Beyond Synchrony: The Role of Electrical Synapses in Neural Pattern Formation | Bastian Pietras

Bastian Pietras (1), Pau Clusella (2), Daniele Avitabile (3,4), Ernest Montbrió (1)
1. Neuronal Dynamics Group, Department of Engineering, Universitat Pompeu Fabra, 08018 Barcelona, Spain
2. EPSEM, Departament de Matemàtiques, Universitat Politècnica de Catalunya, 08242 Manresa, Spain
3. Amsterdam Centre for Dynamics and Computation, Department of Mathematics, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, The Netherlands
4. MathNeuro Team, Inria branch of the University of Montpellier, 34095 Montpellier Cedex 5, France

Electrical synapses, mediated by gap junctions, have historically played a minor role in neuroscience research, often overshadowed by their chemical counterparts. Yet, some hypothesize they may constitute the brain's "dark matter"—essential but elusive. Gap junctions are notoriously difficult to investigate experimentally and theoretically, but recent advances in both domains illuminate their potential significance in neuronal networks. By integrating previously scattered neuroanatomical evidence into established mean-field approaches for networks of spiking neurons with chemical and electrical synapses, we uncover novel and counterintuitive functions of gap junctions in shaping the collective behavior of inhibitory neurons.

We propose an exactly reduced neural field model for quadratic integrate-and-fire neurons that incorporates the distinct spatial connectivity ranges of chemical and electrical synapses. This analytically tractable model not only reveals, through bifurcation analysis, unexpected roles of gap junctions beyond synchronization and collective oscillations, but it provides insights how electrical synapses contribute to the formation and modulation of neural patterns. Numerical simulations demonstrate that these analytical results are robust and extend to other neuron models, including exponential integrate-and-fire neurons. Our findings suggest a paradigm shift in understanding neural pattern formation, extending Turing's foundational principles of reaction-diffusion systems to account for neural dynamics that emerge through the intricate interplay of electrical and chemical synapses.