

Neuroeconomics

Intermediate article

Kevin McCabe, George Mason University, Fairfax, Virginia, USA

CONTENTS

Introduction
 A framework for decision making
 Decision making by neurological patients
 Choices between competing alternatives

Monetary reward
 Choices under uncertainty
 Strategic choices with others

Neuroeconomics is the study of how the embodied brain interacts with its external environment to produce economic behavior. Research in this field will allow social scientists to better understand individuals' decision making, and consequently to better predict economic behavior.

INTRODUCTION

Recent breakthroughs in neuroscience models and technologies allow us to study *in vivo* brain activity as individuals solve problems involving tasks such as making choices between alternative actions, forming expectations about the future, carrying out plans, and cooperating, producing, investing and trading with others. Knowledge of how the brain interacts with its environment to produce economic behavior will allow social scientists to better understand the variation both within and between individuals' decision making, and consequently to better predict economic behavior. In addition, understanding how the brain processes information can facilitate the building of economic institutions that better serve as extensions of our minds' capacities for social exchange.

A FRAMEWORK FOR DECISION MAKING

Figure 1 shows an abstract flowchart of the steps involved in decision making. Information inputs include internal states associated with the homeostasis of the decision maker, sensory information from the external world, and prior knowledge of the decision maker. This information is used to form subjective beliefs about the likelihood of different outcomes and an objective that the decision maker will try to attain. Choices interact with events outside the control of the decision maker to produce outcomes, which are then valued. Feedback allows the decision maker to improve his or

her prior knowledge and leads to a return to homeostasis. Outcomes from choices may also affect future events and consequently influence new sensory data.

We can model the ultimate decision-making system as one that results in choices that maximize the genetic fitness of the organism as studied by sociobiology and evolutionary psychology. This leads to hypotheses about the neuronal encoding of decision-making variables that can be tested with a variety of neuroscientific methods.

DECISION MAKING BY NEUROLOGICAL PATIENTS

A famous early case illustrating the importance of prefrontal lobe lesions in decision making is that of Phineas Gage (Harlow, 1848). More recently, Bechara *et al.* (1997) have studied patients with similar ventromedial prefrontal damage in an individual-choice problem called the 'gambling task'. In this task, a subject is asked to choose cards from one of four decks starting with 40 cards each. Each deck has a fixed pay-off per card of \$50 in decks C and D and \$100 in decks A and B. Behind each card is a cost, ranging from \$0 to \$1250. The subject

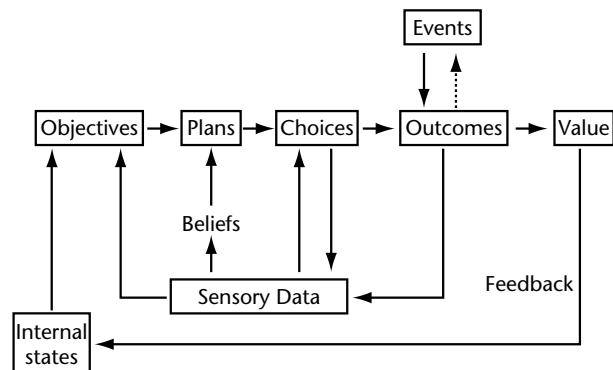


Figure 1. The steps involved in decision making.

must choose a card with a fixed pay-off, only then to learn the cost, if any, associated with the card. The subject starts with 2000 fictional dollars. On each draw, the fixed pay-off minus the cost is added to the initial amount. Although subjects did not get paid the final amount of dollars, it is assumed that they were motivated to do as well as possible in maximizing their fictional earnings.

While the subjects learn fairly quickly the location of the \$50 and \$100 decks, they must also learn which decks have positive net pay-offs. The decks are designed by the experimenter to have large punishments in the \$100 decks, resulting in an overall loss if decks C and D are played for too long. The punishments in the \$50 decks are much smaller resulting in an overall expected gain if decks A and B are played for long enough. Thus, the subject must learn to ignore the favorable signals of the \$100 decks and instead play the \$50 decks.

The typical behavior of a control subject is to shift play largely to the \$50 (C and D) decks by period 60. By contrast, patients with ventromedial prefrontal damage do not shift away from the disadvantageous decks (A and B). Further research helped eliminate working-memory impairments as the reason for poor performance (Bechara *et al.*, 1997). However, subjects with bilateral amygdala damage not only show similar behavioral impairment in the gambling task, but they also fail to show skin conductivity responses to rewards, punishments, or anticipation.

