Reward-based emotions: affective evaluation of outcomes and regret learning

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Summary (150 words)

This chapter concerns the behavioral effects and the neural substrates of a class of reward-based emotions, which are emotions elicited by rewards and punishers. We describe how outcome evaluation is influenced by the level of responsibility in the process of choice (agency) and by the available information regarding alternative outcomes. The data we report suggest that cognitive context, exemplified by counterfactual thinking (what might have been if a different state of the world had realized) exerts a modulatory influence on the orbitofrontal cortex activation to rewards and punishers. The orbitofrontal cortex is also critically involved in learning in environments where the information about the rewards of the alternative foregone actions is available. These processes are addressed in humans, both in the context of normal and altered brain functions.

Key points/concepts

Immediately after the Summary provide around 5 separate sentences presenting key concepts developed in the chapter.

- *The emotions related to experiencing rewards or punishers are not independent from the outcomes that have not occurred. Indeed, it is the counterfactual reasoning between the obtained and unobtained outcomes that determines the quality and intensity of the emotional response*.
- *A key behavioural observation is that patients with lesions in the orbitofrontal cortex are unable to experience regret and to anticipate the potential affective consequence of their choices.*
- *There exists a neuroanatomical dissociation of regret versus disappointment. The ventral tegmental area and ventral striatum are associated with the reward prediction error models, while regret learning is associated with the orbitofrontal cortex.*
- *Negative affective consequences (regret) induce specific mechanisms of cognitive control on subsequent choices.*
- *The counterfactual reasoning extends from private to social learning.*

This chapter outlines the neural basis of a class of reward-based emotions and their fundamental role in adaptive behavior. We address the following questions: What are the neural underpinnings of reward-based emotions such as disappointment and regret? What are the theoretical implications of incorporating reward-based emotions into the process of choice, and into adaptive models of decision making? We discuss scientific literature which uses a fundamentally multidisciplinary approach drawing from economics, psychology, cognitive and computational neuroscience. Our approach relies on robust behavioral tasks for which the computation underlying optimal responses is established, and we investigate how emotional states affect these optimal responses. In line with recent work on emotion-based decision making we attempt to characterize the brain areas underlying decision processes in individual and social settings and, more specifically, define the functional relationship between “rational” decision making and emotional influences that impact on these decisional processes. Our focus, by way of illustration, is on the contribution of the orbitofrontal cortex (OFC) in both the experience and anticipation of reward-based emotions, such as regret.

Reward-based emotions: Emotions as affective evaluations of outcomes

Emotions may be considered as the affective evaluation of a difference between an expected and a realized reward. For instance, the negative (positive) difference between the realized and the expected reward may elicit disappointment (elation), while regret is elicited by a comparison (counterfactual (Roese and Olson, 1995; Byrne, 2002; Zeelenberg and van Dijk, 2004)) between the outcome of a choice and the better outcome of a foregone rejected alternatives (what might have been). Regret differs from disappointment in its abstract point of reference: it arises from a discrepancy between the actual outcome and an outcome that would have pertained had an alternative choice been taken. Regret is an emotion characterized by the feeling of responsibility for the negative outcome of our choice (Bell, 1982; Loomes and Sugden, 1982; Gilovich and Melvec, 1994); while, disappointment is the emotion related to an unexpected negative outcome independently of the responsibility of the chooser (Loomes and Sugden, 1986; Bell, 1995).

Anticipation of regret induces changing in behavioral strategies (Ritov, 1996), and characterizes the learning process in decision-making (Zeelenberg et al., 1996). Regret results from a decision made and the possibility to compare the obtained outcome with better outcomes of rejected alternatives. The type of feedback information is indeed crucial to determine the emotional response (Frijda, 1986) and the decisional process is influenced from the knowledge about the future feedback available. Therefore, the psychological and behavioral impact of outcome (win and losses) is influenced by the amount of feedback information provided to subjects.

