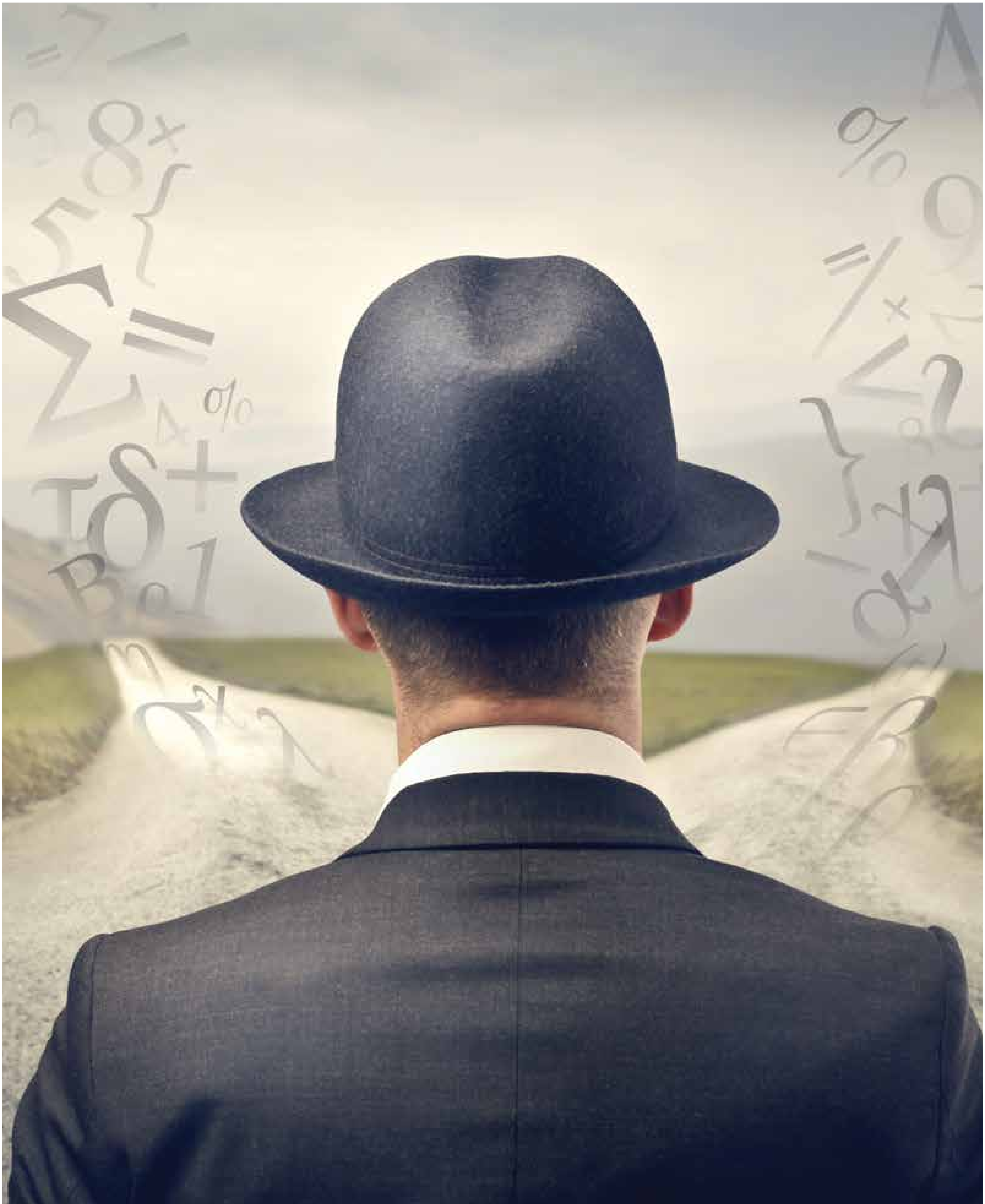

Valuable Decisions

by Kimm Fesenmaier

You've just finished eating a healthy, balanced meal and are now faced with two dessert options: a slice of ooey, gooey chocolate cake or a nutritious fruit cup. After considering your choices, and with a bit of a sigh, you reach for the fruit cup.

It's not the most exciting decision you will ever make—you make many like it every day. Still, your brain received sensory information and, after a bit, you acted on it. But what happened in between? What transpired in your brain before you actually picked up the more healthful option?

