

Comment

Establishing the first theoretical basis of neuronal chimera states
Comment on “Chimera states in neuronal networks: A review”
by M. Perc et al.

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As the most complicated information processing system in nature, our mysterious brain is composed of nearly 100 billion neurons that conduct signals via thousands of times more synapses. From a dynamic perspective, the brain behaves highly nonlinearly and can generate a variety of self-organized dynamical states, such as rhythmical oscillations [1], neuronal avalanches [2] and chimeras [3–5]. Among them, the chimera state is believed to be one of the most counterintuitive phenomena and was initially referred to as the coexistence of synchronous and asynchronous behavior in a symmetry-coupled oscillatory system [6]. In particular, the emergence of this specific self-organized cortical state is not only associated with several normal brain functions [7,8] but also linked to several mental disorders [9].

A deep understanding of the neural mechanisms involved in chimera states promises to unlock the secrets behind both normal and abnormal dynamics in the brain. In this context, computational models of neuronal chimera states try to reproduce the mixed coexistence of coherent and incoherent dynamics in the brain [3–5]. Importantly, modeling chimera states in neuronal networks may not only provide a theoretical basis of neuronal chimera states but also direct further experimental investigations. However, although previous simulations have identified that the emergence of neuronal chimera states might be due to diverse factors [3–5], a sufficient literature review to systematically integrate these contributing factors and establish a theoretical framework for neuronal chimeras is still lacking.

Luckily, a timely literature review from M. Perc et al. summarized some recent studies investigating the origination of chimera-like states in neuronal systems [10]. In particular, the authors showed that chimera states can appear in either purely electrical-coupled or purely chemical-coupled networks with both identical and nonidentical spiking model neurons [3,11]. Under suitable conditions, such a brain state has also been observed in neuronal networks with hybrid electrical and chemical couplings [4]. Remarkably, M. Perc et al. further noted that several synaptic-related parameters, such as synaptic transmission delay and coupling strength, may significantly impact and modulate the chimera states generated in neuronal networks [12–14]. Among these parameters, the synaptic transmission delay due to both the finite propagation speeds and time lapses associated with synaptic processing has been considered a critical intrinsic regulatory factor that participates in controlling chimera states, even though such states have been observed in

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neuronal networks with and without synaptic delays [11–14]. Their comprehensive review emphasizes the functional significance of synaptic interactions in controlling neuronal chimeras and builds the static synaptic basis of chimera states in the brain.

Furthermore, noise serves as an inherent part of neuronal dynamics and is ubiquitous in the brain [15]. In addition to the synaptic-related parameters mentioned above, M. Perc et al. also believed that neuronal noise is another important factor that largely regulates the chimera states in the brain [10], an idea supported by sufficient computational studies [5,16]. For instance, in [16], the authors investigated the effect of noise on the emergence of chimera states in purely electrical-coupled neuronal networks, and their results indicated that neuronal noise may perform a constructive role for the temporal motion of the chimera states. In another example, the authors in [5] studied the chimera-like states in a neuronal network model of the cat brain. The authors clearly observed that a small level of neuronal noise had no significant effect on the chimera-like states but that strong neuronal noise was able to suppress neuronal chimeras via desynchronization. Further simulations also revealed that the bursting chimera-like state is more robust to noise than the spiking chimera-like state.

Note that although the first observation of coexisting coherence and incoherence patterns was discovered in non-locally coupled phase oscillators, such chimera states may appear in neuronal networks with different structures. As M. Perc et al. mentioned in this literature review [10], chimera states have been commonly observed in neuronal networks with local, nonlocal and global topologies. In addition, chimera states have also been found to be able to emerge in multilayer neuronal networks [14]. Overall, these findings provide computational evidence that neuronal chimeras are a generalized brain state and may be observed in different brain regions, as their emergence does not highly rely on the network structures.

To deepen our understanding of the underlying mechanisms of chimeras in the brain, we must be cognizant that there are still several challenges that need to be solved urgently. First, the current computational models of neuronal chimera states are too simplified and highly idealized. Several important intrinsic biological factors, such as synaptic plasticity and neuronal excitability [1], are not considered in these models. An increasing number of studies have confirmed that these biological factors are critical for triggering and modulating both synchronous and asynchronous oscillations in neural systems [17]. However, whether these intrinsic factors also take part in the emergence and regulation of neuronal chimera states remains unknown and is a question that can be tested in future modeling studies. Second, the current modeling studies mainly considered chimera states in neuronal networks with spiking dynamics [3–5,11–14]. Such models are often used to simulate the population dynamics of neurons from a local brain region. Examining whether chimera states can be observed at different spatiotemporal scales remains a challenge. Third, in addition to chimera states, our brain can also generate other self-organized neuronal activity, such as neuronal avalanches, irregular firing and stochastic oscillations [2]. Recent studies have shown that the coexistence of some of these different behaviors can ensure the high-efficiency information processing of the brain [18]. A comprehensive theoretical framework that incorporates these brain states together will surely be rewarding in future modeling studies. Finally and most importantly, the current studies on chimera states are mainly based on computational models. To date, there are only a few pieces of experimental evidence supporting the existence of this specific self-organized collective neural activity in the brain [7,8]. Further experimental verifications are needed using electrophysiological data recorded at different spatiotemporal scales.

