Neural foundation for regret-based decision making

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Neural foundation for regret-based decision making

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Humans decisions are not only driven by rationality but they are strongly influenced by emotions. Neuroscientific evidence shows how the brain attributes affective values to the alternative of our choices in terms of current or anticipated emotional experience.

Patterns of reactivation of neural circuitries related to emotional responses are found at the time of choice when the brain is anticipating future consequences. Those patterns are the result of learning mechanisms derived from cumulative emotional experience. Here we describe the theoretical and neural basis of such adaptive processes based on regret.

emotions - neuroeconomics - decision making - rational choice - regret theory

Les fondements neuronaux de la décision basée sur le regret

Chez l'Homme, les décisions ne sont pas seulement déterminées par la rationalité, mais se trouvent également fortement influencées par les émotions. Les recherches en neurosciences ont montré que le cerveau attribue une valeur affective à chacune des alternatives d'un choix. Cette valeur affective est basée sur une expérience émotionnelle actuelle ou anticipée. Les circuits neuronaux liés aux réponses émotionnelles sont réactivés lors d'un choix, au moment où le cerveau anticipe les futures conséquences de ce choix. Ces patterns d'activations résultent de mécanismes d'apprentissage liés à l'accumulation d'expériences émotionnelles. Nous décrivons ici les bases théoriques de ces processus adaptatifs liés au regret ainsi que les mécanismes neuronaux associés.

émotions - neuroéconomie - choix rationnel - théorie du regret

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Introduction

Economists have produced remarkable data describing how we make our choices (how much we save, why there are strikes, why the stock market fluctuates, and so forth). Until very recently, this approach treated the human brain as a "black box" and suggested mathematical equations which simplify what it is doing. This "rational choice" approach has been enormously successful at yielding a simplified theory of the brain processes underlying these economical strategies. More recently, the introduction of neuroscience tools (brain imaging techniques, lesion studies, single cell recording in non-human primates) and increasing evidence as to the importance of emotional and social states in economic decision-making, are opening new perspectives in the field of neuroeconomics (McCabe [2003]; Camerer [2004]; Camerer *et al.* [2004]; Glimcher and Rustichini [2004]; Sanfey [2006]).

This paper concerns the representation of value and the influence of emotions in decision making. We discuss scientific literature which uses a fundamentally multidisciplinary approach drawing from economics, psychology, neuropsychology, neuroimagery, and cognitive neuroscience. Our approach relies on robust behavioral tasks for which the optimal response is established, and we will investigate how emotional states affect these optimal responses. These processes are addressed in human subjects, both in the context of normal and altered brain functions.

How the brain mediates hedonic experience. Subjective hedonic processing

An economic choice is based on the evaluation of the choice alternatives. In what follows we describe how the brain assigns values. We use the terminology, commonly used in neuroscience, thus we talk about rewards or punishers, to indicate any external object for which an organism would make an effort for obtaining or avoiding it, respectively (Rolls [1999]). The correspondents of the economics gains and losses.

Rewards (and punishers) processing mechanisms: from a fast *bottom-up* process (first level) to a *top-down* representational system (second level). There are different levels of reward processing in the brain. A first level is based on the activity of the dopaminergic neurons. Dopamine is a chemical (that works as neurotransmitter) released in the midbrain areas, such as the ventral tagmentum, and the substantia nigra. The activity of these neurons is characterized by a fast (bottom-up) process of alert and teaching signal, which represent an efficient basic learning mechanism (error prediction).

Midbrain neurons are able to distinguish rewarding from no-rewarding stimuli (punishers) in the environment; they define expectations, and detect the mismatch between expected and actual responses. Once the stimulus response association is established, those neurons are active only when the response is larger than the expected and suppressed (deactivated) when the response is unexpectedly unfavorable. Formally activity related with expectation formation and error detection can be modeled as follows:

$$EV_t = k if \phi(s) \geq \lambda, or 0 if \phi(s) < \lambda \qquad [1]$$

$$Errorsignal_t = \Delta(RV_t - EV_t) \qquad [2]$$

Where EV is the expected value; λ is a threshold below which there is no evaluation about the stimulus (s); ϕ is a learning function monotonically increasing with respect to the experiencing of s until learning is completed, and then is stationary at k; RV indicate the response value. The error signal is positive (negative) if the value of the response is greater (lower) than expected (Schultz *et al.* [1997]; Schultz [1998, 2002]; Tobler [2005]). This learning and alert activity is extremely efficient, but limited to "single" reward processing.

