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Editorial

Model-based cognitive neuroscience

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HIGHLIGHTS

- Mathematical psychology and cognitive neuroscience come together in a powerful new approach called *model-based cognitive neuroscience*.
- This approach can both inform cognitive modeling and help to interpret neural measures.
- This article provides an introduction to the field of model-based cognitive neuroscience and to the articles contained within this special issue.

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ABSTRACT

This special issue explores the growing intersection between mathematical psychology and cognitive neuroscience. Mathematical psychology, and cognitive modeling more generally, has a rich history of formalizing and testing hypotheses about cognitive mechanisms within a mathematical and computational language, making exquisite predictions of how people perceive, learn, remember, and decide. Cognitive neuroscience aims to identify neural mechanisms associated with key aspects of cognition using techniques like neurophysiology, electrophysiology, and structural and functional brain imaging. These two come together in a powerful new approach called *model-based cognitive neuroscience*, which can both inform cognitive modeling and help to interpret neural measures. Cognitive models decompose complex behavior into representations and processes and these latent model states can be used to explain the modulation of brain states under different experimental conditions. Reciprocally, neural measures provide data that help constrain cognitive models and adjudicate between competing cognitive models that make similar predictions about behavior. As examples, brain measures are related to cognitive model parameters fitted to individual participant data, measures of brain dynamics are related to measures of model dynamics, model parameters are constrained by neural measures, model parameters or model states are used in statistical analyses of neural data, or neural and behavioral data are analyzed jointly within a hierarchical modeling framework. We provide an introduction to the field of model-based cognitive neuroscience and to the articles contained within this special issue.

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Exciting new synergies between mathematical psychology and cognitive neuroscience have emerged. This special issue of the *Journal of Mathematical Psychology* includes reviews, tutorials, and original research papers highlighting this new area of *model-based cognitive neuroscience*. In this opening article, we outline this new approach and introduce the articles contained in this special issue.

1. What is model-based cognitive neuroscience?

Alternative approaches to theory in both psychology and neuroscience often begin by considering Marr's (1982) classic three levels: The *computational level* considers the goals of the organism and the structure of the environment, without considering mechanism, typified by many Bayesian theories of the mind (e.g., Anderson, 1990; Oaksford & Chater, 2007; Tenenbaum, Kemp, Griffiths, & Goodman, 2011). The *algorithmic level* considers what representations and processes underlie cognition and perception, without considering their biological realization, typified by many mathematical and computational models of cognition and

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perception (e.g., Busemeyer, Wang, Townsend, & Eidels, 2015; Sun, 2008). The *implementation level* asks how mechanisms are physically realized within a biological substrate, namely neurons and their connections in the brain, typified by classical theoretical work in neuroscience (e.g., Carnevale & Hines, 2006; Dayan & Abbott, 2005).

While Marr envisioned connections between these levels, there often had been intellectual and disciplinary barriers to considering explanations that crossed levels. This led theorists to work traditionally within only one level of analysis. Not so long ago, a graduate student trained in mathematical psychology considering postdoctoral training in neuroscience might have been about as sensible as considering running off to join the circus. For some, the brain could well be made of tinker toys for its relevance to understanding human cognition. As well, not so long ago, few trained in systems neuroscience would ever consider whether insights from cognitive and mathematical psychology might inform understanding of neural function. Cognitive conceptual building blocks were often thought little more than folk psychology, with philosophical arguments lending support to a strict reductionist approach to understanding the brain (e.g., Churchland, 1986).[1]

Early attempts to address this impasse focused on connectionist models of cognition that took inspiration from the brain. Connectionists viewed the brain as consisting of simple computing units (akin to neurons) that integrated signals passed across connection weights that were adjusted by learning rules. However, these models rarely made contact with the implementational details of the brain. In most cases these models served as existence proofs that a model consisting of many simple computing elements could accomplish a task in roughly the same fashion as a human. Nevertheless, these models were attempts to bridge levels of analysis and were championed as more biologically plausible than competing models at the algorithmic or computational levels. Unfortunately, notions of biological plausibility were rarely defined nor evaluated rigorously. The gap between levels of analyses stubbornly remained.