This research leads Bechara *et al.* to hypothesize that the amygdala couples a stimulus configuration with a 'somatic state' triggered by primary reward or punishment. The ventromedial prefrontal cortex is then responsible for coupling a strategy with a somatic state elicited by beliefs about how that strategy may produce outcomes.

To what extent do patients with similar ventromedial damage have difficulty with real-world decision making? In a series of articles, Jordan Grafman and colleagues have looked at the role of prefrontal cortex in allowing individuals to solve complex decision problems involving sophisticated planning and feedback. Goel *et al.* (1997) study the performance of ten patients with frontal lobe lesions in a financial planning task in which they were asked to prepare a budget, with planned projections, for a fictional couple's cash flow, in order to solve the following problems. First, get the couple out of the red. Second, allow them to buy a house in the next two years. Third, send their two children to college (in 15 to 20 years). Fourth, allow them to retire at the age of 65 (in 35 years). When

compared to ten normal controls, the patients take much longer than normal subjects in structuring the problem, and in inferring abstract principles from particular instances, both of which are necessary in formulating a plan. Patients are also bad at processing feedback and judging performance, causing them to finish the task before the four problems have been adequately solved.

CHOICES BETWEEN COMPETING ALTERNATIVES

Economists have long studied decision making as the maximization of objective functions, such as utility or profit, subject to individual budgetary constraints. An important question is whether specified collections of neurons encode decision variables critical for optimization. For example, consider the simple utility-maximization problem of choosing x_1^* and x_2^* so as to maximize $U(x_1, x_2)$ subject to the budget constraint $p_1x_1 + p_2x_2 \leq m$, where x_1 and x_2 represent quantities of two different goods, p_1 and p_2 represent the prices of the goods, and m represents the money the person has at his or her disposal.

In Figure 1, the step marked 'choices' involves the ability to balance the relative gains of the two goods against the relative costs. The marginal utility of good 1 is the change in utility that the decision maker would receive for an additional unit of good, holding the amount of good 2 constant, or more formally, the partial derivative of the utility function, i.e. $U^1(x_1, x_2) = \partial U(x_1, x_2) / \partial x_1$, and similarly for good 2. Relative gains can then be measured as the ratio of marginal utilities $U^1(x_1, x_2) / U^2(x_1, x_2)$. A necessary condition for (x_1^*, x_2^*) to be a solution to this utility-maximization problem is that the ratio of marginal utilities should equal the ratio of the costs of acquiring the goods, i.e. $U^1(x_1^*, x_2^*) / U^2(x_1^*, x_2^*) = p_1 / p_2$.

In making trade-offs between alternatives, we would expect the objective function to be sensitive to the relative reward value of the alternatives, independently of the alternatives in question. Is there any evidence that the brain encodes this kind of information? Tremblay and Schultz (1999) show that the firing rates of orbitofrontal neurons in two *Macaca fascicularis* monkeys were modulated by the relative reward values of different food (or, in separate trials, different drink) items. For example, the authors knew *a priori* that the monkeys preferred a piece of banana (B) to a piece of apple (A), which was in turn preferred to a piece of lettuce (L). Within a block of choice, symbols for two of the rewards were alternatively

shown on the left or right side of the screen. After a delay the monkey had to press a lever indicating where the picture was presented in order to get the reward symbolized. In different blocks, the monkeys were presented with all combinations of rewards.

Prior to choice, the same neurons in the orbitofrontal cortex would fire more frequently when the more desired food item symbol was displayed, compared with the less desired food item. Similarly, other neurons would fire more frequently when the symbol for the less desired item was presented. The authors conclude that such neurons encode relative preferences of food items, independently of the items themselves. However, it is still an open question how neurons encode the balancing of relative gains with relative costs.