With the first level of reward processing the brain is not able to discriminate between different rewards (alternatives), which is the main point of economic decision making. Other reward systems are related with neuronal activity in the orbitofrontal cortex, anterior cingulate, and the amygdala. Those systems are related with learning to select appropriate rewards on the basis of relative preferences or affective values.

The orbitofrontal cortex represents the relative values of different rewards, and the subjective pleasantness of reinforcers (primary reinforcers, such as food, sex; and secondary, abstract reinforcers, such as money). In economic terms, it represents the subjective preferences. Neurons in this region of the brain encode the relative values of different choice alternatives (Padoa-Schioppa and Assad, [2006]). Tremblay and Schultz ([1999]) demonstrated how OFC neurons fire when the relatively preferred available reward, between pairs of rewards, is delivered, thus "revealing" the monkey preferences. Corroborating results come from a more recent study (Padoa-Schioppa and Assad [2006]), where monkey is asked to choose between combinations of amounts of different rewards. Also in this case, the OFC neurons fire according to the monkey's preference structure and actual choices. This activity of the OFC corresponds to an high level representational function of the values of external stimuli.

First and second level of reward processing are strongly interconnected. Indeed, reward information coming from the first level can be used to define and update relative reward values and subjective preferences. The information coming from the dopamine reward responses (first level) enter into the cognitive/emotional representations of the reward, in terms of subjective preferences and affective values.

The neural basis of emotions elicited by rewards (gains) or punishers (losses)

The above distinction between first and second level of reward processing could apply also to emotions (Schachter and Singer 1962, Cognitive arousal theory of emotion). In what follows we describe evidence from patients and neuroimaging studies that show the neural correlates of human emotional processing in decision making.

Evidence from brain injured patients

Evidence in cognitive neuroscience shows that patients with focal lesions of the prefrontal lobe are impaired in many aspects of social and individual decision-making (Damasio [1994]; Bechara *et al.* [1994]; Eslinger and Damasio [1995]; Goel *et al.* [1997]; Bechara *et al.* [1997]; Anderson *et al.* [1999]). The consequences of their behavior are often disadvantageous and socially inappropriate. Examples are the tendency to loose their job, the inability to maintain stable personal relationships, and the repeated engagement in disastrous financial investments. The major anomaly consists in the fact that their behavior is not due to lack of knowledge or to limited intelligence (Saver and Damasio [1991]). They are, indeed, able to represent and judge correctly abstract social and individual contexts, while failing in analogous real-life situations.

Damasio and colleagues (Damasio [1994]; Bechara *et al.* [2000a], Bechara *et al.* [2000b]) explain the orbitofrontal patients' impairment in decision-making by their inability to generate "somatic markers" that might anticipate the consequence of their actions. This hypothesis has been exclusively tested with a gambling task characterized by the complete uncertainty of the outcomes, before choosing; and the impossibility for the subject to compare the outcome of the chosen alternative and the outcome of the rejected alternatives, when the feedback is provided. In our study (Camille *et al.* [2004]; Coricelli *et al.* [2005]) we extended Damasio's analysis to a context of risky choice in which the subject knows, before choosing, the probabilities and the outcomes of the possible alternatives. In addition, by manipulating in the feedback the subject's exposure to the outcome of the rejected alternative we can distinguish between (specific) emotions involving disappointment and regret.

The somatic marker hypothesis principally emphasized bottom-up influences of emotions on cortical decision processes (Damasio, [1994]; Bechara et al, [1994; 2000]). We propose a different role whereby the orbitofrontal cortex exerts a top-down modulation of the gain of emotions thanks to counterfactual reasoning, after a decision has been made and its consequences evaluated. As shown by the model of choice, the feeling of responsibility for the negative result, *i.e.* regret, reinforces the decisional learning process.

Normal control subjects (Camille *et al.* [2004]) report emotional responses consistent with counterfactual reasoning between obtained and non-obtained outcomes; they choose to minimize future regret and learn from their emotional experience. The intensity of an emotional response, which can transform disappointment into painful regret when the outcome of a rejected alternative turns from mildly to highly valuable, has been found a better predictor of subsequent choices than expected utility alone. By contrast, patients with lesions of the orbitofrontal cortex do not report regret and do not anticipate negative consequences of their choices. These results suggest that orbitofrontal cortex has a fundamental role in experiencing regret. The orbitofrontal cortex thus appears to be at the interface of emotion and cognition, and is ideally suited to control emotional experience through mechanisms such as counterfactual reasoning (Byrne [2002]).

