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Approaches to analysis in model-based cognitive neuroscience[☆]

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HIGHLIGHTS

- We review current approaches for linking neural and behavioral data.
- We compare and contrast these current approaches on a variety of factors.
- We provide a guideline for selecting the appropriate approach in a variety of contexts.

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ABSTRACT

Our understanding of cognition has been advanced by two traditionally non-overlapping and non-interacting groups. Mathematical psychologists rely on behavioral data to evaluate formal models of cognition, whereas cognitive neuroscientists rely on statistical models to understand patterns of neural activity, often without any attempt to make a connection to the mechanism supporting the computation. Both approaches suffer from critical limitations as a direct result of their focus on data at one level of analysis (cf. Marr, 1982), and these limitations have inspired researchers to attempt to combine both neural and behavioral measures in a cross-level integrative fashion. The importance of solving this problem has spawned several entirely new theoretical and statistical frameworks developed by both mathematical psychologists and cognitive neuroscientists. However, with each new approach comes a particular set of limitations and benefits. In this article, we survey and characterize several approaches for linking brain and behavioral data. We organize these approaches on the basis of particular cognitive modeling goals: (1) using the neural data to constrain a behavioral model, (2) using the behavioral model to predict neural data, and (3) fitting both neural and behavioral data simultaneously. Within each goal, we highlight a few particularly successful approaches for accomplishing that goal, and discuss some applications. Finally, we provide a conceptual guide to choosing among various analytic approaches in performing model-based cognitive neuroscience.

1. Introduction

Our understanding of cognition has been advanced by two nearly non-overlapping and non-interacting groups. The first group, mathematical psychologists, is strongly motived by theoretical accounts of cognitive processes, and instantiates these theories by developing formal models of cognition. The models often assume a system of computations and mathematical equations intended to characterize a process that might actually take place in the brain. To formally test their theory, mathematical psychologists rely on their model's ability to fit behavioral data. A good fit is thought to reflect an accurate theory, whereas a bad fit would refute it (Roberts & Pashler, 2000). The second group, cognitive neuroscientists, rely on statistical models to understand patterns of neural activity, often without any attempt to make a connection to the computations that might underlie some hypothesized mechanism. For example, some statistical approaches (e.g., multivariate pattern analysis) explicitly condition on the neural data to determine which aspects of the data produce better predictions for

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behavioral outcomes. Such an analysis can tell us *which* brain regions are predictive of a particular behavior and even *by how much*, but they say nothing about neither *how* nor *why* particular brain regions produce said behavior.

Although both groups are concerned with explaining behavior, they tend to approach the challenge from different vantage points. Thinking in terms of Marr (1982)'s levels of analysis, mathematical psychologists tend to focus on the computational and algorithmic levels, whereas cognitive neuroscientists focus more on the implementation level. Although progress can be made by maintaining a tight focus, certain opportunities are missed. As a result of their single-level focus, both approaches suffer from critical limitations (Love, 2015). Without a cognitive model to guide the inferential process, cognitive neuroscientists are often (1) unable to interpret their results from a mechanistic point of view, (2) unable to address many phenomena when restricted to contrast analyses, and (3) unable to bring together results from different paradigms in a common theoretical framework. On the other hand, the cognitive models developed by mathematical psychologists are inherently abstract, and the importance of physiology and brain function is often unappreciated. After fitting a model to data, mathematical psychologists can describe an individual's behavior, but they can say nothing about the behavior's neural basis. More importantly, neural data can provide information that can help distinguish between competing cognitive models that cannot be uniquely identified based on fits to behavioral data alone (Ditterich, 2010; Mack, Preston, & Love, 2013; Purcell, Schall, Logan, & Palmeri, 2012).