Model-based cognitive neuroscience breaks the traditional barriers between models and the brain (e.g., Forstmann, Wagenmakers, Eichele, Brown, & Serences, 2011; Forstmann, 2015; Palmeri, Schall, Logan, & Townsend, 2015; Smith & Ratcliff, 2004). From the perspective of cognitive and mathematical psychology, formal models explain behavior in terms of representations and processes instantiated in mathematics and computations, and observed variation in behavior across experimental conditions and individuals is explained in terms of variation in model parameters and model states. Model-based cognitive neuroscience allows for consideration of whether these latent model parameters or model states might be related to, or constrained by, observed brain measures or brain states, over and above whether a model fits or predicts observed behavior. From the perspective of systems and cognitive neuroscience, a key component of understanding neurons, neural circuits, or brain areas is explaining the computations that they perform. In a model-based cognitive neuroscience approach, to the extent that brain measures or brain states are predicted by model parameters or model states, those models provide a potential explanation of brain function, regardless of whether or not those models are implemented in neuron-like elements.

The emergence and growth of model-based cognitive neuroscience over the past decade can be attributed to a number of converging forces. One was the recognition on the part of cognitive modelers and mathematical psychologists interested in understanding the mechanisms that brain data is simply additional data by which to constrain and contrast models. Response probabilities, response times, confidence ratings and the like are the outcomes of processing. Brain data reflect intermediary states. Considering how internal processes predicted by a model relate to internal processes measured in the brain can break theoretical stalemates caused by model mimicry. While two different models making different mechanistic assumptions about representations and processes may make similar predictions about observed behavior, they may well make different predictions about internal model states, which can then be compared with or constrained by measured brain states (e.g., Boucher, Palmeri, Logan, & Schall, 2007; Mack, Preston, & Love, 2013; Palmeri, 2014; Purcell et al., 2010; Purcell, Schall, Logan, & Palmeri, 2012).

Another force was the recognition on the part of cognitive and systems neuroscientists for the need for new approaches to making sense of the growing body of neural data from functional brain imaging, electrophysiology, neurophysiology, and other neuroscience techniques. Correlating brain measures with stimuli, conditions, and responses provides only a rather limited window on understanding brain function. To go beyond merely mapping out which brain areas or which neurons modulate their activity under which conditions means to explain and understand what mechanisms and computations are engaged within those brain areas or neurons. Algorithmic and computational models provide a language and a body of viable hypotheses, as well as a set of tools, for explaining and understanding those neural mechanisms and computations.

Recognition has grown for considering the algorithms and computations that underlie neural processing. Carandini (2012) characterized any direct link between neural circuits and behavior as a "bridge too far", and argued that it was necessary to theorize at an intermediate level in Marr's hierarchy, considering the algorithms and computations that neural circuits perform. The purely bottom-up approach to understanding the brain that characterized the initial stages of the billion Euro Human Brain Project was widely criticized by cognitive and computational neuroscientists and led to a shake-up of its leadership and vision (e.g., Enserink & Kupferschmidt, 2014; Theil, 2015). Rather than adopting a strictly bottom-up (or top-down) approach, model-based cognitive neuroscience can be characterized as an inside-out approach (Love, 2015), that may well be a level of theorizing that is just right (Logan, Yamaguchi, Schall, & Palmeri, 2015).

Perhaps the most potent force propelling model-based cognitive neuroscience over the past decade has been its demonstrated success in providing new insight at both the cognitive and neural levels. One especially salient body of work has centered around accumulator models of decision making, a well-known class of models with a long history in cognitive psychology (e.g., Ratcliff & Smith, 2004). These models assume that variability in choice probability and response times arise from variability in the, often noisy, accumulation of evidence to response thresholds, and variants of these models have accounted for decisions in perception, memory, categorization, and other tasks (e.g., Bogacz, Brown, Moehlis, Holmes, & Cohen, 2006; Brown & Heathcote, 2008; Forstmann, Ratcliff, & Wagenmakers, 2016; Nosofsky & Palmeri, 1997; Palmeri, 1997). As one of the first examples of systems neuroscience making contact with cognitive modeling, when Hanes and Schall (1996) were interested in understanding how neurons in Frontal Eye Field (FEF) decide where and when to saccade in the visual field, they turned to the cognitive modeling literature for inspiration and insight. Based on the fact that the dynamics of certain FEF neurons

[1] Of course, there were exceptions to barriers between the algorithmic level and the implementation level, to again cast this in Marr's terms. In the case of relatively low-level visual sensation and perception, there have long been deep connections between theoretical work in visual psychophysics and the underlying visual neurophysiology and neuroanatomy, in part because the relevant neural hardware is not far removed from the source of visual stimulation. And the field of cognitive neuropsychology has long considered theoretically how cases of brain damage and neurodegenerative and neurodevelopmental disorders influence understanding of human cognition.

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