Journal of Multiscale Neuroscience

Brief Report

On multiscale analyses of neural processing, motor movement, and cognition

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Abstract

This brief report provides an overview of the Special Issue on *The Mind and The Brain: A Multiscale Interpretation of Cognitive Brain Functionality*. It serves as a concise guide for the initial motivation for the special issue and for how best to read the articles inside it and identify their connections. This special issue combines experts from the philosophy of complex systems, ecological perception, embodied cognition, dynamical systems theory and comparative cognition to enable a widened perspective on cognition that is both multiscale and multidimensional. By looking at the mutual overlap between perception, action, and cognition, and the multiscale methods that allow novel insights into the interactive processes that underly them, this special issue provides a unique assemblage of methods, findings, and theoretical advances. The reader should expect to come out of it with a slightly different understanding of what cognition is made of.

Keywords: Multiscale Systems, Nonlinear Dynamics, Time Series, Neural Networks, Cognition, Perception

Introduction

Neuroscience spans a much wider range of spatiotemporal scales than all other fields related to the cognitive and neural sciences (Sejnowski et al., 2014). For example, philosophy of mind tends to focus at the spatial scale of a single nervous system (though some philosophers study group and swarm intelligence; Theiner, 2018). Cognitive psychology tends to focus at the spatial scales of brains and cortical regions (though some psychologists have studied transactive memory; Wegner, 1987). By contrast, neuroscience research spans a vast range from the nanoscopic scale of neurotransmitter molecules (Poznanski et al., 2022a) to the microscopic scale of neurons (Hubel & Weisel, 1959) to the mesoscopic scale of groups of neurons coordinating their activity (Freeman, 2000) to the macroscopic scale of entire brains (Ramirez-Aristizabal & Kello, 2022) and even further to coordinated activity among two brains (Kuhlen et al., 2012). As a result of this extremely wide range of spatial scales and temporal scales, all of which overlap and interact, it seems clear that neuroscientists could benefit from adopting a multiscale approach to their theories and their methods.

When examining a phenomenon at one particular spatiotemporal scale, one must always keep in mind that the measures being used necessarily perform a coarse-grain filtering of the many underlying micro-phenomena from which it is composed (Spivey, 2018; Spivey et al., 2009). For example, a cognitive neuroscientist examining a single voxel of neuroimaging data may find it far too fine-grained of an analysis for their purposes. But with many thousands of neurons inside that one voxel, an electrophysiologist who records electrical activity from individual neurons might see that one voxel as far too coarse-grained of an of analysis. Likewise, a molecular neuroscientist who studies the action of ion pumps in a cell membrane might find the action potentials recorded by the electrophysiologist to be too coarse-grained a method as well. The challenge is in getting these different subdisciplines to share their findings with one another in a commensurable fashion (Sejnowski et al., 2014).

There was a time when many neuroscience-minded cognitive scientists focused on one particular scale of analysis, treating action potentials almost as if they were the only significant medium of information transmission in a neural system (Churchland & Sejnowski, 1992). This perspective led to the field of artificial neural networks focusing almost exclusively on spikes and mean firing rates as their sole medium of communication between nodes in a network (Anderson, 1995). This despite the fact that a wide variety of additional mechanisms of information transmission are known to exist alongside action potentials. For example, graded potentials involve a milder depolarization, lasting over a longer period of time than action potentials, that also contribute to sensory and cognitive computations (Poznanski & Bell, 2000; Roberts & Bush, 1981). The electric fields emitted by neurons cannot help but influence neighboring neurons (e.g., ephaptic as opposed to synaptic transmission) and may themselves transmit coherent patterns of information between neurons (Kamermans & Fahrefort, 2004; Poznanski et al., 2022b). A flood of neurotransmitters and hormones can wash over a neural network and substantially reconfigure its entire connectivity pattern (Harris-Warrick & Marder, 1991). Glial cells do more than just provide infrastructure and insulation for spiking neurons; they also transmit metabolic informational signals of their own (Nampoothiri et al., 2022). And animals without a cortex (Güntürkün & Bugnyar, 2016) or even without a centralized nervous system (Turvey & Carello, 2012) are nonetheless capable of foraging, nesting, predation, and even tool-use and puzzle-solving (Richter et al., 2016).

