nature neuroscience

Focus on decision making

The ability to make appropriate choices is critical for survival. Successful decision making requires the integration of sensory information, motivational states and potential outcomes to select the best action. Animals at all levels of the phylogenetic tree make decisions, such as those about where to forage for food or which mate to choose, but the complexity of these decisions varies widely between pigeons and people. We are often most fascinated by the kinds of decisions that we think make us uniquely human—those requiring the ability to reason abstractly and use language to frame and execute our choices. However, it is clear that even with our higher faculties, we are still the product of evolution, and instinctual, sometimes irrational, decisions are just as much a hallmark of our choice behavior. In this issue, a special focus containing four reviews explores recent advances in this important field.

A number of streams of research, including behavioral psychology, cognitive neuroscience and economics, have traditionally been concerned with the mechanisms underlying choice behavior. Each of these fields has focused on particular areas of interest, working with animals or humans, financial decisions or more primary needs. However, recent work combining theory and protocols that cross these disciplinary boundaries has led to a broader understanding of the neural circuitry underlying decision making.

Two advances in the recent past have contributed this new cross-disciplinary synthesis. One was the realization that the responses of the midbrain dopamine neurons that Wolfram Schultz and colleagues had been recording in monkeys for some time looked remarkably similar to the reward prediction error signal critical for learning in a class of models based on reinforcement learning theory[1]. This finding supported a range of behavioral work showing that animal behavior is guided by expectations about the values of different choice options, but, more importantly, it strongly suggested one possible way in which the neural circuitry underlying those choices might be organized. The results also led to a host of new studies looking at whether reinforcement learning models were a good match for other physiological and behavioral measures of reward sensitivity.

In parallel, the field of cognitive neuroscience was rapidly expanding, with the increased use of functional magnetic resonance imaging (fMRI) technology making possible the study of the neural basis of a variety of human behaviors. This was particularly important for opening up the examination of topics such as emotion, language and cognitive control, processes that are critical for making complex choices. The new understanding of how rewards may be encoded in the brain, combined with a new line of research on human cognition, led to a serendipitous confluence of ideas about the basic brain mechanisms of decision making.

A prime example of this synergy comes from studies of the frontal cortex. The anterior cingulate and frontal cortices have been of particular interest to cognitive neuroscientists because they are proposed to underlie higher cognitive function, although animal work has also suggested the importance of analogous areas found in smaller mammals, such as rats. Matthew Rushworth and Timothy Behrens review recent research in understanding uncertainty—how do you know what to choose when you are not even sure what your options are? They build the parallels between estimating the likelihood of a particular outcome and learning about the contingencies in the environment, uniting the cognitive decision making and learning literatures.

There is a also a long history of studying decisions under uncertainty in the social sciences. Michael Platt and Scott Huettel review recent advances in understanding risky decision making from the perspective of neuroeconomics, which combines economic theory about choice behavior with the search for the underlying neural mechanisms. They capitalize on a strong tradition of understanding how individuals develop representations of value to better understand how the neural circuitry of decision making is organized.

Social decision making has also advanced by combining psychological and economic models with imaging technology. Daeyeol Lee explores research using game theory, in both monkeys and people, to shed light on how we interact with others and on the neural circuitry that may support social interactions. He also provides neural and behavioral support for the idea that reinforcement learning might contribute even to these complex social behaviors.

The discovery of a reward prediction error signal in the brain was a critical validation of reinforcement learning models of decision making, but it was only a first step. Kenji Doya explains how a simple, physiologically based reinforcement learning model can been extended to account for a wide range of choice behavior in humans and animals, and how global neuromodulators other than dopamine, such as serotonin and norepinephrine, might contribute to decision making.

The research described in this focus has made substantial progress toward understanding the brain systems that underlie decision making in both animals and humans. We hope that these reviews may inspire further basic work on these mechanisms, potentially leading to a more developed understanding of this critically important behavior that makes us unique individuals.

Hannah Bayer
Associate Editor

1. Schultz, W., Dayan, P. & Montague, P.R. *Science* **275**, 1593–1599 (1997).