We showed that regret generates higher physiological responses and is consistently reported by normal subjects as more intense than disappointment. This was not the case in orbitofrontal patients, demonstrating that distinct neural processes generate these two emotions. The specificity of the orbitofrontal region in mediating regret is strengthened by the finding that three control patients with lesions in other parts of the frontal lobes showed normal regret levels and choice behavior in our gambling task.

The emotions related to experiencing gains or losses are not independent from the alternative outcomes

Indeed, it is the counterfactual reasoning between the obtained and unobtained outcomes that determines the quality and intensity of the emotional response. Regret and disappointment are elicited by two different counterfactual comparisons characterized by two different levels of personal responsibility for the consequence of one's own choices. The absence of regret in orbitofrontal patients suggests that these patients fail to grasp this concept of liability for one's own decision that colors the emotion experienced by normal subjects.

A neuroimaging study of choice behavior

We conducted a neuroimaging study in collaboration with Ray Dolan and Hugo Critchley from UCL, London (Coricelli *et al.* [2005]). We measured brain activity using functional magnetic resonance imaging (fMRI) while subjects selected between two gambles wherein regret was induced by providing information about the outcome of the unchosen gamble. Increasing regret enhanced activity in the medial orbitofrontal region, the anterior cingulate (Bush [2000]) cortex and hippocampus (Eichenbaum [2004]). Crucially, across the experiment subjects became increasingly regret aversive, a cumulative effect reflected in enhanced activity within medial orbitofrontal cortex and amygdala. This pattern of activity was re-expressed just prior to making a choice, suggesting that the same neural circuitry mediates direct experience of regret and its anticipation. These results demonstrate that medial orbitofrontal cortex modulates the gain of adaptive emotions in a manner that may provide a substrate for the influence of high level emotions on decision-making.

We show that activity in response to this negative emotion is distinct from activity seen for mere outcome evaluation. In our brain imaging data, the influence of personal responsibility on outcome processing was evident while contrasting outcome-related activity for choose trials (where the subject selected which gamble to "play") with follow trials (where "choice", *i.e.*, follow, was computer-selected). In accordance with psychological theory we also find a neuroanatomical dissociation between regret and disappointment. Thus, outcome evaluation is influenced by the level of responsibility in the process of choice (agency) and by the available information regarding alternative outcomes (complete or partial feedback). The level of regret, calculated in terms of the magnitude of the difference between a forgone and obtained outcome was strongly correlated with activity in the medial OFC. These findings point to a more complex relationship in OFC than a simple medial- lateral specialisation for reward or punishment. Our data would suggest that cognitive context, exemplified by counterfactual thinking in relation to states of the world, exerts a modulatory influence on OFC activation related to reward and punishment. The critical finding in our study concerns the role of OFC which we suggest integrates cognitive and emotional mechanisms following a declarative process in which distinct counterfactual processes engender a high level emotion of regret. Our data suggest a mechanism through which comparing choice outcome with its alternatives, and the associated feeling of responsibility, promotes behavioural flexibility and exploratory strategies in dynamic environments so as to minimise the likelihood of emotionally negative outcomes.

In what follows we show how this evidence from the brain is related with recent theoretical works in economics. Both theory and neural data show the adaptive role of emotions such as regret.

Economics models of adaptive behavior: Regret based adaptive heuristics in an interactive dynamic settings (in which the same game is repeatedly played over time)

Economists propose a class of learning rules based only on "realized payoffs". The computational simplicity of those rules resolves the difficulties and limitations of the rational Bayesian approach. These form of regret based rules have optimal long term properties (converge to correlated equilibria).

For instance, Hart & Mas-Colell [2000, 2001, 2003] consider the 'regret-matching' procedure as an adaptive heuristic (suboptimal behavioral rule). With regret matching, *players may depart from their current play with probabilities proportional to measure of regret for not having used other strategies in the past.* Thus, they randomize among actions considering the regret of not having used those actions in the past. This procedure deviates from full rationality in the short run, but theoretically converge to a specific set of correlated equilibria. The matching rule leads the joint empirical frequency distribution of the players to converge to a set of correlated equilibria. The correlated equilibrium is a game theoretical solution concept (a refinement of Nash equilibrium) introduced by Auman in 1974. Correlated equilibrium arises when players choose their actions according to a set of received signals or instructions (which do not affect the payoffs of the game). If the signals are stochastically independent among players, then the correlated equilibrium is equivalent to Nash equilibrium of the original game; in case of dependence of the signals there would be additional correlated equilibria of the game. The context of the correlated equilibrium is one in which there is a "device" (or referee) that assigns (privately) play instructions to the players of a game. The equilibrium is a probability distribution of those instructions, which provide the best response (rational) to the others' players instruction-based actions. The signal based (correlated equilibrium) solution concept in practice extremely relevant (considered as the most relevant by Hart and Mas-Colell), considering that correlated signals are almost always available in interactive settings. Also emotions (emotional expressions) could be considered as signals (payoff irrelevant signal that players show before playing the game).