MONETARY REWARD

Notice that money is not directly valuable to decision makers. But with fixed prices p_1 and p_2 , we can always write $x_1^* = m_1/p_1$, where m_1 is the amount of money budgeted for good 1. In economics experiments human subjects are paid money as their salient reward. This raises the question: is there neuronal activity specifically associated with decision making over money? In general, neuroscientists predict that rewards are processed in the ventral striatum and orbitofrontal regions of the brain (Schultz, 2000). Using positron emission tomography, Thut *et al.* (1997) studied brain activation in ten humans who received either a monetary reward or a simple 'OK' reinforcer for performance on a delayed 'go-no-go' task. The monetary reward resulted in significantly higher activation of the dorsolateral and orbitofrontal cortex, and also involved the midbrain and thalamus.

In an event-related functional magnetic resonance imaging study, Knutson *et al.* (2000) studied brain activation in 12 subjects who engaged in a monetary-incentive delay task similar to a task originally designed for monkeys (Schultz *et al.*, 1997). In the human task, subjects were shown a cue indicating that they would receive some level of monetary reward (\$0.20, \$1.00, or \$5.00), or nothing, or a punishment represented as a monetary loss (\$0.20, \$1.00, or \$5.00). This was followed by a random delay of 2000–2500 ms, and then the appearance of a white target lasting 160–260 ms. Subjects received the relevant reward if they had got that reward cue and pressed a response button while the white target was visible. Subjects paid the relevant punishment if they were cued for that

punishment and they failed to press the response button when the white target was visible. Levels of activation in the nucleus accumbens increased as anticipated rewards (but not punishments) increased.

CHOICES UNDER UNCERTAINTY

A simple example is the choice between two gambles g_1 and g_2 . If the gamble g_1 is played, the decision maker gains \$10 or \$6, each with probability $\frac{1}{2}$. Playing the gamble g_2 results in a gain of \$14 or \$2, each with probability $\frac{1}{2}$. We assume that the decision maker prefers more money to less, so the utility function U satisfies $U(\$14) > U(\$10) > U(\$6) > U(\$2)$. In an experiment, these probabilities are likely to be shown to the subject in frequency terms, such as an urn containing 50 red balls and 50 blue balls. A subject is asked to pick a gamble. A ball is then randomly chosen. A red ball is worth \$10 if g_1 is chosen and \$14 if g_2 is chosen; and a blue ball is worth \$6 if g_1 is chosen and \$2 if g_2 is chosen.

Returning to our example, the expected value (calculated as $\frac{1}{2}(\$10) + \frac{1}{2}(\$6)$ for gamble g_1) is \$8 for both gambles. However, if, in comparing the two gambles, the decision maker is more concerned about the potential loss of \$4 ($\$6 - \2) when a blue ball is chosen, compared with the potential gain of \$4 ($\$14 - \10) when a red ball is chosen, then the decision maker may choose to play the 'less risky' gamble g_1 . This decision is consistent with an expected-utility calculation of the form $EU(g_1) = \frac{1}{2}U(\$10) + \frac{1}{2}U(\$6) > EU(g_2) = \frac{1}{2}U(\$14) + \frac{1}{2}U(\$2)$, which holds when the function U is concave, implying that $U(\$6) - U(\$2) \geq U(\$14) - U(\$10)$.

Suppose now that the dollar amounts in both gambles are replaced with negative amounts of the same magnitude: for example, \bar{g}_1 is a gamble whereby a subject loses \$10 or \$6, each with probability $\frac{1}{2}$, giving an expected loss of \$8. While \bar{g}_1 and \bar{g}_2 both have an expected loss of \$8, our subject may prefer to play the gamble \bar{g}_2 in order possibly to lose only \$2, and take the risk of losing \$14. In this case we would call the person a 'risk-taker', since he or she prefers the possibility of avoiding a \$4 loss (by going from \$6 to \$2) to the prospect of losing an additional \$4 (by going from \$10 to \$14). In this case, the utility function over losses is convex to the origin, satisfying $U(-\$10) - U(-\$14) < U(-\$6) - U(-\$2)$. Behavioral data support the hypothesis that individuals are risk-taking over losses, and risk-averse over gains (Friedman and Savage, 1948; Tversky and Kahneman, 1986). (See Figure 2.)

