



## Comment

# Intriguing coexistence of synchrony and asynchrony in the brain

## Comment on “Chimera states in neuronal networks: A review” by Soumen Majhi, Bidesh K. Bera, Dibakar Ghosh, Matjaž Perc

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The collective behavior in networks is of great current interest with a plethora of applications in nature and technology [1]. For a long period complete and cluster synchronization in networks have been intensively studied, and a special attention has recently been paid to *chimera states* where incoherent and coherent oscillations occur in spatially coexisting domains. Especially surprising was the first observation of this symmetry-breaking behavior for identical elements and symmetric coupling configurations [2,3].

One of the most promising applications of chimera states is the study of complex partially synchronized patterns in neural networks. Synchronization and desynchronization of neural activity is essential for understanding the functionality of a healthy brain as well as neurological disorders, such as epileptic seizures [4–6] and Parkinson’s disease [7]. The synchronization patterns of neural activity depend on two main factors: the structural connectivity, and the type of individual neuron dynamics. Moreover, numerous parameters such as signal transmission delays, random fluctuations, strength of the interactions, inhomogeneities, are relevant for explaining the synchronization alterations. For instance, during an epileptic seizure the electrical activity in the brain is excessive and synchronous, and studying chimera states can provide further insight into the underlying mechanisms of the initiation or termination of epileptic seizures. In the Parkinson’s disease, the synchronization of neural activity is also treated as pathological, and, therefore, predicting synchronization as well as finding new mechanisms of its control are promising.

Before the invention of chimera states, the partial synchronization of the neural activity was addressed as *bump states* [8]. Since 2002, the scientific community has been paying a lot of attention to the phenomenon of chimera states, going far beyond the simple phase oscillator networks. The first review article on chimera states by Mark J. Panaggio and Daniel M. Abrams appeared in 2015 [9], followed by the review by Eckehard Schöll in 2016 [10]. Analytical study of chimera states appeared to be a challenging issue and current achievements on the mathematics behind chimeras are summarized in the review by Oleh Omel’chenko [11]. A recent article by Anna Zakharova and Eckehard Schöll accessible to a broad audience discusses the aspect of control and the importance of chimeras for the study of brain networks [12].

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In their article “Chimera states in neuronal networks: A review” [13], the authors Soumen Majhi, Bidesh K. Bera, Dibakar Ghosh, and Matjaž Perc, provide a deep and timely review on the current studies of chimera states focusing on neuronal networks. The authors themselves have substantially contributed to this topical research direction. Having introduced the mostly used dynamical systems describing individual neuron dynamics, the authors discuss in detail two types of neuronal synaptic communication. In the topological aspect of neuronal networks, the interactions through electrical and chemical synapses are defined via different coupling functions between the neurons. It is important to note that recently, multilayer networks have been shown to provide a better representation of the dynamics and structure of neural networks [14]. Chimera states have been studied for multilayer topologies [15–17] and allow to model the two types of neuronal interactions as intra- or inter-layer connections.

The present review includes an impressive bibliography of over 100 references, although some of the important works have been unfortunately left without attention. For example, those discussing the analogy between chimeras and epileptic seizures [4,18]. In our opinion, it would be helpful to summarize the extensive material presented in the review in the form of tables as it has been done in [9,11].

In the studies of chimera states in complex networks, mainly numerical exploration of the patterns observed is provided. Thus, the measures and criteria used to distinguish chimera states from other complex patterns are crucial. The authors of the present review introduce the standard measures such as mean phase velocities, local order parameter, and strength of incoherence. We would like to point out that one should also take into account the complexity of the realistic neural networks, where the spatial order between the nodes is not defined. Moreover, coherent and incoherent domains of chimera patterns can often be moving in space [19]. Thus, adjusting the existing measures and developing new qualitative characteristics remain important open questions.

In the neuronal systems, the propagation of signals can often be characterized by time delays. In the context of chimera states, time delays in the dynamical equations can dramatically influence the chimera patterns [20–22]. It was shown recently, that time delay can induce or suppress chimera states, as well as provoke their motion in space [19].

In the final part of their review, the authors provide a list of possible directions of the further research on chimera states in neuronal networks, naming very interesting and promising problems. In some of them, there is indeed a significant progress in very recent studies. For instance, in the context of the networks with temporal synaptic connections, chimera states have been observed recently in dynamical networks with adaptive couplings [23] and, in particular, in adaptive networks of pulse-coupled oscillators [24].

Further, in the context of neural diseases treatment and surgery, the aspects of controlling chimera states have recently received growing interest and should be mentioned here. It was demonstrated, that there are direct analogies between epileptic seizures and collapses of chimera states [18]. At the same time, recent studies show possible ways to control lifetime of chimera states and avoid their collapses [25], it is also possible to control both lifetime and spatial position of coherent and incoherent domains of chimera states using tweezer control [26,27], which can be successfully extended to multilayer networks [28].