The regret-matching (*per se*) is a simple behavioral procedure not based on best reply, but on better replies to any possible action of others. Any better action can be chosen with probability proportional to a measure of regret. In a dynamic setting (repeated game), the player needs to decide in each trial between keeping the strategy just played or switching to other strategies. Based on regret matching procedure, the player would change his current strategy for a forgone alternative that would have given higher payoff. Calling U the player's total payoff resulting from strategy j, and $V(k)$ the forgone payoff if was played strategy k every time in the past, then $V(k) - U$ represents the regret (if $V(k) > U$) of having played the strategy j instead of k. The probability of switching behavior is proportional to the value of the measure of regret. This simple adaptive (in the sense that leads to flexible behavior) procedure (heuristic) is a boundedly rational strategy leading in the long run (at infinitive) to the rational and sophisticated solution of the game (correlated equilibrium). The regret matching requires low level of rationality. It is based on simple computations of the realized payoff (as the result of the used strategy) and the forgone payoffs of alternative strategies. Using the regret matching rule, the player does not need any information about the opponent's payoffs or actions (Hart and Mas-Colell, prove that the convergence of the regret matching rule to the correlated equilibria arises also for *the (extreme) case of the unknown game,* in which players do not know the game and the choices of other players). This computations being dramatically less complex and demanding compared with full rational optimization dynamics; such as belief-learning process (Bayesian learning), which requires updates at any period of (prior) beliefs of others using Bayes' rule, and the definition of best replies to them, thus choosing the optimal action given their beliefs (Kakai & Lehrer [1993]). Critics to the Bayesian approach, emerge from the fact that Bayesian players often deviate from Nash in a period-by-period behavior in situations of incomplete information (the payoff of the opponents are unknown) even when the prior about others' players payoff are correct.

The regret matching rule is adaptive in the sense that it leads to flexible behavior (switching to "better" strategies), inducing dynamics similar to reinforcement learning models based on stationary stochastic adjustment, such as the fictitious player. These characteristics of the regret matching procedure make it reasonably suitable for being implemented in actual ("real") decision making in interactive dynamic settings. For example, in financial decisions investors often behave using a regret matching procedure, switching to other investment when they realize they would have gained more money if they had chosen another investment, this switching probability being proportional to the amount of missed gains.

Foster and Young propose a similar adaptive procedure, called *regret testing.* This procedure is analogous to aspiration learning models, in which players stochastically change actions if the realized payoff are less than an aspiration level (payoff that the subject hope to achieve). With this rule the players' decision to switch (probabilistically) to other distribution over actions is driven by regret. Regret arises when the payoff from a randomly chosen action is higher than the current aspiration level (realized payoff). Foster and Young prove that the regret testing procedure leads to (arbitrarily close to) Nash equilibrium of the period-by-period behavior in any finite two-person game. Thus, showing how payoff-base rules can approach equilibrium behavior.

Both Hart and Mas Colell and Foster and Young theories of adaptive learning based on regret aim at supporting rational equilibrium concepts, but not a positive description of decision making (as stated by Rustichini).

Maccheroni-Marinacci-Rustichini [2007] give an axiomatic theory of regret based on data from brain processes, and a positive theory of the function of regret in adaptive learning processes. Findings on the OFC and amygdala activity in Coricelli *et al.* [2005] gambling task, suggest an involvement of regret in learning processes. As stated by the authors "While it is conceivable that regret serves no functional purpose in decision making and learning, the evidence reported in Coricelli *et al.* [2005] induces us to postulate and theorize about the connection between learning and regret."

Conclusions

Experimental and theoretical results demonstrate an adaptive role of cognitive based emotions, such as regret, while those emotions also figures prominently in the literature of learning in games. A remarkable result in this literature is that if players in a game minimize regret, the frequency of their choices converges to a correlated equilibrium (*i.e.*, the rational solution) of the game. This has a general implication for our understanding of the role of emotions in decision making and rejects the dual/conflict view of "emotion vs. cognition" (rationality) by showing the powerful consequences of full integration between those two components of human decision making.

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