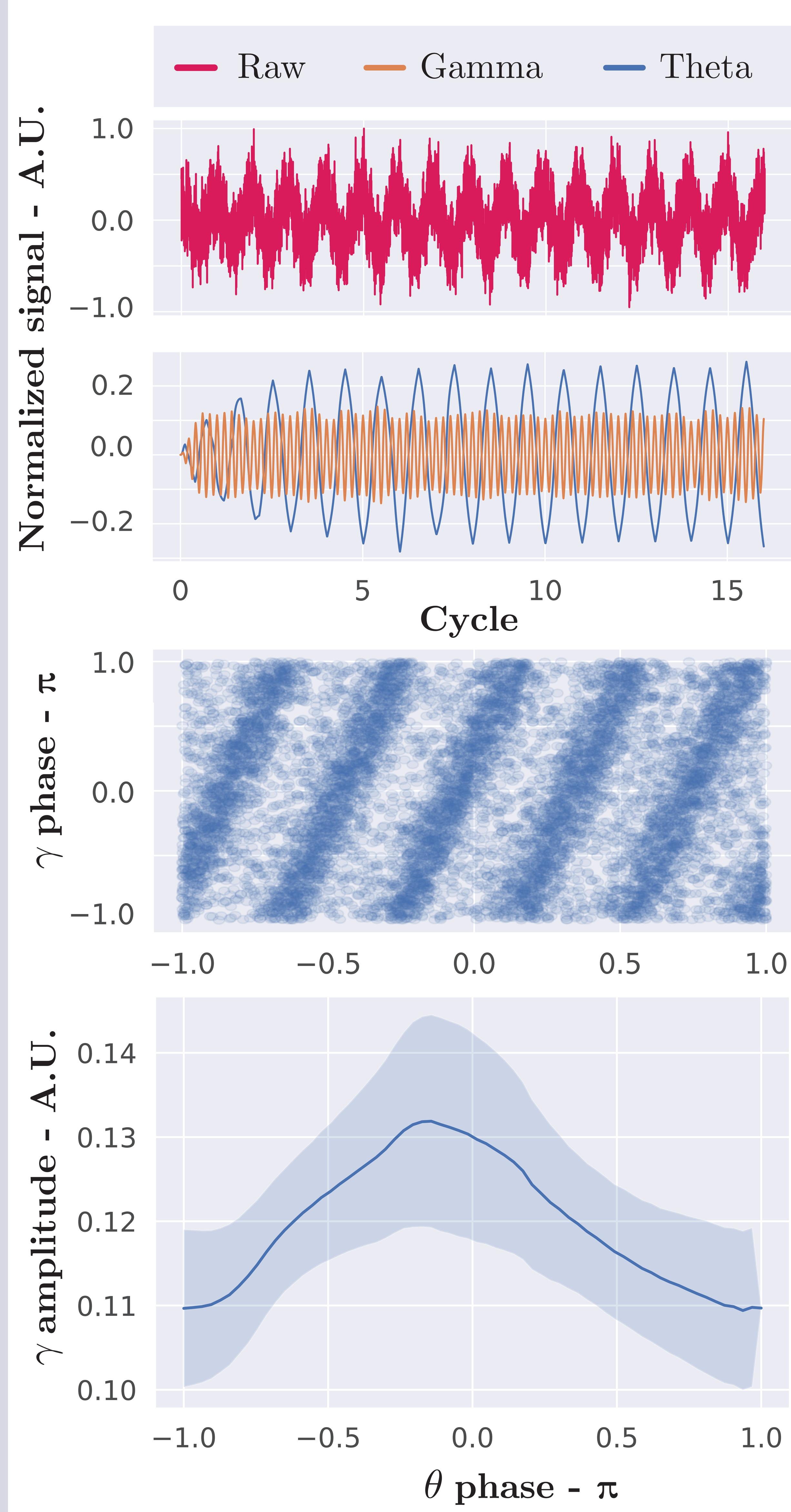
OR via continuous oscillator dynamics with SHIL

$$\frac{\partial \phi_i}{\partial t} = -\epsilon \sum_{i \neq j} R_{ij} \sin(\phi_i - \phi_j - \Phi_{ij}) - h \sin(Q\phi_i)$$

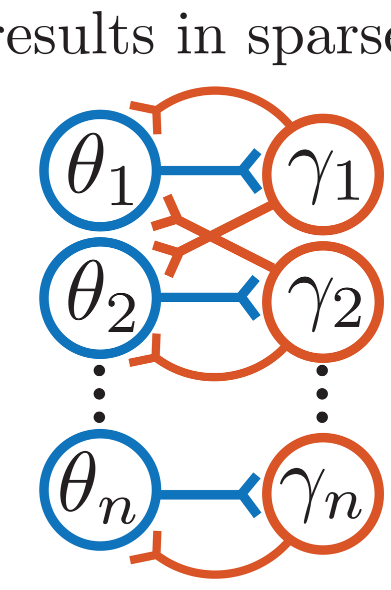
$$\Phi_{i,j} = \angle W_{i,j},\ R_{i,j} = |W_{i,j}|$$



Cross-Frequency Analysis



Simulation of PAM with Q=5 implemented in an ONN. Phase-Phase Coupling (PPC) and Phase-Amplitude (PAC) are two types of CFC. (**Top**) Raw signal obtained from the superposition of theta and gamma neurons with additive white Gaussian noise. (**Top-middle**) Filtering the raw signal yields theta/low and gamma/high-frequency components. (**Bottom-middle**) PPC between theta phase and gamma phase results in banding. The number of bands is equal to the frequency ratio $\omega_\gamma/\omega_\theta$=5. (**Bottom & Bottom-right**) Modulating the SHIL parameter, h, with the theta phase results in sparse PAC.



Conclusion

- Q-state PAMs achieve large synaptic capacity for content-addressable memory
- Efficient ONN Q-state PAMS exhibit CFC

References

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