One important question is whether regret and disappointment are encoded by specific cerebral regions. Camille et al. (Camille et al., 2004) studied the relationship between decision-making and emotion in normal subjects and in patients with selective lesions to the OFC. The experimental task (regret gambling task, see Fig. 1) required subjects to choose between two gambles, each having different probabilities and different expected outcomes. Disappointment could arise when, on a selected gamble, the alternative outcome is more positive than an experienced outcome. Regret was induced by providing information regarding the outcome of the unchosen gamble. When subjects were asked to rate their emotional state after seeing the obtained outcome, normal controls reported emotional responses consistent with counterfactual thinking between obtained and non-obtained outcomes. Thus, a win of $50 when the alternative gamble won $200 induced a strong negative emotion. Conversely the same outcome when confronted with a losing alternative gamble (-$200) created a feeling of relief. After being exposed to a number of trials where they experienced regret, control subjects subsequently begun to choose the gambles with probable outcomes likely to produce minimal regret, indicating that they learnt from their prior emotional experience. Therefore, control subjects chose between risky gambles by a process that involves anticipating regret, thus integrating consideration about future emotional responses to the outcome of their choice.

By contrast, patients with lesions of the orbitofrontal cortex did not report regret and did not anticipate negative affective consequences of their choices. They reported as being happy when winning and disappointed when losing. Their emotional states were even modulated by the amount of win (+$50 or +$200) or the amount of loss (-$50 or -$200) but not by the value of the outcome in the alternative unchosen gamble. More striking, they persisted in choosing the gamble that normal subjects avoided because more likely to produce regret. Thus, OFC patients are unable to generate outcome evaluation and outcome expectancies, based upon a counterfactual comparison between the value of a chosen and a rejected alternative. Formally, they are unable to generate a specific function, called regret function (Bell, 1982), which represents the counterfactual comparison between the realized outcome and the outcome of the unchosen alternative. Furthermore, the OFC patients are not able to incorporate experienced regret into the process of choice behavior, and do not anticipate regret or learn from their regret inducing decisions.

The study by Camille et al. 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 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. It is important to highlight the fact that OFC patients are not emotionally flat or unresponsive. For instance these patients expressed a normal level of disappointment in Camille et al.(Camille et al., 2004), and a higher than normal level of anger in response to unfairness in social situations (unfair offers in an Ultimatum Game)(Koenigs and Tranel, 2007). *Thus, a key behavioural observation is that patients with lesions in the orbitofrontal cortex are unable to experience regret and to anticipate the potential affective consequence of their choices.* This result has been confirmed by a recent neuropsychological study that demonstrates the critical role of the OFC in learning from the experience of negative feedback (Fellows 2008).

Coricelli et al. (Coricelli et al., 2005) measured brain activity using functional magnetic resonance imaging (fMRI) while subjects participated in the regret gambling task. Increasing regret was correlated with enhanced activity in the medial orbitofrontal region, the dorsal anterior cingulate cortex (ACC) and anterior hippocampus. This hippocampal activity is consistent with the idea that a cognitive-based declarative process of regret, is engaged by the task. This supports a modulation of declarative (consciously accessible) memory (Eichenbaum, 2004; Steidl et al., 2006) such that after a bad outcome the lesson to be learnt is: "in the future pay more attention to the potential consequences of your choice". Furthermore, Coricelli et al. (Coricelli et al., 2005) showed that activity in response to experiencing regret (OFC/ACC/medial temporal cortex) is distinct from activity seen with mere outcome evaluation (ventral striatum), and in disappointment elicited by the mismatch between actual and expected outcome of choice. Indeed, the magnitude of disappointment correlated with enhanced activity in middle temporal gyrus and dorsal brainstem, including periaqueductal gray matter, a region implicated in processing aversive signal such as pain. This suggests distinctive neural substrates in reward processing, and the fact that the OFC and medial temporal cortex areas can bias basic dopamine mediated reward responses (De Martino et al., 2006).

OFC activity related with the level of responsibility in the process of choice (agency), and with the available information regarding alternative outcomes (regret), influences basic responses related to reward (monetary wins) and punishers (monetary losses). *Thus, the emotions related to experiencing rewards or punishers 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.