Moving beyond the nervous system itself, we can see a further panoply of mechanisms for information transmission that are at work in perception and action, separate from the use of electrochemical signals. For instance, the connective tissue between muscles in the body appears to transmit information in its own way. The myofascia does more than simply hold those muscles in place, it can transmit force information across body tissues almost instantaneously simply by the propagation of its tissue deformation. Thus, when a limb is undergoing some physical perturbation in a particular region, mechanoreceptors *all over that limb* will experience that tissue deformation and thus send their electrochemical signals, thereby transmitting a complex and nuanced distributed pattern of information to the spinal cord (Huijing, 2009; Turvey & Carello, 2011). In plants, a distributed network of hormones allows them to exhibit gravitropism, heliotropism, chemotropism, and even carnivorism (Chamovitz, 2012). A slime mold can use its cytoskeletal network of proteins to carry out chemotaxis and even solve a maze (Mayne et al., 2015). Individual bacteria forage intelligently and a colony of them can engage in quorum sensing and exhibit bacterial sociality (Whiteley et al., 2017). Even nonbiological systems can exhibit self-organization, coordination, and self-preservation behavior under magnetic fields (Snezhko & Aranson, 2011) and electrical fields (Davis et al., 2016). In fact, Darwinian natural selection itself may be merely a biological subcomponent of a larger evolutionary process whereby physical systems of all kinds evolve toward self-organized metastable processes that generate more overall entropy when organized than when not, a kind of fourth law of thermodynamics (Swenson, 2010, 2020).

These neural and non-neural displays of intelligence extend from the minimally-cognitive (e.g., homeostasis and self-repair) to the moderately-cognitive (e.g., complex motor actions) to maximally-cognitive (e.g., music and language). All this is to say that there are more ways to transmit complex adaptive information patterns (i.e., produce cognition) than are dreamt of in your traditional neuroscience. When cognitive scientists let go of their singular fixation on the action potential as the primary implementation of cognitive information transmission, they can see that it is merely one level of analysis in a deeply nested hierarchy of methods of transmission at many different spatial and temporal scales from which various forms of cognition can emerge. Perhaps when information is transmitted in an adaptive feedback loop via *any* physical process (biotic or abiotic), that recurrence itself may be sufficient to identify the system as "living," and in some cases at least minimally-cognitive (Churchland, 1995; Beer, 2020; Turvey & Carello, 2012; Spivey 2020). Drawing on this insight, Levin (2022) has proposed a continuum of agency that is testable as an "axis of persuadability" for any system.

In this special issue of the *Journal of Multiscale Neuroscience*, we have six peer-reviewed articles that span this range of minimally-cognitive to moderately-cognitive to maximally-cognitive and all find novel insights resulting from the use of multiscale analyses. Whether from a philosophical perspective of nested causal relations and causal loops, or a kinematic perspective on distributed sources of visual information regarding postural body movements, or a neural perspective on the multi-layered structure of music perception, or an artificial neural network perspective on the temporal dynamics of language comprehension, or a comparative cognition perspective on intelligence emerging among neurons, among people, and among insect swarms, what these articles have in common is a view of multiscale distributed relations between sub-elements that allow a "whole" to exhibit coherent cognitive behavior.

The reader is, of course, welcome to peruse these papers in any order they prefer, but my recommended playlist is the following. Starting with Favela (2023) promotes a brand of multiscale analysis called *nested dynamical modeling* (for nested network modeling, see also Poznanski & Riera, 2006). By ensuring that equations used for one level of analysis include some parameters that are also used in the neighboring levels of analysis (above and below), Favela (2023) encourages the field to strive for a responsible pluralism among theories that apply to different spatiotemporal scales, and yet they keep in touch enough to avoid becoming incompatible with one another (see also, Contreras et al., 2022; Dale & Spivey, 2005; Spivey, 2023).

After Favela (2023) has shown how nested dynamic modeling is a key *mathematical* framework that helps explain multiscale dynamics of cognition, Silberstein (2023) shows the reader how contextual emergence is a key *theoretical* framework that helps explain the multiscale dynamics of cognition. Contextual emergence offers an account of how self-organized coherent cognitive structures arise among the nonlinear recurrent interactions of the many sub-elements that make up any complex system that is exhibiting cognition (see also, Atmanspacher & beim Graben, 2009; Bishop & Atmanspacher, 2006). Rather than defining emergent properties as non-decomposable and thus preventing any form of reductionism (Chalmers, 2006) or imbuing them with the power to exert downward causation in a fashion that robustly violates causality (Andersen et al., 2000), contextual emergence treats emergent properties as resulting from both bottom-up and top-down contextual constraints whose nonlinear causal influences (which are not always easily labeled) loop back on one another over time. Stability conditions thus arise at a higher level of analysis that can provide constraints on activity at the lower level of analysis, thereby making a purely bottom-up account untenable. In the contextual emergence framework, a linear mechanistic form of reductive analysis will fail to elucidate an emergent property like cognition, however, a form of analysis that allows for multiscale constraints to have mutual influences on one another has promise for decomposing an emergent property into its constituent nonlinear interactive and recurrent *processes*, if not its constituent *parts* (Bickhard, 2009; Falandays, 2021; Kallfelz, 2006).

