Switching States: Heteroclinic Cycles as Organizing Centers of Neuronal Dynamics

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Abstract

Neuronal networks exhibit spontaneous and evoked transitions between high- and low-activity regimes, referred to as up and down states. These states, along with the network's rhythmic patterns, are critical for perception, memory consolidation, and sensory processing. Due to their importance, identifying the fundamental dynamical principles that organize these large-scale state transitions is a major open question. Here, we propose necessary conditions for the existence of a novel bifurcation structure as a universal organizing center governing these transitions. Using bifurcation analysis and simulations of two-dimensional canonical mean-field network models we show that this bifurcation structure emerges robustly in this setting. An extension of the Wilson-Cowan model incorporating astrocyte dynamics and the Jansen-Rit model, enable us to demonstrate the persistence of the organizing center in higher dimensions. Our results reveal that the dynamic interplay between external inputs and network (synaptic) connectivity converges onto this shared mechanism, providing a fundamental principle for understanding how distinct brain states arise and are regulated across neuronal systems. Extending beyond phenomenological mean-field network models, we further show that it is the shared mathematical structure of the nonlinear input–output relationships rather than model-specific details that preserves the organizing center across modeling frameworks, thus revealing a fundamental and general mechanism underlying dynamic state transitions.