In several studies medial OFC activity reflects reward attainment (Rolls, 2000; Breiter et al., 2001; Gottfried et al., 2003); while lateral OFC is often associated with reversal learning, where subjects need to change behavioral strategies that are no longer advantageous (Elliott et al., 2000; O'Doherty et al., 2001; Fellows and Farah, 2003; Hornak et al., 2004). This has been interpreted as suggesting that medial OFC may support positive emotions, and lateral OFC may support emotions with negative valence. Nevertheless, other neuroimaging studies (Coricelli et al., 2005) highlight a more complex role in reinforcement representations that is also suggested by lesion data (Camille et al., 2004)(lesions of medial OFC do not impair processing of primary rewards).

OFC has a fundamental role in adaptive behavior. Coricelli et al. (Coricelli et al., 2005) reported that, across their fMRI experiment subjects became increasingly regret aversive, a cumulative effect reflected in enhanced activity within ventro-medial orbitofrontal cortex and amygdale (see Fig. 2). Under these circumstances the same pattern of activity that was expressed with the experience of regret was also expressed just prior to choice, suggesting the same neural circuitry mediates both direct experience of regret and its anticipation. OFC activity related to the effect of experienced emotions in relation to potential behavioral adjustment has been also found in a recent study by Beer et al. (Beer et al., 2006). Thus, the OFC and the amygdala contribute to this form of high level learning based on past emotional experience, in a manner that mirrors the role of these structures in acquisition of value in low-level learning contexts (Gottfried et al., 2003). Indeed, animal (Amorapanth et al., 2000) and human neuroimaging (Buchel et al., 1998; LaBar et al., 1998; O'Doherty et al., 2002; LaBar and Cabeza, 2006) studies assign a fundamental role to the amygdala in classical conditioning experiments, indicating its role in associative learning (acquiring cue outcome association). Schoenbaum et al. (Schoenbaum et al., 2003a), recording in the OFC in ABL lesioned rats, found loss of acquisition of associative information, while the process of outcome anticipation remained intact. This suggests that the basolateral amygdala inputs value-related associative information into the OFC (Schoenbaum et al., 2003b). On the other hand, lesions on the rats' OFC reduced ABL associative encoding ability, showing that OFC itself facilitates learning (Saddoris et al., 2005).

Moreover, the affective consequences of choice, such as the experience of regret, can induce specific mechanisms of cognitive control (Yarkoni et al., 2005). Coricelli et al. (Coricelli et al., 2005) observed enhanced responses in right dorsolateral prefrontal cortex (see Fig. 2), right lateral OFC and inferior parietal lobule during a choice phase after the experience of regret (Coricelli et al., 2005), where subsequent choice processes, induced reinforcement, or avoidance of, the experienced behavior (Clark et al., 2004). Corroborating results from Dimon-Thomas et al. (Simon-Thomas et al., 2005) show that negative emotions can recruit cognitive-based right hemisphere responses. *Thus, negative affective consequences (regret) induce specific mechanisms of cognitive control on subsequent choices.*

These data suggest a mechanism through which comparing choice outcome with its alternatives, and the associated feeling of responsibility, promotes behavioral flexibility and exploratory strategies in dynamic environments so as to minimize the likelihood of emotionally negative outcomes. In what follows we show how this evidence from brain studies is related with recent theoretical works in economics. Both theory and neural data show the adaptive role of emotions such as regret.

Reward-based emotions implement learning

Emotions may be considered as the affective evaluations of a difference between an expected and a realized value. What ``value'' is depends on the specific choice that is being considered. This general hypothesis assigns to emotions a functional role: learning of the agent is adaptive learning (as opposed to Bayesian learning), and therefore it has to adjust the current value function to a new, updated value function. Emotions keep track of the difference between expected and realized value, and increase or decrease the value depending on the difference.

