Complex spatiotemporal oscillations emerging from transverse instabilities in large-scale brain networks

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The interplay between neurons in the brain produces collective rhythmic behavior at multiple frequencies and spatial resolutions. This oscillatory activity is fundamental for proper cognitive function, and displays a plethora of spatiotemporal phenomenology in recorded signals. Recent advances on neuroimaging allow for representing the brain's inner organization as a complex network in which each node is a well-defined brain region composed of densely interconnected neurons, and edges across nodes represent pairwise interactions across distant regions. Combining neural-mass models (NMM) with connectomics data, one can create large-scale brain models whose dynamical properties reflect the principles underlying macroscopic neural activity. Nonetheless, many aspects about the mechanisms through which large-scale brain models reproduce spatiotemporal brain dynamics are still unknown.

In this work we uncover the onset of irregular spatiotemporal dynamics in a simple large-scale brain model. The model consists of 90 brain regions connected through a complex network obtained from tractography data. The activity of each brain area is governed by the dynamics of a Jansen-Rit NMM [1]. In close analogy to pattern-formation mechanisms in reaction-diffusion systems, we show that the coupling among brain regions alone is enough to spontaneously destabilize an underlying synchronized state, thereby generating complex oscillatory behavior.

Our analysis relies on a suitable normalization on the incoming input of each brain region and consists of two parts. First, we show that the network possesses an invariant homogeneous manifold, i.e., a set of states in which the behavior of each node is identical across all brain regions. These states are described by a self-coupled version of the NMM used for the evolution of each brain region. Bifurcation analysis of this low-dimensional system reveals how the different parameters modify the onset of synchronized oscillatory states within the homogeneous manifold. Second, we employ the Master Stability Function formalism [2] to investigate the stability of the homogeneous states to heterogeneous perturbations, i.e., perturbations that are transversal to the uniform dynamics of the system. According to this technique, the growth rate of any perturbation can be decomposed as a function of the structural connectivity eigenmodes, thereby providing a direct relation between topology and dynamics.

The combination of these two steps provides a comprehensive bifurcation diagram of the system in which the synchronized oscillatory solution turns out transversally unstable in a large region of the parameter space (see Fig 1a). Numerical simulations reveal that this instability gives raise to complex spatiotemporal dynamics, including travelling waves, multistability, and high-dimensional chaos. We study the synchronization and propagation properties of these regimes (see Fig 1b), and show that their complexity increases by reducing the external input of the system.

In order to extend our model to a more realistic setup, next we perform extensive numerical simulations of the unnormalized version of the system. The outcome reveals that irregular oscillations emerge through a mechanism similar to that of the simplified formulation, but differ on how the patterns synchronize and travel across the network. Finally, we also apply the same analysis to investigate the emergence of irregular spatiotemporal activity using a next-generation NMM [3]. Overall, our work reveals that transverse instabilities are an ubiquitous mechanism for the onset of irregular spatiotemporal oscillations in large-scale brain networks.

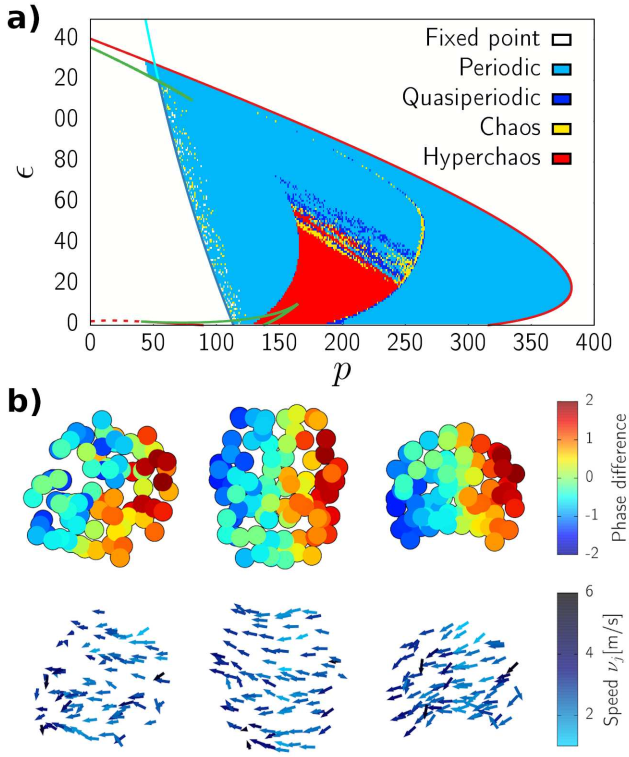

Fig. 1. (a) Bifurcation diagram of the system as obtained from the bifurcation analysis (continuous lines) and numerical simulations (colored regions). Parameters ϵ and p correspond to the coupling strength and external subcortical input respectively. (b) Travelling waves in the large-scale brain model. The top figures show the phase difference between brain regions (three different views of same snapshot). The bottom panels show the direction and speed of propagation.

[1] B. H. Jansen and V. G. Rit, Biol. Cybern. **73**, 357–366 (1995).

[2] L. M. Pecora and T. L. Carroll, Phys. Rev. Lett. **80**, 2109 (1998).

[3] E. Montbri, D. Paz, and A. Roxin, Phys. Rev. X **5**, 021028 (2015).