That mysterious in-between is the focus of a fledgling field known as neuroeconomics, or decision neuroscience. Neuroeconomists recognize that while decision making is complex and a bit messy, it is also so central to our daily lives that a better understanding could greatly enhance our grasp of human nature.

Neuroeconomists contend that, when weighing the value or worth of various choices, people do not always behave as standard economic theories would suggest. Rather than always acting rationally and in their own best interests, people can be unduly influenced by emotions, unusual experiences, and automatic reflexes, which can lead to poor choices. For that reason, neuroeconomists say it's time to begin using the most advanced tools for analyzing the biological response to choice in order to update our models of decision making.

The field got its start—at least in part—at Caltech, growing out of the discipline of behavioral economics as researchers like Colin Camerer began to wonder if they could dig deeper and try to update economic theory using not only psychology and sociology to inform its economic models but the actual workings of the human brain. Today, a little over a decade after this new approach began to be pursued on campus, a core group of researchers, including Camerer, Ralph Adolphs, John O'Doherty, and Antonio Rangel, is approaching the question of decision making from many angles, using experimental economics and studies of the brain to peer into that ultimate of black boxes to see what truly happens when you select the fruit cup—or double down on a bet or opt to buy shares of a particular stock.

"Caltech has been at the forefront of creating this new field," says Jonathan Katz, Caltech's Kay Sugahara Professor of Social Sciences and Statistics and the former chair of the Division of the Humanities and Social Sciences (HSS). Part of the reason is Caltech's size and concentration of specialties, he says. "Caltech is unique in that it's the only place where under one roof, in one department, there are both card-carrying neuroscientists and card-carrying social scientists interested in neuroscience." But beyond that, he says, is the fact that HSS has always been successful at seeking out interesting fields that need a bit of intellectual trailblazing. "We've always chosen areas that sort of fall between disciplinary cracks and that are a bit risky," Katz says. "Neuroeconomics is the latest incarnation of that."

"It's quite a radical combination of methods," agrees Camerer. "Our view is that anything which we, as economists, used to just infer—like whether people think something is going to happen in the future or how much they value something—we should try to measure biologically."

That is a radical viewpoint in light of the fact that, for most of the last 100 years, standard economics has held that the choices we make provide all the information needed to understand how much we value something. So although economists spend a lot of time building formal models of how they think economic decision making happens, the only variable they typically use is the choices that people make. Neuroeconomists, on the other hand, consider what actually happens in the brain when we make those choices.

O'Doherty, whose background is in psychology and mathematics, explains the differences between the two methodologies by comparing the decision-making brain to an electrical generator that runs on water. Water goes into the generator, something happens inside, and electricity comes out. You could look at what comes out at the end—the electricity—in order to try to understand how the generator works, he says. But that's not going to cut it if you want to understand exactly what's going on inside the generator, so that you can predict why it keeps breaking down.

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Similarly, simply looking at the economic choices people make will give you an overview of their preferences. But it doesn't help you understand exactly how the brain generates those choices. It is necessary to know this if you want to have an accurate model of how people make decisions, which among other things you could then use to make predictions about when people might be vulnerable to making poor or suboptimal decisions. The neuroeconomics approach, then, is akin to actually opening up the generator, looking inside, and seeing the different components that are transforming the water into electricity.

"In decision neuroscience," says O'Doherty, "we start with a model of what we think might be happening during decision making. Then, using techniques like neuroimaging and electrophysiology, we find out what the neural circuits are actually doing as they transform information and generate decisions. That allows us to compare and contrast different models and to find out which model is the best predictor of actual behavior."

That last bit about using and testing models is known as a computational approach—or, as Camerer refers to it, the Caltech group's "secret sauce." It's what sets true neuroeconomics apart from other types of neuroscientific work in which researchers simply try to figure out which areas of the brain are active, or "light up," during a particular task. Instead, neuroeconomists aim to produce and/or test mathematical models that represent how the brain assesses components of value, such as temptation, risk, and social consequences, and integrates them in order to produce decisions. Then they work to make sure that these models jive with the behavioral data—the records of what people actually *do*—and with the brain's actual activity, as measured through imaging and other techniques.

For example, Camerer has conducted several studies looking at the choices people make when risk is involved. In these studies, subjects might lie in a functional Magnetic Resonance Imaging (fMRI) machine that measures the blood flow in their brains as they are offered a risky choice, such as buying a lottery ticket, which has a varying chance of paying off different amounts of money. (In fMRI, blood flow is a proxy for neural activation; the more blood, and therefore oxygen, in a particular part of the brain, the more active it is. An area that is active likely plays a role in whatever decision is being made.)

