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Comment

From theory to experimental evidence
Comment on “Chimera states in neuronal networks: A review” by S. Majhi, B.K. Bera, D. Ghosh and M. Perc

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Since the early 2000s, when *chimera state* has been firstly discovered by Kuramoto and Battogtokh in their pioneer work [1], this nonlinear phenomenon continues to arouse interest of scientific community. Despite the fact, that network models considered in numerous theoretical studies of chimera states represent simplified versions of real living systems, they surprisingly exhibit various types of unobvious emergent behavior [2]. Lately, much attention is payed to the analysis of more realistic models with complexly organized structure and different types of possible links between the elements [3–7]. In this sense, human brain represents “a very challenging complex system where neurons [...] form possibly the most complicated structure” as Majhi and colleagues expertly stated at the beginning of their review [8]. Indeed, self-organization, synchronization and chimera state as a particular case of pattern formation are inherent in normal brain functioning since these processes provide the mechanisms for neural communication and cognitive activity. In this context, the present article is extremely relevant. The Authors provide a comprehensive review on recent advances in theoretical analysis and state-of-the-art problems of chimera pattern formation with emphasis on neuronal networks. The paper is easy to follow and we have been pleased to learn that the Authors payed a special attention to biological background of the reviewed models.

However, one of the important problems of this field is a lack of focused experimental studies of the chimera states in neurobiological systems. This is due to the complexity of neural systems on the one hand and the non-triviality of their control schemes on the other hand. Further, we are going to propose a few possible directions for experimental investigation of chimera patterns in biological systems.

Recent advances in neurophysiological techniques for studying and control of single neuron behavior provide necessary tools for fundamental research in the area of self-organization of neural systems. In particular, the approach based on optogenetic neural stimulation and closed-loop control demonstrated by Pashaie et al. [9] might be extremely helpful in this context. Using electrode array one may drive the dynamics in a whole neural population recreating interaction mechanisms from theoretical works. This technique opens a way for the development of methods for either generation or suppression of locally coherent patterns with given properties in brain neural network. Besides

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pure fundamental prospects, such direction of research have a clear practical application in the field of neural disease therapy and brain functioning improvement.

Another interesting research topic, in our opinion, is searching for the chimera patterns in normal human brain activity. This kind of behavior may not be as pronounced as pathological brain activity, but it reflects more fundamental aspects of brain dynamics. According to *coordination dynamics* theory [10,11] human cognitive functioning is associated with activation of neural groups of brain cortex, wherein the manner of interdependence among them switches in real-time due to performed task. This theory is closely related with concepts of multi- and metastability originated from nonlinear dynamics [12]. Generation of such self-organized dynamical patterns in cortical network may be refereed to as chimera-like states. Recent experimental studies on perception of ambiguous visual stimuli show the multistability of cognitive brain activity in visual cortex, which manifests as emergence of different coherent patterns depending on image interpretation [13,14]. These findings could be considered as a starting point for a detailed experimental study of chimera-like behavior in normal brain activity.

Finally, we suggest that chimera-like patterns may be observed in experimental realization of theoretical concept of *network of networks* [15] as a mental interaction in a group of people. In recent work [6], the network of networks topology has been proved to promote chimera behavior. The mechanism of brain dynamics control through mental interaction in a pair of participants via brain-to-brain interface (BBI) during the performance of common cognitive task has been proposed in [16]. When sharing cognitive load, brain dynamics of both participants self-organizes into either anti-phase synchronization (optimal interaction) or desynchronization (non-optimal interaction) due to proper choice of coupling delay. Expanding this concept to a group of people one may expect to observe the emergence of various regimes of collective brain behavior, i.e. collective decision-making, including chimera-like patterns. It is remarkable that, in this case one may achieve chimera behavior on the different levels of such living network of networks: (i) on the macroscopic level, represented by group interactions; (ii) on the microscopic level manifested as neural interactions within a brain network of each participant.

To conclude, we consider that the problems reviewed by Majhi et al. are significant for multidisciplinary field of science and relevant for a wide audience including specialists from physics, network theory, biology and neuroscience. It has a potential to inspire future research in the area of theoretical and experimental studies of the chimera states in living systems. We strongly support the materials and the way they are presented in the Review paper. The Authors have accounted broad range of theoretical findings concerning chimera states in neural network, but they have payed sufficiently less attention to discussion of possibilities of chimera behavior experimental evidence. We believe that our brief comments partially make up this lack and complement the main Review paper.

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