Corbin et al. (2023) report a clear example of this kind of rich contextual information (which is not always easily labeled) in the motion capture data of sit-to-stand actions, where upcoming intended arm actions are detectable in the postural movements that precede the initiation of those arm actions. By applying principal components analysis (PCA) to the time series of data from 7 motion capture markers, Corbin et al. (2023) were able to identify the regions of the body that were most diagnostic of sit-to-stand movements that would be followed by upward or downward reaches of the arm. Then, they tracked human observers' eye movements while they watched those point-light displays of various sit-to-stand movements, and sure enough, an observer's gaze generally tends to go toward the same regions of the body that the PCA indicated were most diagnostic of the different upcoming reach movements. Thus, hidden in the high-dimensional pattern of many joint movements over time is a lower-dimensional manifold that carries information about upcoming movement intentions, and human observers are visually attuned to that manifold.

Stepping up from moderately-cognitive activities like sit-to-stand movements, Waddington & Balasubramaniam (2023) take a multiscale perspective on music perception and production. They provide insight into scale-free power laws that are often present in the structure of music itself and then also emerge in the activity of the body and brain during the production and experiencing of music. By tracking the resonance and entrainment that musical sensory input induces in a human brain and body, using recurrence quantification analysis and Allan factor analysis on time series data from neuroimaging and motion-capture methods, Waddington & Balasubramaniam (2023) review the findings for how bodies and brains produce time series of activity that exhibit hierarchical temporal structure, long-range temporal correlations, and 1/f scaling just like the music does -both for moderately-cognitive activities like listening to music and maximally-cognitive activities like producing music.

Also using recurrence quantification analysis to identify both short-term and long-term temporal correlations, Nguyen & Spivey (2023) hunt for multiscale information patterns hidden inside the layered time series of activity of an artificial recurrent neural network undergoing external perturbations and then also inside the layered time series of activity of a human understanding spoken sentences that undergo temporary syntactic ambiguities (e.g., "garden path" sentences). Using a novel continuous meta-cognitive report of "ease-of-comprehension," they find that undisrupted spoken language comprehension exhibits smooth predictable multiscale recurrence loops in the embedded state space of the data stream – much like a smoothly functioning recurrent network does. However, a temporary disruption in syntactic processing, such as that induced by a "garden-path" sentence, triggers a reduction in that multiscale recurrence and an increase in entropy – much like that seen in a disrupted recurrent network. Based on results like this, Nguyen and Spivey (2023) recommend a theoretical approach to syntactic processing that draws on neural network simulations and trajectories through state space (Elman, 2009; Onnis & Spivey, 2012), rather than one that relies solely on abstract rules and symbols (Staub, 2015).

Many of these papers point to statistical signatures of self-organized emergence in the multiscale time series of cognition, perception and action. But nowhere is that self-organization more apparent than in the capstone article of this special issue, by Falandays et al. (2023). They document a dizzying array of collective processes that generate minimally-cognitive, moderately-cognitive and maximally-cognitive behaviors in multicellular organisms, colonies of insects, schools of fish, flocks of birds, human brains, groups of humans, and entire human societies. As a result of their analysis, it becomes clear that "collective intelligence" is not a *special case* of intelligence. Rather, all examples of naturally-occurring intelligence appear to emerge from the interaction of many sub-elements in a fashion just like collective intelligence. Thus, the nonlinear self-organization that is inherent to the popular examples of collective intelligence may be what underlies the processes involved in all known cases of intelligent behavior (including human intelligence) - and "individual unitary intelligence" would be the *special case*, if it exists at all.

After reading this playlist that samples widely across different multiscale perspectives on perception, cognition, and action, I hope the reader sees the processes that generate mental activity in a new light. For me, the insights include: 1) a sense of optimism for cohering different levels of analysis and accommodating their bi-directional influences, 2) a realization that the high-dimensional information patterns that mental activity emits have hidden inside them compact manifolds that can reveal the emergent multiscale structure of that intelligence, especially when the data stream is densely-sampled and analyzed with nonlinear time series analysis methods, and finally, 3) mental activity can be observed at an extremely wide range of spatiotemporal scales. If that does not change the way you think about what "a mind" can be, then I do not know what to tell you.

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