The model Camerer has developed for this set of decisions suggests that people compute values for the rewards that they believe they are likely to receive if they take a financial risk and also if they do nothing. Then they compare the two and choose the option that yields the highest value. In the risky case, the model says that people multiply the value of possible outcomes by the likelihood of those outcomes to arrive at an overall valuation.

Over the course of a study, it might become clear that one participant doesn't value high payoffs enough to compensate for the high risk involved in betting on those low likelihood outcomes. Another might be putting too large a value on a huge payoff given the low chance of winning the jackpot. Camerer and his colleagues look through the fMRI data to see if they can identify one or more brain regions that are "encoding" these different values, meaning that neurons in those areas are activated to an extent that is proportional to the values that the individuals are assigning. And with risk-taking, the areas the researchers have pinpointed are the striatum and the insula.

Camerer emphasizes that fMRI is just one of many tools the Caltech team uses to investigate the biology of decision making. They also use EEGs, single-neuron recordings, studies of brain-lesion patients, and skin-conductance and eye-tracking tests. "Every method is fantastic in some way and weak in some other way," Camerer says. "So we basically use whatever tool is best. That often means combining techniques so the strength of one compensates for the weakness of another."

The Making of a Decision

Camerer's most recent work focuses on financial bubble markets—markets in which prices rise well beyond the intrinsic value of the assets in question. The American housing bubble that ultimately caused the recent Great Recession is an example of such a market. By creating experimental markets in the lab—where value, risks, and the number of trading sessions can be controlled and known—Camerer and his colleagues have been able to track the development of bubble markets.

What they found was that the highest earners in such markets were the participants who sold shares while prices were still on the rise. Looking at the behavioral data, the researchers formulated a model that suggested that some kind of brain activity must have prompted these high earners to sell even though the market had not yet peaked. By scanning the brains of some of the participants during the experiment, the researchers were able to see that, several periods before prices reached a peak, the high earners indeed had high levels of activity in the insula, which is associated with negative bodily sensations such as being choked, as well as with social uncertainty and exclusion. For high earners, the insula was serving as a kind of early warning signal, making the high earners feel nervous and uncomfortable and thus causing them to sell off their shares. Meanwhile, the low earners—whose brains showed no signs of increased insula activity—ended up buying shares when prices were far too high, and thus got stuck with shares that were no longer valuable once the bubble burst.

In reflecting on the findings of the study, which was published in July in the journal *Proceedings of the National Academy of Sciences*, Camerer says he and his coauthors were reminded of an unconventional bit of advice once offered by investment guru Warren Buffett to "be fearful when others are greedy and greedy only when others are fearful."

"If you could replace 'fearful' with 'nervous,' his advice would match closely what we see in the brains of successful traders," Camerer says. "This is a case where the brain imaging tells us something very close to what we think is unconventional wisdom in the stock market. These high earners bought early, timed the market a little bit, and sold into a rising market. That's a hard thing to do, and they did it because this warning signal in their brains told them to do it."

Back to Basics

Despite the findings of these kinds of complex economic studies, we still know very little about what happens in the brain when we make even the most basic kinds of decisions. That's why many decision neuroscientists, like Rangel, are focusing on the basics.

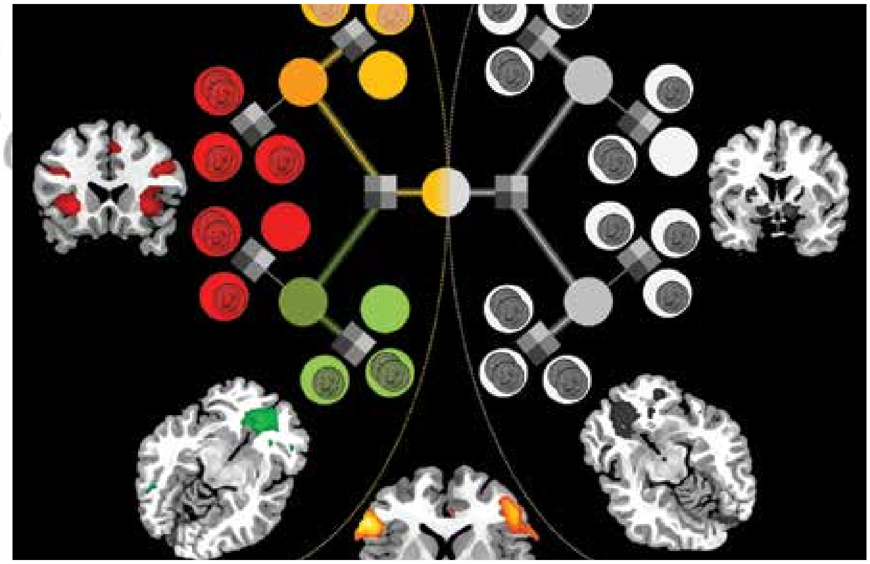
"I'm interested in the simplest type of decision that we can study in the laboratory in a precise way," says Rangel. "Our goal is to understand *exactly* what variables are computed in the brain from the moment you notice that you have a very simple choice—for example, between an apple and an orange—to the moment you actually move your hand to implement the choice. What are the computational models that best describe this process? I want to understand that in exquisite detail."