In conclusion, the present article provides a deep and timely review on the state-of-the-art research on chimera states in neuronal networks and discusses promising directions of future studies in the field. We think that this review is not only of great interest to specialists working on chimeras. It also provides a valuable resource for other scientists working, for example, on neural networks or synchronization and newcomers to the field.

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## References

- [1] Boccaletti S, Pisarchik AN, del Genio CI, Amann A. *Synchronization: from coupled systems to complex networks*. Cambridge: Cambridge University Press; 2018.
- [2] Kuramoto Y, Battogtokh D. Coexistence of coherence and incoherence in nonlocally coupled phase oscillators. *Nonlinear Phenom Complex Syst* 2002;5(4):380–5.
- [3] Abrams DM, Strogatz SH. Chimera states for coupled oscillators. *Phys Rev Lett* 2004;93(17):174102.
- [4] Rothkegel A, Lehnertz K. Irregular macroscopic dynamics due to chimera states in small-world networks of pulse-coupled oscillators. *New J Phys* 2014;16:055006.
- [5] Jiruska P, de Curtis M, Jefferys JGR, Schevon CA, Schiff SJ, Schindler K. Synchronization and desynchronization in epilepsy: controversies and hypotheses. *J Physiol* 2013;591(4):787–97.
- [6] Jirsa VK, Stacey WC, Quilichini PP, Ivanov AI, Bernard C. On the nature of seizure dynamics. *Brain* 2014;137:2210.
- [7] Popovych O, Hauptmann C, Tass P. Control of neuronal synchrony by nonlinear delayed feedback. *Biol Cybern* 2006;95(1):69–85.

- [8] Sakaguchi H. Instability of synchronized motion in nonlocally coupled neural oscillators. *Phys Rev E* 2006;73(3):031907.
- [9] Panaggio MJ, Abrams DM. Chimera states: coexistence of coherence and incoherence in networks of coupled oscillators. *Nonlinearity* 2015;28:R67.
- [10] Schöll E. Synchronization patterns and chimera states in complex networks: interplay of topology and dynamics. *Eur Phys J Spec Top* 2016;225:891–919.
- [11] Omel'chenko OE. The mathematics behind chimera states. *Nonlinearity* 2018;31(5):R121.
- [12] Schöll E, Zakharova A. Chasing chimeras: control of complex networks. *Res Features* 2018;123:34–7.
- [13] 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].
- [14] De Domenico M. Multilayer modeling and analysis of human brain networks. *Gigascience* 2017;6(5):1–8.
- [15] Ghosh S, Jalan S. Emergence of chimera in multiplex network. *Int J Bifurc Chaos* 2016;26(07):1650120.
- [16] Majhi S, Perc M, Ghosh D. Chimera states in a multilayer network of coupled and uncoupled neurons. *Chaos* 2017;27:073109.
- [17] Mikhaylenko M, Ramlow L, Jalan S, Zakharova A. Weak multiplexing in neural networks: switching between chimera and solitary states. *Chaos* 2019;29:023122.
- [18] Andrzejak RG, Rummel C, Mormann F, Schindler K. All together now: analogies between chimera state collapses and epileptic seizures. *Sci Rep* 2016;6:23000.
- [19] Sawicki J, Omelchenko I, Zakharova A, Schöll E. Delay controls chimera relay synchronization in multiplex networks. *Phys Rev E* 2018;98:062224.
- [20] Gjurchinovski A, Schöll E, Zakharova A. Control of amplitude chimeras by time delay in dynamical networks. *Phys Rev E* 2017;95(4):042218.
- [21] Sawicki J, Omelchenko I, Zakharova A, Schöll E. Chimera states in complex networks: interplay of fractal topology and delay. *Eur Phys J Spec Top* 2017;226(9):1883–92.
- [22] Sawicki J, Omelchenko I, Zakharova A, Schöll E. Synchronization scenarios of chimeras in multiplex networks. *Eur Phys J Spec Top* 2018;227:1161.
- [23] Kasatkin DV, Yanchuk S, Schöll E, Nekorkin VI. Self-organized emergence of multi-layer structure and chimera states in dynamical networks with adaptive couplings. *Phys Rev E* 2017;96(6):062211.
- [24] Kasatkin DV, Klinshov V, Nekorkin VI. Itinerant chimeras in an adaptive network of pulse-coupled oscillators. *Phys Rev E* 2019;99:022203.
- [25] Sieber J, Omel'chenko OE, Wolfrum M. Controlling unstable chaos: stabilizing chimera states by feedback. *Phys Rev Lett* 2014;112:054102.
- [26] Omelchenko I, Omel'chenko OE, Zakharova A, Wolfrum M, Schöll E. Tweezers for chimeras in small networks. *Phys Rev Lett* 2016;116:114101.
- [27] Omelchenko I, Omel'chenko OE, Zakharova A, Schöll E. Optimal design of tweezer control for chimera states. *Phys Rev E* 2018;97:012216.
- [28] Omelchenko I, Hülser T, Zakharova A, Schöll E. Control of chimera states in multilayer networks. *Front. Appl. Math. Stat.* 2019;4:67.