Towards bifurcation theory for rhythmogenesis in neural networks

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Rhythmic motor behaviors such as heartbeat, respiration, chewing, and locomotion on land and in water are produced by networks of cells called central pattern generators (CPGs). A CPG is a neural microcircuit of cells whose interactions can autonomously generate an array of polyrhythmic patterns of activity that determine motor behaviors in animals and humans. Modeling studies have proven to be useful to gain insights into operational principles of CPGs. Although various models, reduced and feasible, of specific CPGs have been developed, it remains unclear how the CPGs achieve the level of robustness and stability observed in nature. Whereas a dedicated CPG generates a single pattern robustly, a multifunctional CPG can flexibly produce distinct rhythms, such as temporally distinct swimming and versus crawling locomotion, and alternation of direction of blood circulation in leeches. Switching between various attractors of a CPG network causes switching between locomotion behaviors. Each attractor is associated with a definite rhythm running on a specific time scale with well-defined and robust phase lags among the constituting neurons. The emergence of synchronous rhythms in neural networks is closely related to temporal characteristics of coupled neurons due to intrinsic properties and types of synaptic coupling. We identify and describe the key qualitative rhythmic states in network motifs of a multifunctional central pattern generator. Such microcircuits of cells whose synergetic interactions produce multiple states with distinct phase-locked patterns of bursting activity. To study biologically plausible CPG models we develop a suite of computational tools that reduce the problem of stability and existence of rhythmic patterns in networks to the bifurcation analysis of fixed points and invariant curves of a Poincare return maps for phase lags between cells. We explore different functional possibilities for motifs involving symmetry breaking and heterogeneity. This is achieved by varying coupling properties of the synapses between the cells and studying the qualitative changes in the structure of the corresponding return maps. Our findings provide a systematic basis for understanding plausible biophysical mechanisms for the regulation of rhythmic patterns generated by various CPGs in the context of motor control such as gait-switching in locomotion. Our approach is applicable to a wide range of biological phenomena beyond motor control.

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