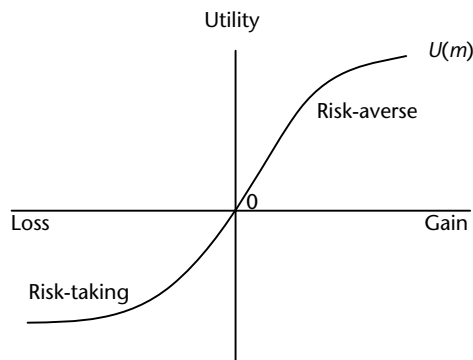


Figure 2. Utility $U(m)$ as a function of monetary gain ($m > 0$) or loss ($m < 0$). In experiments, subjects tend to apply a convex utility function for gains and a concave utility function for losses (see Friedman and Savage, 1948).

What objective function will the decision maker use to choose between the gambles? We would expect it to be sensitive to both probabilities and outcomes. Is there any evidence that the brain encodes this kind of information? Platt and Glimcher (1999) showed that the firing rates of lateral intraparietal neurons, in the posterior parietal cortex of rhesus monkeys, were modulated by the ratio of expected gains between two (juice reward) gambles, and consistent with the choices of the monkeys. In these cued saccade tasks, the experimenters varied both the gain associated with a particular response and the probability that a specific task would be required. As these variables were increased there was a commensurate increase in firing rates of specific lateral intraparietal neurons. The effects of both expected gain and outcome probability were strongest just before the monkey knew which response would be rewarded. Finally, in a free-choice task, where the monkey was not instructed, behavioral response frequency (towards the more favorable outcome) and the firing rate of posterior parietal neurons were correlated.

Using event-related functional magnetic resonance imaging, Breiter *et al.* (2001) studied brain activation in 12 humans who received monetary rewards or losses based on the outcome of a gamble chosen by the experimenter. Three different gambles were presented visually as spinners to subjects in a pseudorandom sequence. Each spinner had three equally likely outcomes. There was a 'good' spinner with outcomes of \$10, \$2.50 and \$0, an 'intermediate' spinner with outcomes of \$2.50, \$0 and $-\$1.50$, and a 'bad' spinner with outcomes of \$0, $-\$1.50$ and $-\$6$. Subjects were paid the

cumulative results from the gambles they played. This allowed the experimenters to examine the activation associated with reward expectancy, prospect stage, and the actual outcome stage. They observed a broadly distributed set of brain regions active in both the prospect and outcome stages of the gamble. They also observed significant hemodynamic response in the sublenticular extended amygdala and orbital gyrus, with both regions of interest rising monotonically with the expected value of the spinner, that is, from the bad spinner to the intermediate spinner to the good spinner. Finally, they observed some evidence for hemispherical specialization, with the right hemisphere predominantly active for gains, and the left hemisphere predominantly active for losses.

Using positron emission tomography, Smith *et al.* (2002) studied brain activation in nine humans who made choices between gambles resulting in monetary gains or losses based on the outcome of the gamble they had chosen. Within each block of choices, subjects chose several times between two different gambles. Each gamble had three possible outcomes, which depended on the random draw of a red, green, or blue ball from a container of balls at the end of the experiment. Each of the four blocks of choices consisted of either risky choices or ambiguous choices over either monetary gains or monetary losses. In the risky-choice treatment, subjects were shown a depiction of each gamble as a container with the number of balls of each color and the monetary payoff associated with each color, either positive (in the gain condition) or negative (in the loss condition). In the ambiguous treatment, the total number of balls was given, but not completely broken down by color, that is, the subjects could not be sure of the color of some of the balls in the container.

As expected from previous studies, subjects were risk-averse in the risky-gain condition and risk-taking in the risky-loss condition. Subjects showed ambiguity-aversion over both the loss and gain treatments. They showed a set of ventromedial activations consistent with the observations of Bechara *et al.* (1997) and Breiter *et al.* (2001) in the risky-gain condition. However, in the risky-loss condition, they showed a different set of dorsomedial activations.