As we have seen, the difference between the expected and the realized reward of the chosen action may be called disappointment (Loomes and Sugden, 1986; Bell, 1995). This is a first example of the association between an affective evaluation of the difference between expected and realized value. In current theories of temporal difference (TD) prediction error (Dayan, 1994; Schultz, 2002; Montague et al., 2006a), and in current analysis of the dopaminergic implementation of the TD model (Schultz et al., 1997; Schultz, 1998a; Schultz et al., 1998; O'Doherty, 2004; Seymour et al., 2004), disappointment is the only emotion that is being considered.

Reward prediction error model. The prediction error is a fundamental component in the adaptive learning of optimal actions (Dayan and Niv, 2008). In the prediction error model, a value is assigned to every state that the individual faces in his choices. This value is an approximation, and it is updated in every period. The value at the current state is equal to the sum of two terms: the reward at the current state and action plus the continuation value from future state. The prediction error is the difference between what is realized and what is expected. The realized value is the current reward plus the continuation value in the next state, according to the current value function. The expected value is the current value of the current state. The value function is updated by adding a term, typically linear in the difference, to the current value. This process has, under some technical conditions, good properties: the value function converges to the solution of the optimal dynamic programming problem, that is to the true (under the optimal policy) value function at that state. In this evaluation, the action is the chosen action for the current period. Actions that were available and not chosen are ignored, even if the outcome of those actions is known to the individual.

A model of counterfactual evaluation: Regret learning. Regret embodies the painful lesson that things would have been better under a different choice, thus inducing a disposition to behavioral change. People, including those with a deep knowledge of optimal strategies often try to avoid the likelihood of future regret even when this conflicts with the prescription of decisions based upon rational choice, which predicts that individuals faced with a decision between multiple alternatives under uncertainty will opt for the course of action with maximum expected utility, a function of both the probability and the magnitude of the expected payoff (Von Neumann and Morgenstern, 1944). The theory we adopt makes reference to existing theories of regret as a form of adaptive learning, in the tradition of the Megiddo-Foster-Vohra-Hart-MasColell (Megiddo, 1980; Foster and Vohra, 1999; Hart and Mas-Colell, 2000; Foster and Young, 2003; Hart, 2005) regret-based models. In these theories, learning adjusts the probability of choosing an action depending on the difference between the total rewards that could have been obtained with the choice of that action and the realized rewards. For example, in the Hart-MasColell (Hart and Mas-Colell, 2000) *regret-matching rule model* the regret for having chosen the action *k* instead of *j* is the difference between the total reward obtained if action *j* had been chosen instead of *k* in the past, and the total realized value. The probability of choosing an action is determined in every period by adjusting upwards the probability of choosing the actio *j* by an amount proportional to the regret. This type of procedures have optimality properties just as the adjustment process based on prediction error: the Megiddo theorem (Megiddo, 1980) for the single player case, and the Foster-Vohra-Hart-MasColell theorems for games show that this procedure converges to optimal choices in the single player case and to correlated equilibria in the case of games.

The regret matching rule is adaptive in the sense that 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 dynamic settings. For example, in financial decisions investors often behave using a regret matching procedure, switching to other investment when they realize that they would have gained more money if they had chosen other investment, and this switching probability is proportional to the amount of missed gains.

Foster and Young (Foster and Young, 2003) 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.

In computational neuroscience a similar type of reinforcement learning is called 'fictive learning' or counterfactual Q-learning (Montague et al., 2006b; Lohrenz et al., 2007). In these models the error signal is a 'fictive error' computed as the difference between the obtained reward and the rewards of alternative foregone actions. The function that represents the effect of the foregone actions contributes to the update of values in addition to a standard Q-leaning critic function.

What should adaptive learning do?

Two problems seem important. The first is that any adaptive procedure to be plausible should have a satisfactory performance from the point of view of the reward: for example, the regret matching rule leads the choice of an action maximizing expected reward. The fictive learning does not satisfy this condition in an obvious way.