The many limitations of single-level analyses have inspired researchers to combine neural and behavioral measures in an integrative fashion. The importance of solving the integration problem has spawned several entirely new statistical modeling approaches developed through collaborations between mathematical psychologists and cognitive neuroscientists, collectively forming a new field often referred to as model-based cognitive neuroscience (e.g., Boehm, Van Maanen, Forstmann, & Van Rijn, 2014; Forstmann, Wagenmakers, Eichele, Brown, & Serences, 2011; Love, 2015; Mack et al., 2013; Palmeri, 2014; Palmeri, Schall, & Logan, 2015; Turner et al., 2013b; Turner, Van Maanen, & Forstmann, 2015b; van Maanen et al., 2011). We refer to these as "approaches", because they are general strategies for integrating neural and behavioral measures via cognitive models, and are neither restricted to any particular kind of neural or behavioral measure, nor any particular cognitive model. However, with each new approach comes a unique set of limitations and benefits. The approaches that have emerged in the recent years fill an entire spectrum of information flow between neural and behavioral levels of analysis, and deciding between them can be difficult. Given the overwhelming demand for these integrative strategies, we believe that an article surveying the different types of analytic approaches could be an invaluable guide for any would-be model-based cognitive neuroscientist.

Here we survey and characterize the many approaches for linking brain and behavioral data. We organize these different approaches into three general categories: (1) using the neural data to constrain a behavioral model, (2) using the behavioral model to predict neural data, and (3) modeling both neural and behavioral data simultaneously. For each specific approach within each category, we highlight a few particularly successful examples, and discuss some applications. In an attempt to draw a detailed comparison between the approaches, we then organize each of the approaches according to a variety of factors: the number of processing steps, the commitment to a particular theory, the type of information flow, the difficulty of implementation, and the type of exploration. In short, we discuss the ways in which current approaches bind data at multiple levels of analysis, and speculate about how these methods can productively constrain theory. We close with a discussion about additional considerations in model-based cognitive neuroscience, and provide an outlook toward future development.

2. Specific analytic approaches

For ease of categorization and subsequent comparison, we will hypothetically assume the presence of neural data, denoted N, and behavioral data, denoted B, which may or may not have been collected simultaneously. The neural data N could be neurophysiological recordings, functional magnetic resonance imaging (fMRI), electroencephalography (EEG), or other physiological measures. The behavioral data B could be response probabilities, response times, confidence ratings, or other typical behavioral data collected in a cognitive experiment. Cognitive modelers are interested in characterizing the mechanisms – specified in mathematical and computational terms – that lead to the behavior B observed in a given experimental condition. Commonly, this characterization is derived from fitting a cognitive model to behavioral data, interpreting the resulting parameter estimates, and comparing (qualitatively or quantitatively) the observed behavior and the behavior predicted by the model. Cognitive neuroscientists are interested in uncovering the neural mechanisms that lead to the behavior B observed in a given experimental condition. Commonly, this process involves a statistical analysis of neural data with respect to observed behaviors and experimental manipulations. However, model-based cognitive neuroscientists are interested in integrating neurophysiological information N and behavioral outcomes B by way of a cognitive model. The central assumption of these analyses is that information obtained from either source of data (N or B) can tell a similar story – albeit in different languages – about some aspect of cognition, and the integration of the these measures assimilates the differences in languages across data modalities.

As model-based cognitive neuroscientists, we have many choices in deciding which story we would like to tell, and these choices depend on our research goals. In practice, there seems to be at least three general categories of approaches in the emerging field of model-based cognitive neuroscience. These three categories are illustrated in the rows of Fig. 1. The first set of approaches uses neural data as auxiliary information that guides or constrains a behavioral model. There are several ways in which the neural data can constrain modeling choices, and we will discuss three such approaches in the subsequent sections. The second set of approaches uses a behavioral model as a way to interpret or predict neural data. Behavioral models assume a set of mechanisms that theoretically mimic a cognitive process of interest, making them an interesting way to impose theory in data analyses. Moreover, while competing cognitive models might predict the same or similar patterns of behavioral data B, they might differ considerably in what they predict about neural data N, creating a powerful approach to model selection. We are faced with many choices in using these model mechanisms to guide our search for the interesting neural signatures. In the sections that follow, we will discuss two such approaches for accomplishing this goal. The third set of approaches builds a single model that jointly accounts for the random variation present in both the neural and behavioral data. With the proper model in place, one can simultaneously achieve constraint on the behavioral model while retaining the ability to interpret the neural data. In the sections that follow, we will discuss two approaches designed to accomplish this goal. We do not necessarily think this is a comprehensive list; in fact, we suspect that there is room for further development, and possibly the creation of entirely new analytic approaches.

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