STRATEGIC CHOICES WITH OTHERS

When the economic environment contains other individuals, their behavior must be anticipated in order to achieve good pay-offs. Figure 3 shows a

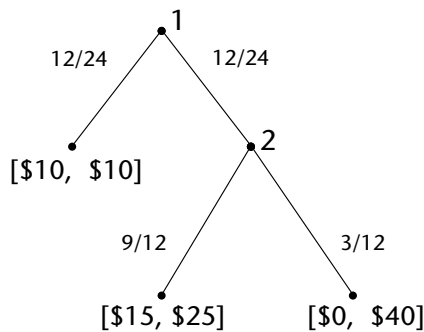


Figure 3. A simple game in which player 1 can either choose a pay-off vector of [\$10, \$10] or allow player 2 to choose between pay-off vectors of [\$15, \$25] and [\$0, \$40]. (The vectors represent the pay-offs to player 1 and player 2 in that order.) Out of 24 anonymously matched pairs, 12 player 1s chose to cooperate and 9 of their corresponding player 2s reciprocated.

simple example of a game in which cooperation can make both players better off. If player 1 moves right and player 2 moves left, then player 1 gets \$15 and player 2 gets \$25. However, player 2 may decide to move right in order to get \$40. If player 1 believes that this is how player 2 will behave, then player 1 should move left, ending the game and resulting in \$10 for each. In experiments where the game is played once between anonymously matched human subjects, half of player 1s moved right, and three-quarters of the player 2s who had the opportunity to move reciprocated by moving left. Therefore the expected gain for player 1 by moving right is greater than the \$10 sure thing.

In a functional magnetic resonance imaging study, McCabe *et al.* (2001) studied brain activation in 12 humans who played sequential two-person games similar to that shown in Figure 3. Half the time they played as player 1, and half the time as player 2. Each time they played, their counterpart was either a computer playing a fixed probabilistic strategy, or a human who was recruited to play outside the scanner. Subjects were told before the game began whether they were playing the computer or the human.

On the basis of their individual plays, 7 of the 12 subjects were labeled as 'cooperators' while 5 were labeled as 'non-cooperators'. The cooperators all showed greater prefrontal activations in the computer condition than in the human condition, but with greater individual variation in and around BA-8. A conjunction analysis also suggested a

common pattern of parietal, prefrontal, and frontal (BA-10) activations. By contrast, the non-cooperators did not generally display greater frontal activations in the human treatment than in the computer treatment. The observed activations in cooperators seem to be consistent with shared reciprocity intentions, resulting in both the inhibition of individual reward-seeking by player 2s and the inhibition of risk-avoiding behavior by player 1s.

References

- Bechara A, Damasio H, Tranel D and Damasio AR (1997) Deciding advantageously before knowing the advantageous strategy. *Science* **275**: 1293–1295.
- Breiter HC, Aharon I, Kahneman D, Dale A and Shizgal P (2001) Functional imaging of neural responses to expectancy and experience of monetary gains and losses. *Neuron* **30**: 619–639.
- Friedman M and Savage J (1948) The utility analysis of choices involving risk. *The Journal of Political Economy* **56**: 279–304.
- Goel V, Grafman J, Tajik J, Gana S and Danto D (1997) A study of the performance of patients with frontal lobe lesions in a financial planning task. *Brain* **120**: 1805–1822.
- Harlow JM (1848) Passage of an iron rod through the head. *Boston Medical Surgery Journal* **39**: 389–393.
- Knutson B, Westdorp A, Kaiser E and Hommer D (2000) fMRI visualization of brain activity during a monetary incentive delay task. *Neuro Image* **12**: 20–27.
- McCabe K, Houser D, Ryan L, Smith V and Trouard T (2001) A functional imaging study of cooperation in two-person reciprocal exchange. *Proceedings of the National Academy of Sciences* **98**: 11832–11835.
- Platt M and Glimcher P (1999) Neural correlates of decision variables in parietal cortex. *Nature* **400**: 233–239.
- Schultz W (2000) Multiple reward signals in the brain. *Nature Reviews: Neuroscience* **1**: 199–207.
- Schultz W, Dayan P and Montague R (1997) A neural substrate of prediction and reward. *Science* **275**: 1593–1599.
- Smith K, Dickhaut J, McCabe K and Pardo J (2002) Neuronal substrates for choice under ambiguity, risk, gains, and losses. *Management Science* **48**: 711–718.
- Thut G, Schultz W, Roelcke U *et al.* (1997) Activation of the human brain by monetary reward. *NeuroReport* **8**: 1225–1228.
- Tremblay L and Schultz W (1999) Relative reward preference in primate orbitofrontal cortex. *Nature* **398**: 704–708.
- Tversky A and Kahneman D (1986) Rational choice and the framing of decisions. *The Journal of Business* **59**: S251–S278.