If we do impose some performance criterion, then a second problem arises. Recall that an action has a dual role: it affects the current reward and the transition to the next state. This makes introducing counterfactual thinking into adaptive learning a subtle problem, because we can observe the rewards from other actions, but we cannot observe the transition that would have been produced by them. When an action *a* out of a set A, say, is chosen, the individual may have available the information on the reward of all the elements in A, and can then compare the reward from *a* with the reward from the other actions. If the reward from an element in A, *b* say, different from *a* is larger, then regret seems natural, and an effective way to use the counterfactual information. It would however be deeply wrong, since it would ignore the effect that the actions have on the transition to the next state. Differently from the rewards, the information on where the state would have transited to if *b* had been chosen is not available to the individual. But if the effect on the transition is ignored, then the relative value of the two actions can be grossly distorted. For example, suppose that the action *b* gives a large reward today but makes the state go to a state tomorrow where rewards are very low, while a gives a smaller reward, but also keeps the state in a good position. If *a* is chosen, the regret we feel by looking at the reward from *b* would be mistaken, because *b* free rides on the good effect of *a* on the state.

We suggest a general theoretical framework to address the general issue of integrating adaptive learning with counterfactual thinking. One important difference between the prediction error model and the counterfactual model is the neural basis of the two: from the existing literature on the topic we know that the ventral tegmental area (Schultz, 1998a, b) and ventral striatum (O'Doherty, 2004; Seymour et al., 2004) are usually associated with the reward prediction error models, while we propose that 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 can be evaluated. Thus, the feeling of responsibility for the negative result, i.e. regret, reinforces the decisional learning process.

Private and Social rewards

Regret is an emotion which is limited to the private sphere: the counterfactual comparison that motivates regret is limited to the set of choices that were available to the individual decision maker. But we live in a society, and many if not most of our choices are not made in isolation: we observe others that make similar choices, and we can observe their outcome as well. The same logic suggesting that using the information on the outcome of the actions we did not choose is useful in improving our future performance also suggests that we should use the information on the outcome of actions that *others* chose. *The counterfactual reasoning extends from private to social learning.* This is Festinger’s idea, presented in his theory of Social Comparison ((Festinger, 1954). In this view, regret has a social correspondent, envy. Just as regret derives from the comparison between what we received from an action, and what we could have received from action that we did not take, so envy may simply derive from the comparison between the outcome from the action we chose and the outcome from an action we did not choose but someone else did.

Emotional evaluation of social rewards is more complex, however, because outcomes that are socially observable also affect the relative ranking of individuals, and so this evaluation is the result of social learning and social ranking. The work by Bault et al. is a way of experimentally separating the two components (Bault et al., 2008). The goal of this study was first to directly compare how individuals evaluate the outcome of their decision in private versus social contexts, with the hypothesis that for a given outcome, social context will enhance emotional responses due to social comparison. More importantly, the study was designed to investigate whether social and private emotions influence monetary decisions in different ways. In Bault et al. participants choose among lotteries, with different levels of risk, and observe the choice that others have made. They are then informed of the monetary outcome of their choice and the choice of others, and have the opportunity in this way to experience regret and envy, or their positive counterparts (relief and gloating). Emotions in the social condition, for the events in which participants made different choices, are stronger than in the single player condition. The second result is that social emotions operate differently from private ones: while regret looms larger than relief, gloating looms larger than envy. The effect in not induced by any social emotion (as opposed to non-social) as shared regret and shared relief received weaker ratings than regret and relief experienced in a non-social context. Thus, envy and gloating matter more because they are socially competitive emotions not just interpersonal ones (Fig. 3). When analyzing choice behavior Bault et al. found an important difference between the private and the social dimensions. In both cases deviations from expected utility are explained by the effect of the difference between the obtained outcome and the alternative possible outcome. In the private domain, the alternative outcome is that of an action that was not chosen, and aversion to loss (regret) dominates. In the social environment the alternative outcome is that of a choice made by another person, and love of gain (gloating) dominates.

A particularly important issue is the relative attitude to gains and losses in counterfactual evaluations. Regret is a negative affective state: but counterfactual thinking may produce, if the choice was right, an opposite emotion, a positive affective state induced when the outcome of the chosen action is better than the outcome from actions that were not taken. This emotion we may call relief. The general idea described in Prospect Theory (losses loom larger than gains) may be translated in the present context into the conjecture that counterfactual losses (regret) loom larger than counterfactual gains (relief).

