INTRODUCTION
Editors’ Introduction to the Issue: Theoretical Ideas in Motor Neuroscience and Their Capacity for Falsification
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Motor neuroscience is expanding at a remarkable rate, with data accumulating rapidly at all levels from the molecular to the behavioral. While these data offer the possibility of gaining new insights into fundamental questions such as how the brain controls movement, the reality is that fields like motor neuroscience are becoming increasingly overwhelmed with potentially interesting data sets that, however, cannot yet be integrated into cohesive explanatory frameworks. Since models and theories provide the conceptual “glue” for binding observations together into a principled body of knowledge, it is inarguable that motor neuroscience needs models and theories. To this end, many large experimental laboratories currently have their own modeler, and numerous theoreticians run their own independent research programs pursuing modeling work exclusively. The result is an abundance of models. With every issue of this or related journals, someone, somewhere, publishes another model. There are models to explain behavioral data, neural data, and biomechanical data. There are models that are mathematically sophisticated and models that are essentially conceptual. There are models designed to have broad explanatory scope and models restricted to relatively narrow experimental contexts.

Models are intended to enhance our understanding by reducing the dimensionality of the large number of observations to a few “principle components.” This approach works when the models perform so well as to prove themselves worthy of broad acceptance. Motor neuroscience, however, has many problems left to be solved, and many different proposals for how to solve them. There is no “standard model” to carry the day, so many different cliques within the field adopt their own modeling approach, and the number and type of models continues to expand. In fact, one might say that we now find ourselves in the predicament of too many models. Today it is virtually impossible, even for a dedicated theorist, to stay on top of the modeling literature, let alone compare, contrast or classify the abundance of models. Thus, each individual motor neuroscientist is faced with the reality of more data than can be digested and more models than can be assimilated. The key question is: how can data and theory best be integrated to advance the field?

More specific questions naturally follow. Given the increased emphasis on modeling, is there sufficient communication between experimentalists and theorists in their joint efforts to understand motor behavior? Are the experimentalists and theorist working in sufficiently close contact, with the experimental data driving the theorizing and the models motivating further experiments in a beneficial cycle of mutual reinforcement? Ideally, the answer to these questions should always be “yes.” Our concern is that in motor neuroscience, the answer, too many times, is “no.”

In any field in which there is rapid theoretical development, there is always the danger of hyperspecialization: the theorists in the clouds can become disconnected from the experimentalists on the ground. In physics, for example, string theorists and experimental particle physicists do not always speak the same language. Has a similar situation arisen in motor neuroscience? Are the efforts of the typical experimentalist facilitated by the framework of stochastic optimal feedback control? Can the typical neurophysiologist gain greater insight into single-cell recording data by understanding the current information–theoretic models? We would suggest that the answer is on many occasions “no.” Indeed, from our perspective, there is the potential for a troublesome divide developing between experimentalists and theorists.

For this reason, we organized a satellite conference in April of 2009 entitled “Theoretical Ideas in Motor Neuroscience and their Capacity for Falsification.” This purpose of this conference—an adjunct to the 2009 Neural Control of Movement Conference—was to provide a forum for improving communication between theoreticians and experimentalists by explicitly grounding their interaction in the universal scientific language: experimental predictions and falsification. After all, from the point of view of the experimentalist, theories should provide the conceptual structure for guiding experimental inquiry. From the point of view of the theorist, the suitability of theory should be demonstrated by testing the predictions it generates. Every scientist knows this. But all of us, at one time or another, become so engulfed in the details of our own work that we temporarily lose sight of this basic fact. This conference was intended to serve as a gentle reminder of the integral role of falsification in creating and consolidating knowledge in a scientific field.

Toward this end, speakers at the conference were given a very specific requirement. Theoreticians were asked to devote time, after introducing a theoretical idea, to discussing the testable predictions that idea generates. Experimentalists were asked to devote time to discussing the specific theoretical idea supported or falsified by their experimental results. After each individual talk, ample time was allotted for panel discussion, during which the viability of the experimental predictions and inferences of the speakers were critically discussed.
assessed. The conference proceedings were videotaped and are available on the National Institute of Neurological Disorders and Strokes Web site at National Institute of Health.

This special issue of the Journal of Motor Behavior came into being as a result of this conference. It, too, is intended to stimulate readers to think more deeply about the role of falsification in theory building. The article by Ajemian and Hogan critically assesses the role of falsification in theoretical motor neuroscience as referenced to progress in certain branches of theoretical physics. Subsequently, two popular motor control theories, equilibrium point theory and optimal feedback control, are compared as to the extent each model lends itself toward falsification, modification, and long-term experimental testing. Fernandes and Körding present reflections on the truth and falsity of models: all useful models are false as they need to abstract from reality. Given their falseness, an attempt to falsify will be successful but not very informative. It is, instead, the structure of differences between data and model that should illuminate for the scientist the underlying reality. Wolpaw’s article addresses the critical question of how invasive neural recording devices need to be in order to make neural prosthetic devices that function effectively. Wolpaw challenges the current thinking that single-neuron recordings are necessary to obtain good performance; the corroborate or falsification of this point of view in the years ahead will have major clinical, as well as theoretical, consequences. Ganguly and Carmena address a related question in neural prosthetics: should the decoder be adaptive (with the learning taking place in the decoder) or should it be fixed (allowing the brain to adapt around the decoder). The field will grapple with this question for many years to come, and this article provides a state-of-the-art look at the level of performance that can be achieved by fixing the decoder.

The article by d’Avella and Pai elaborates an experimental method for testing the “synergy” hypothesis popularized by Bizzi and colleagues. While many researchers have adopted the approach of extracting synergies from data using a variety of data-analytic techniques, the physiological reality of modular control has yet to be rigorously established. Doya’s study addresses the question of how learning proceeds in stages from cognitive task involvement to relative autonomy in task performance. Motivated by different learning methods in reinforcement learning and the recognition that there are different parallel control loops in the brain, the authors critically examine behavioral results from a sequential key-pressing task for clues concerning the transition between model-free and model-based learning stages. The article by Ajemian and colleagues addresses the issue of “warm-up decrement” in the execution of fine motor skills: why do professional athletes need so much time warming up immediately before an event to realize a peak level of performance? While this phenomenon has been studied for well over a half-century, few theoretical explanations exist; here one is provided, along with a strong testable prediction. Ronsse and Sternad review their research on rhythmic ball bouncing that has gone through several cycles of testing and falsifying model predictions followed by partial refinements of the model. Recently, the original dynamic model was complemented by an optimal feedback controller to generate racket trajectories to account for deviations of model assumptions in different gravity conditions. While successful, new fine-grained data analyses do not conform with predictions, revealing further avenues to amend the model. Sanger addresses the extremely challenging issue of how biological motor systems, faced with noisy actuators and uncertain state estimates, nonetheless reliably accomplishes challenging real-world tasks. A key hypothesis of the model—that probability densities of system states are represented internally, and these densities are used for planning—is described, along with experimental predictions that follow from this hypothesis.

We hope that readers find these articles interesting and insightful. We additionally hope that these articles stimulate the readers into thinking more deeply about the falsifiability (or lack thereof) of their own favorite models.