Some of those details are starting to become clear. Through fMRI and EEG studies—as well as single-neuron recordings of epileptic patients—Rangel's group has found that a region of the brain called the ventral medial prefrontal cortex (vmPFC), which sits about an inch behind the midbrow, assigns a value to each of the choices available at the time of decision, indicating how attractive your options are. The higher the value the brain assigns to a particular choice, the more often a group of neurons in the vmPFC will fire when you evaluate that choice, and thus the more likely it is that you will select it.

Rangel began his career as a classical economist—he was an assistant professor of economics at Stanford University when he took his first steps toward neuroeconomics. At the time, he was working on a project to try to come up with the optimal public policy toward addictive substances, including how the substances should be regulated or taxed, how addicts should be treated, and whether public-health campaigns should be implemented. Part way through the project he realized that if he was to find the best solution he needed to know more about how addicts decide to continue using drugs. Looking for answers, he turned to psychology and neuroscience.

The standard view in economics had been what's called rational addiction. It says that as long as people are capable of understanding the possible consequences of drug use, addiction can be perfectly rational. This is very much in line with the thinking that humans make rational decisions, seeking out information and doing what's in their own best interest at all times. "But this is highly inconsistent with what we now know about how the brain is affected by addictive substances and how they impair decision making," Rangel says. After researching the neural basis of addiction, he and a colleague published an influential paper that argued that drug use can be rational but is often a mistake based on a malfunction of the brain's decision-making circuitry.

Today, Rangel is a neuroscientist, and much of his work focuses on the seemingly simple realm of food choice. In one study, his group showed self-reported dieters photos of 50 foods ranging from cauliflower to Snickers



bars. The subjects were first asked to rate the foods in terms of how tasty they thought they would be and, separately, how healthful they considered the foods to be. Using those ratings, the researchers then pinpointed one food for each subject that that subject had ranked in the middle of the pack on both scales. The subjects were then put into an fMRI scanner and shown all of the foods again, answering this time whether they would rather eat their middle-of-the-pack food versus each of the other items. The researchers found that the dieters fell into two groups—those who chose mostly healthy foods over their middle-of-the-pack food were deemed "healthy eaters" based on their higher level of dietary self-control; those who made unhealthy decisions were "unhealthy eaters."

The researchers found that the brains of the healthy and unhealthy eaters differed in a significant way at the time of decision: although in all of the subjects the vmPFC encoded a value signal that seemed to guide their food choices, the healthy eaters had additional activity in a part of the brain called the dorsolateral prefrontal cortex (dlPFC), which adds to the basic value signal in the vmPFC, allowing it to take into account more abstract attributes, such as long-term health. The model that Rangel and his team created to represent this decision system involves the brain mapping out a series of such attributes for each food choice, assigning a value to each attribute, and then integrating those values into an overall decision. Bad dieters, the model says, simply do not integrate the more abstract attributes, such as the health consequences of eating a particular item, into the final valuation. This leads those dieters to make choices based mostly on taste—a hypothesis borne out by the fMRI experiments.

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In a follow-up experiment, Rangel's group did the same fMRI study with self-proclaimed nondieters. In half of the trials, the researchers asked the participants to make whatever decisions they liked; in the other half, the subjects were asked to make their decisions while paying attention to how healthful the items were. Interestingly, that simple instruction led to the subjects making healthier choices; the imaging results showed that it activated the same dlPFC/vmPFC network as in the good dieters. The stronger the connection between the two, the researchers found, the healthier the dieters' choices became. "That was interesting to us because it suggests that this difference between dieters is not something that is hardwired but something that can be modified," Rangel says.