Since, as we have just seen, social counterfactual thinking have special motivations (because social ranking is added to social learning) the effect might be different in social environments. Indeed the effect of the social ranking component might be the opposite: since many environments follow the rule winner-takes-all, and being first is much better than being second, while the latter is not much different from being third, gains might loom larger than losses.

The two hypotheses that the attitude to counterfactual gains and losses is similar to that to real gains and losses in private domains, and opposite in social ones is confirmed in Bault et al. (Bault et al., 2008).

Conclusions

Experimental and theoretical results demonstrate experimentally an adaptive role of reward-based emotions, such as regret. These emotions also figure 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. Within this hypothesis, emotions do not necessarily interfere with rational decision making, and on the contrary they may implement it: they are a way of evaluating past outcomes to adjust choices in the future. These are features which are common between the prediction error model and the counterfactual learning. The crucial difference between TD learning and regret learning is the counterfactual difference between the rewards the individual received and those he would have received had he chosen a different action. One important difference between the prediction error model and the counterfactual model is of course the neural basis of the two: from the existing literature on the topic we know that the ventral tegmental area and ventral striatum are usually associated with the prediction error, while counterfactual learning is associated with the OFC.

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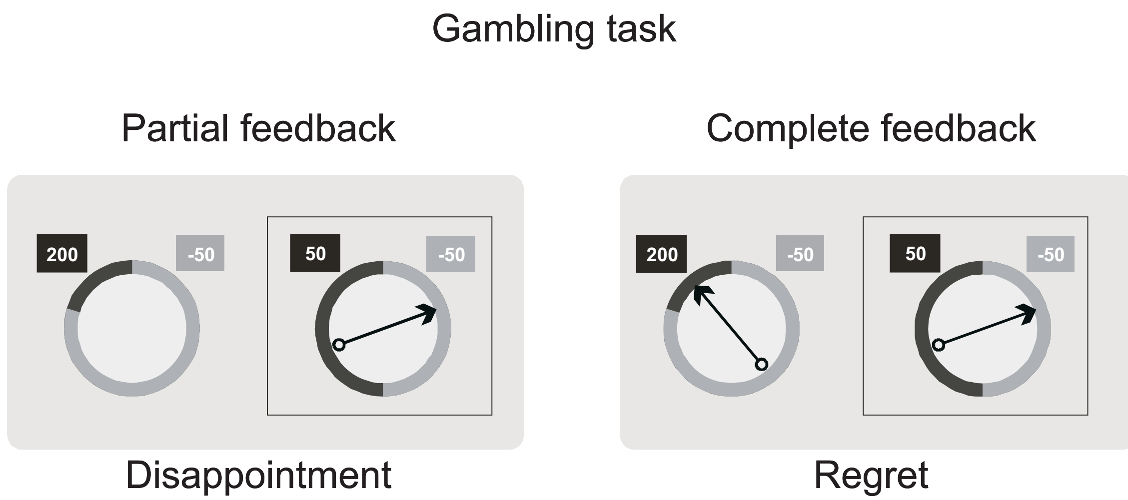

Fig. 1 The regret gambling task. In the gambling task subjects choose between two gambles (depicted as two 'wheels of fortune'). For instance, if subjects choose the gamble on the left, they might win 200 euros with 20% probability or lose 50 euros with 80% probability; if they choose the gamble on the right, they might win or lose 50 euros with equal probabilities. There are two main contextual conditions in terms of the feedback provided partial feedback and complete feedback. In partial feedback, only the outcome of the chosen gamble is provided, whereas in the complete feedback condition, both the outcome of the chosen (-50) and the unchosen (+200) gambles are provided. Complete feedback enables the subjects to judge not only the financial consequence of their choice, but also the outcome if they had they selected the other option (regret or relief).

