The Neural Basis of Choice and Decision Making

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Decision making refers to the ability of humans and other animals to choose between competing courses of action based on the relative value of their consequences. This capacity is, therefore, fundamentally integrative, melding the complex cognitive processes through which causal relations between actions and consequences are encoded, retrieved, and maintained in working memory with the motivational processes that determine the value, or utility, of actions or sequences of actions. As readers of this journal will be well aware, research in decision making has expanded in a variety of directions in recent years, but most notably into neuroscience. There are many reasons for this development, some merely technical, such as the increased use of functional magnetic resonance imaging (fMRI) in humans, but others that are more obviously innovative and that mark a change in the dominant approach to investigating the neural bases of the complex capacities of animals. There appears to be a developing consensus that the long tradition of studying these capacities by examining analogous processes in simple model systems has become an old tradition; that, rather than using a simple neural or behavioral preparation, methodologies better suited to examining functional, as opposed to structural, problems will provide a more secure basis for rapid progress. Indeed, much of the success of recent research in decision making has come from recognizing that the interaction of the cognitive, motivational, and behavioral processes engaged during the course of specific decisions cannot be reified to a single specialized circuit, cell type, or intracellular process and are best understood at a systems level.

As a consequence, the neuroscience of decision making is a very broad enterprise and crosses many traditional boundaries between research disciplines, species, and brain regions. This breadth is immediately apparent from a cursory survey of the range of interests of the authors of the following Mini-Reviews. There are, however, clear areas of overlap, and these have been exploited to explore what we see as emerging themes in decision-making research. In this series, these include descriptions of studies integrating computational and neuroeconomic approaches to investigate subjective decision variables, financial decisions, and the executive and evaluative functions of prefrontal cortex [particularly the role of orbitofrontal cortex (OFC) in establishing a common currency of value], together with reviews of recent research examining the functions of discrete corticostriatal networks

and their integrated dopaminergic afferents in the acquisition and control of goal-directed and habitual instrumental actions.

Although the individual papers review themes that are, themselves, complex areas of issue around which substantial research efforts are currently organizing, they are each presented within a larger context and so, together, provide a general overview of this developing area. For example, in their description of the application of computational approaches to decision making, Doya and Corrado (2007) review both the development of computational models capable of capturing the dynamics of individual choice and specific cases in which the internal variables of these models have provided the basis for extracting the correlates of subjective choice from the electrophysiological data of primates. In this case, it is the dynamic integration of the computational, neural, and behavioral data that has provided insight into the subjective variables controlling choice. Similarly, Knutson and Bossaerts (2007) describe the emerging neurofinance approach to decision making but also examine the specific application of models of decision making under risk and the behavioral tasks that have been developed to examine financial decision processes in human subjects together with their neural correlates using fMRI.

Lee et al. (2007) review research on the involvement of prefrontal cortex in decision making in primates and, in the light of the connectivity of subdivisions of this region and of formal theories of decision making, propose that the lateral, medial, and ventral subregions may have the more specialized task of deriving predictions regarding the future value of reward on the basis of states, actions, and local predictive cues, respectively. Interestingly, Murray et al. (2007) come to similar conclusions with regard to the role of OFC in decision making based on a review of the comparative literature. They point particularly to its role in deriving reward value from predictive cues as well as to evidence suggesting that the OFC may play a specialized role by allowing animals to compare values across distinct event categories.

Finally, it is interesting to note convergence in the proposed functions of corticostriatal circuits and their midbrain dopaminergic afferents in decision making that has emerged in recent research. Although the involvement of the basal ganglia in motor learning, particularly in sensorimotor association, has long been recognized, recent evidence, reviewed by Balleine et al. (2007), suggests that they also play a critical role in the acquisition of actions instrumental to gaining access to reward (i.e., in goal-directed actions). Importantly, studies using rodent, nonhuman primate, and human subjects have found evidence of heterogeneity of neural function not previously anticipated, particularly in the striatum. Furthermore, there is evidence of a corresponding heterogeneity in neurodegenerative disorders, in neuronal

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plasticity, and in the involvement of dopaminergic processes across striatal subregions. The suggestion that the burst-firing pattern of midbrain dopamine neurons serves as an error signal for the prediction of reward has generated close collaboration between researchers using computational and neurophysiological approaches to study dopamine function. More recently, alterations in dopamine signaling have been reported to lead to regional changes in plasticity in the corticostriatal pathway together with changes in the excitability of the striatal output neurons. Indeed, as reviewed by Wickens et al. (2007), rapid alterations in dopamine transmission are related to substantial changes in the coordinated activity of neuronal ensembles in discrete corticostriatal circuits in a manner that could lead to the emergence of distinct patterns of behavioral abnormality. Clearly, the involvement of dopamine in striatal function, and in decision making generally, is rich and varied and is something that we are only beginning to understand.

There are, of course, still many open questions, a number of which are raised in the following Mini-Reviews, and the inter-

ested reader will undoubtedly think of many more. Nevertheless, given the diverse opportunities for integrative research that the neuroscience of decision making provides, these questions only serve to emphasize the generative nature of experimental work in this area and the vibrancy of its future.

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