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The emulation theory of representation: Motor control, imagery, and perception

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Abstract: The *emulation theory of representation* is developed and explored as a framework that can revealingly synthesize a wide variety of representational functions of the brain. The framework is based on constructs from control theory (forward models) and signal processing (Kalman filters). The idea is that in addition to simply engaging with the body and environment, the brain constructs neural circuits that act as models of the body and environment. During overt sensorimotor engagement, these models are driven by efference copies in parallel with the body and environment, in order to provide expectations of the sensory feedback, and to enhance and process sensory information. These models can also be run off-line in order to produce imagery, estimate outcomes of different actions, and evaluate and develop motor plans. The framework is initially developed within the context of motor control, where it has been shown that inner models running in parallel with the body can reduce the effects of feedback delay problems. The same mechanisms can account for motor imagery as the off-line driving of the emulator via efference copies. The framework is extended to account for visual imagery as the off-line driving of an emulator of the motor-visual loop. I also show how such systems can provide for amodal spatial imagery. Perception, including visual perception, results from such models being used to form expectations of, and to interpret, sensory input. I close by briefly outlining other cognitive functions that might also be synthesized within this framework, including reasoning, theory of mind phenomena, and language.

Keywords: efference copies; emulation theory of representation; forward models; Kalman filters; motor control; motor imagery; perception; visual imagery

1. Introduction

The idea that one of the central tasks performed by the brain is to internally model various brain-external elements and processes is not new. In the twentieth century, Kenneth Craik was one of the most explicit proponents of this view (Craik 1943). In various guises the view has been taken up as an approach to understanding reasoning (Johnson-Laird 1983), theory of mind phenomena (Gordon 1986), mental imagery (Kosslyn 1994), and even aspects of motor control (Kawato 1999). The metaphor of "internal modeling" aside, these approaches have not (yet) been synthesized into anything approaching a unified and flexible framework.

In this article I have four goals. The first is to articulate an information-processing strategy that I will call the *emulation theory of representation.* This strategy is developed using tools from control theory and signal processing, especially drawing on pseudo-closed-loop control and Kalman filtering. I will try to use just enough mathematical formalism to ensure that the main ideas are clear. The second goal is to show the use of this framework in understanding certain aspects of motor control and motor imagery. Many researchers in the two fields of motor control and motor imagery currently appeal to constructs related to those I will develop, but such appeals rarely go into much detail concerning the overall information-processing structures involved, and little by way of clear synthesis has emerged. In providing such a structure, I hope to do a service to both of these areas of research by providing a framework within which various results can be synthesized, and within which a number of issues can be more clearly stated so as to avoid certain kinds of errors.

The emulation framework I will articulate not only allows for a great deal of motor control and motor imagery work to be synthesized in interesting ways, but it also synthesizes certain aspects of visual imagery and visual perception as well. Outlining such a synthesis is the third goal. The final goal, addressed in the last section, is to briefly explore the prospects for addressing other psychological capacities such as reasoning, theory of mind, and language, within the same framework.

RICK GRUSH is Associate Professor of Philosophy at the University of California, San Diego, the same university at which he received a joint doctorate in cognitive science and philosophy in 1995. His research in theoretical cognitive neuroscience is directed at understanding the nature of representation and the structure and neural implementation of fundamental representational capacities of nervous systems, including space, time, and objects. These topics will be explored in detail in his in-progress book, *The Machinery of Mindedness.*

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