A Decision to Learn

While Rangel is particularly interested in what happens in the brain at the moment of decision, O'Doherty has focused on how the brain learns, over time, to make different types of decisions. His group has determined that there may be multiple systems in the human brain that drive decision making: one system that operates at the Pavlovian level; another that responds based on habits learned over time; and yet another, more sophisticated, system that is goal-directed, involving planning and the weighing of possible consequences. O'Doherty notes that each of those systems involves different brain regions to varying degrees. (For more on these systems, see "From Dendrites to Decisions," *E&S*, Fall 2011, p. 14).

O'Doherty is also interested in considering how social situations—where concepts such as trust, altruism, and retribution come into play—impact the process of decision making and learning. "After all," he says, "much of what we learn as children we learn by watching someone else."

In this area of focus, O'Doherty is certainly not alone. In fact, in 2012, the National Institute of Mental Health awarded Caltech a five-year grant of $9 million to create the Conte Center, which involves a group of researchers working together in a sort of virtual hub for studying the neurobiology of social decision making. Work by researchers involved in the center—Adolphs, O'Doherty, and Rangel, as well as Assistant Professor of Biology Doris Tsao and James G. Boswell Professor of Neuroscience Richard Andersen—is concentrated on four projects that look at decision-making scenarios of increasing social complexity through the use of electrophysiology and fMRI.

In one such experiment, you would be asked to lie down on the tubelike bed of an fMRI scanner and to repeatedly select one of two onscreen slot machines to play. In the beginning, you would just pick one or the other; but after switching off between the two for a while, you might learn that one machine pays out more than the other and develop a preference for that one. The researchers would first want to know what happened in your brain as you learned to choose one machine over the other, and then they would want to know how your choices might change over time, especially with the added complications of social interactions and interpersonal relationships. "So if you've learned that one machine is a better choice, can you unlearn that and switch over if the other machine begins paying out more?" says Ralph Adolphs, the director of the Conte Center. "How does that work? What if you're not doing anything, but you're watching someone else do this task? Will you learn in the same way? Now what if you think the person you're watching is really stupid, or you believe they're an expert, or, worst of all, you think they're trying to deceive you?"

A key finding that has emerged from the center's work thus far is that a common core system of reward regions in the brain seems to be activated in all of these decision-making situations, "whether you learn how to make decisions through your own experience or you learn by watching someone else do something," Adolphs says. That core includes two brain regions—the posterior cingulate cortex and the ventral striatum—as well as a portion of the vmPFC. Additional brain systems seem to work with and feed information to these core regions when social rewards are added to the decision-making mix.

Of course, scientists still have much to learn about the core reward system. For example, although fMRI may show a relatively large blobby region being activated during a particular task, researchers would like to find out if all or only some of the neurons in those areas are activated. For that, they need to use additional techniques and consider new, inventive models. Only then will they be able to work out the details of how the core regions are interconnected.

By figuring out how people make decisions when everything is working typically, Caltech's neuroeconomists and their colleagues hope one day to be able to determine what exactly is happening when people make bad decisions—and then to devise strategies to help us all make better choices, whether that be to stop taking drugs, to stay in school, or to behave altruistically.

"If you had to boil it down to 'What's the number one problem in the world?' well, it would be poor decision making," says Adolphs. "It's very hard to make complex decisions, especially when the consequences of those decisions will occur far in the future. Understanding how to improve that kind of decision making, that's the big challenge. And neuroeconomics is the only scientific way to really crack it." e&s

Ralph Adolphs is the Bren Professor of Psychology and Neuroscience and professor of biology. He is also the director of the Caltech Conte Center for Neuroscience. His work is funded by the National Institutes of Health (NIH) and the Simons Foundation.

Colin Camerer is the Robert Kirby Professor of Behavioral Economics. He is supported by the National Science Foundation (NSF), the Gordon and Betty Moore Foundation, the Lipper Family Foundation, and the Neuroeconomics Discovery Fund.

John O'Doherty is a professor of psychology and the director of the Caltech Brain Imaging Center. The NIH, the NSF, the National Center for Responsible Gaming, and the Moore Foundation contribute funding to his work.

Antonio Rangel is the Bing Professor of Neuroscience, Behavioral Biology, and Economics. His neuroeconomics work has been supported by the NSF, the NIH, the Moore Foundation, and the Lipper Foundation.