In summary, computational modeling provides an effective approach to investigate the mechanisms of chimera states. The literature review contributed by M. Perc et al. systematically integrates the current modeling results on neuronal chimeras and, for the first time, establishes a theoretical basis of chimera states in the brain [11]. Nevertheless, further investigations with both realistic computational models and well-designed experiments are required to explore more detailed neural mechanisms of chimera states in future studies.

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References

- [1] Kandel ER, Schwartz JH, Jessell TM, Siegelbaum SA, Hudspeth AJ. *Principles of neural science*. McGraw-Hill Press; 2012.

- [2] Wu SD, Zhang YS, Cui Y, Li H, Wang JK, et al. Heterogeneity of synaptic input connectivity regulates spike-based neuronal avalanches. *Neural Netw* 2019;110:91–103.
- [3] Omelchenko I, Provata A, Hizanidis J, Schöll E, Hövel P. Robustness of chimera states for coupled FitzHugh–Nagumo oscillators. *Phys Rev E* 2015;91:022917.
- [4] Hizanidis J, Kouvaris NE, Zamora-López G, Díaz-Guilera A, Antonopoulos CG. Chimera-like states in modular neural networks. *Sci Rep* 2016;6:19845.
- [5] Santos M, Szezech J, Borges F, Iarosc K, Caldas I, Batista A, et al. Chimera-like states in a neuronal network model of the cat brain. *Chaos Solitons Fractals* 2017;101:86–91.
- [6] Kuramoto Y, Battogtokh D. Coexistence of coherence and incoherence in nonlocally coupled phase oscillators. *Nonlinear Phenom Complex Syst* 2002;5(4):380.
- [7] Rattenborg NC, Amlaner C, Lima S. Behavioral, neurophysiological and evolutionary perspectives on unihemispheric sleep. *Neurosci Biobehav Rev* 2000;24:817–42.
- [8] Mukhametov L, Supin A, Polyakova I. Interhemispheric asymmetry of the electroencephalographic sleep patterns in dolphins links open overlay panel. *Brain Res* 1977;134:581.
- [9] Uhlhaas PJ, Singer W. Neural synchrony in brain disorders: relevance for cognitive dysfunctions and pathophysiology. *Neuron* 2006;52:155–68.
- [10] Majhi S, Bera BK, Ghosh D, Perc M. Chimera states in neuronal networks: a review. *Phys Life Rev* 2019;28:100–21. <https://doi.org/10.1016/j.plrev.2018.09.003> [in this issue].
- [11] Bera BK, Ghosh D, Lakshmanan M. Chimera states in bursting neurons. *Phys Rev E* 2016;93:012205.
- [12] Zakharova A, Semenova N, Anishchenko V, Schöll E. Time-delayed feedback control of coherence resonance chimeras. *Chaos* 2017;27:114320.
- [13] Bera BK, Ghosh D. Chimera states in purely local delay-coupled oscillators. *Phys Rev E* 2016;93:052223.
- [14] Majhi S, Perc M, Ghosh D. Chimera states in a multilayer network of coupled and uncoupled neurons. *Chaos* 2017;27:073109.
- [15] Guo DQ, Perc M, Liu TJ, Yao DZ. Functional importance of noise in neuronal information processing. *Europhys Lett* 2018;124:50001.
- [16] Semenova N, Zakharova A, Anishchenko V, Schöll E. Coherence-resonance chimeras in a network of excitable elements. *Phys Rev Lett* 2016;117:014102.
- [17] Nowotny T, Zhigulin VP, Selverston AI, Abarbanel HDI, Rabinovich MI. Enhancement of synchronization in a hybrid neural circuit by spike-timing dependent plasticity. *J Neurosci* 2003;23:9776–85.
- [18] Yang DP, Zhou HJ, Zhou CS. Co-emergence of multi-scale cortical activities of irregular firing, oscillations and avalanches achieves cost-efficient information capacity. *PLoS Comput Biol* 2017;13:e1005384.