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Special Issue Preface: Complex Systems in Neurobiology

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The last couple of decades have seen a phenomenal level of interest and growth in the study of the human brain. While developments in neuroimaging have provided important insight into macroscopic function of neural ensembles, sophisticated recording techniques at the single neuron level have enabled significant progress at the cellular and molecular levels. However, in the absence of unifying theories of how micro- and macro-structures come together, these two levels remain more disparate than ever.

The purpose of this special issue is to bring the macro and micro pictures together by bringing short and long time-scale activities of the nervous system into a unified framework. The sciences of complexity provide a unique foundation that facilitates this enterprise. By studying stochasticity (noise and variability) at all levels of neural and behavioral organization, we are now able to provide a unique theoretical insight that has otherwise obscured scientists for several decades. It is now possible to connect the high-dimensional activity of elements that make up the neural structure with the low-dimensional nature of behavior as such.

This special issue titled "Complex Systems in Neurobiology" consists of five chapters that are essentially critical reviews of the literature in domains that we consider to be of fundamental interest to individuals studying these problems in the neurobiological sciences, from multiple perspectives.

The first paper in this volume is an introduction to the special issue by Balasubramaniam and Torre that provides an overview of the challenges facing the field of complex systems in neurobiology. In particular, they make the case for the systematic study of noise in steady state and behavioral transitions in neurobiological systems. They present examples from human bimanual coordination, motor learning in intermittent control tasks, and the origin of individual differences. Through these illustrative examples, they demonstrate how noise is adaptively utilized by the nervous system. Further, they make recommendations regarding how one might study complexity by simultaneously focusing on multiple spatial and temporal time scales. Finally, they make the case for the study of functional brain networks by treating cognitive functions as emergent, metastable patterns of coordination between the levels of brain, behavior, and environment.

The second article in this volume is by Kelty-Stephen and Dixon. In this philosophically oriented essay, they make a case for a non-reductionistic approach to neurobiology using physics. There are common misconceptions that complexity science, by taking a relentlessly "physicalist" view, runs the risk of. However, these authors address those misconceptions directly and offer a framework for studying complex systems without reducing the integrity of the phenomena in neurobiology and cognition. Using examples from their recent work on the development of cognitive structure modeled using turbulence and fractal fluctuations, the authors provide a unique approach to studying complexity in neurobiology.

The third paper by Delignières and Marmelat reviews work from their laboratory that has shown long-range correlations in a wide variety of phenomena. In this review, they showcase their take on the state of the theoretical debate about the origins of $1/f$ fluctuations. Particularly novel in this review is a very important attempt to establish a direct link between complexity and fractal fluctuations. This is followed by an important discussion on how their approach has generated important solutions to questions in the realm of human motor control and timing. The work also provides a comprehensive summary of the treatment of fluctuations and noise in models of human sensorimotor timing. Important applications are also discussed in the context of physical medicine and rehabilitation using complexity based approaches.

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Kello, Rodny, Warlaumont, and Noelle provide the fourth paper in this volume. In this paper, they explore the reasons for the emergence of complexity in neuronal spike trains and the propagation of spike activity. In particular, they focus on the relationship between neural plasticity and spike dynamics in the nervous system. The authors conclude that complex spike dynamics are not a hindrance to neural function. On the contrary, they make a case for how complex dynamics are adaptive byproducts of synaptic plasticity when expressed as scaling laws. Examples from critical branching, reinforcement learning and generalization, and selectionist learning via reinforcement are presented to illustrate a wide variety of spike dynamics phenomena.

The final paper in this volume by Newell and Liu is on landscape dynamics in motor learning and development. In this review, they present ideas on how, by borrowing concepts from complex systems theories, motor learning and development can each be conceived and subsequently evaluated as the continuous evolution of movement patterns and outcomes over multiple time scales. The review presents an elegant summary of how a high (or infinite)-dimensional complex system can be projected onto an epigenetic landscape of a few functions. This landscape and the dynamics on it can account for a wide variety of phenomena, including movement degeneracy and redundancy, influence of multiple time-scale processes, practice schedules and rest, etc. The review presents a refreshingly novel approach to motor learning that covers a range of studied phenomena from classic mirror drawing experiments done in the 1920s to the recent study of phase-transitions in a roller ball task.

Taken collectively, these articles represent what we believe to be key developments in the sciences of complexity as applied to problems in neurobiology. What brings these articles together is an underlying commitment to studying the links among various spatial and temporal scales of activity in neurobiology. The ultimate goal of each of these review articles is to contribute to a unified and integrated outlook regarding how a system that is high-dimensional at one level of organization and low-dimensional at the level of behavior can be studied without taking a privileged scale of analysis.

My earnest hope is that these articles will foster greater thinking among neurobiologists to study variability, noise, and fluctuations so they may apply the general principles of complexity to their own domains of research.

I would like to thank Kjerstin Torre (University of Montpellier) for her help in designing this issue and synthesizing this volume as a co-editor. Special thanks to all the contributors, who met impossible deadlines: Damian Kelty-Stephen (Harvard), James Dixon (University of Connecticut); Didier Delignières and Vivien Marmelat (University of Montpellier); Christopher Kello, Jeffrey Rodney, Anne Warlaumont and David Noelle (University of California, Merced); Karl Newell (Pennsylvania State University), Yeou-Teh Liu (National Taiwan University).

My students Tanner Mackenzie and Sebastian Witek deserve a special note of appreciation for their help, especially with illustrations and various aspects of putting together this special guest-edited issue. Several anonymous reviewers participated in reviewing the work published here. I am indebted to all of them.

Much of my own thinking on noise, complexity, and metastability has been profoundly influenced by Dr. Guy Van Orden, a pioneer in this field, who regretfully passed away earlier this year at a relatively young age and at the top of his creative powers. His insight and original thinking with clever design of many experiments have led the way to understanding the complexity of many cognitive phenomena described in this issue. His generosity and kindness have helped the careers of many of my colleagues in various parts of the world. I would like to dedicate this issue to his memory and scientific legacy.