

Oscillatory Dynamics as a Universal Substrate for Computation: From Neural Circuits to Artificial Intelligence

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Oscillatory and wave-based dynamics are ubiquitous in physical and biological systems, from molecular signaling to large-scale cortical rhythms [1,2]. Whether neural oscillations play a mechanistic role in computation or merely reflect epiphenomenal byproducts has been debated for decades. Recent evidence supports the view that synchrony, resonance, and wave interference constitute fundamental computational primitives [2,3]. This principle extends beyond neuroscience: wave physics can function as an analog recurrent neural network [4], and photonic, mechanical, and fluid substrates exploit wave dynamics for information processing [5,6]. The convergence across domains suggests that oscillatory dynamics represent a general physical resource for computation, not a peculiarity of neural tissue.

To test this hypothesis *in silico* and in analog electronic hardware, we developed the Harmonic Oscillator Recurrent Network (HORN, Fig. 1), in which each unit is a damped harmonic oscillator [3]. HORNs exploit computational principles arising from oscillatory physics: dual coding through amplitude and phase, resonance-based frequency selectivity, transient dynamics without convergence to fixed-point attractors, and interference-based memory. Simulations demonstrate improved parameter efficiency, learning speed, and noise robustness relative to non-oscillatory recurrent architectures. An analog-electronic implementation faithfully reproduces its digital twin [7], confirming that wave-based principles transfer to physical hardware. Moreover, quantum-like states emerge from classical oscillatory dynamics through phase-dependent superposition [8].

Taken together, these findings linking neuroscientific theory, computational modeling, analog electronics, and cross-substrate wave physics support the view that transient oscillatory dynamics provide a unifying substrate for analog computation. This perspective bridges neuroscience (biological oscillations as computational primitives), AI (biologically inspired algorithms validated on machine learning benchmarks), and neuromorphic engineering (analog oscillator-based circuits). Implementing wave-based principles in artificial systems opens pathways for adaptive information processing architectures inspired by the physics of natural neural networks.

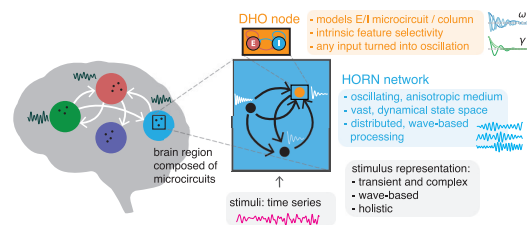


Figure 1: The HORN model: coupled damped harmonic oscillators (ω : natural frequency, γ : damping) process temporal stimuli via transient oscillatory dynamics [3].

- [1] G. Buzsáki and A. Draguhn, *Science*, 304(5679), 1926–1929, 2004.
- [2] W. Singer and F. Effenberger, *Hum. Arenas*, 8, 846–868, 2025.
- [3] F. Effenberger et al., *Proc. Natl. Acad. Sci. USA*, 122(4), e2412830122, 2025.
- [4] T. W. Hughes et al., *Sci. Adv.*, 5(12), eaay6946, 2019.
- [5] A. Todri-Sanial et al., *npj Unconv. Comput.*, 1(1), 14, 2024.
- [6] G. Tanaka et al., *Neural Netw.*, 115, 100–123, 2019.
- [7] P. Carvalho et al., *Phys. Rev. Applied*, 24, 064055, 2025.
- [8] A. Khrennikov et al., *arXiv:2506.00040*, 2025.