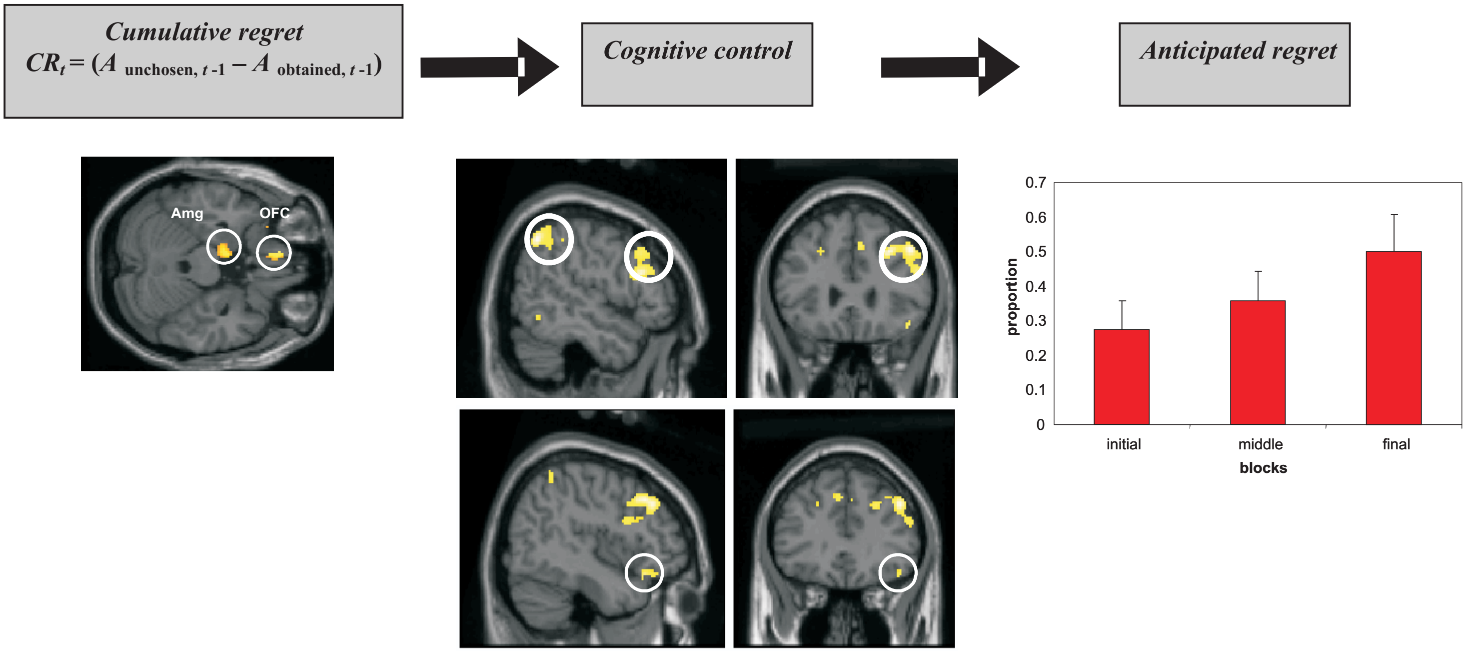

Fig. 2 The neural basis of the adaptive function of regret (Coricelli et al.). The observed reactivation pattern of the OFC and amygdala (Amg) before subjects made their choices accounts for the behavioral impact (anticipated regret). Across iterations of the experiment, subjects' behavior was more and more in line with a pattern that was explained in terms of regret avoidance, reflecting the 'cumulative' (learning) effect of experienced negative outcomes. The process of defining expectancies over possible consequences of the alternative of choice is based on an emotional reinforcement learning account. Cumulative regret (CR) is the difference between the average payoff realized and the average payoff missed (the payoff of the unselected gamble) over time. In other words, the impact of the consequences of rejected choices (regret) is indeed increasingly integrated in the process of choice through experience. Cognitive control activity induced by the experience of regret was observed during choices when the subjects just experienced regret (t -1). Enhanced activity in the dorsolateral prefrontal cortex (DLPFC), parietal cortex (inferior parietal lobule, IPL) and right OFC is observed.

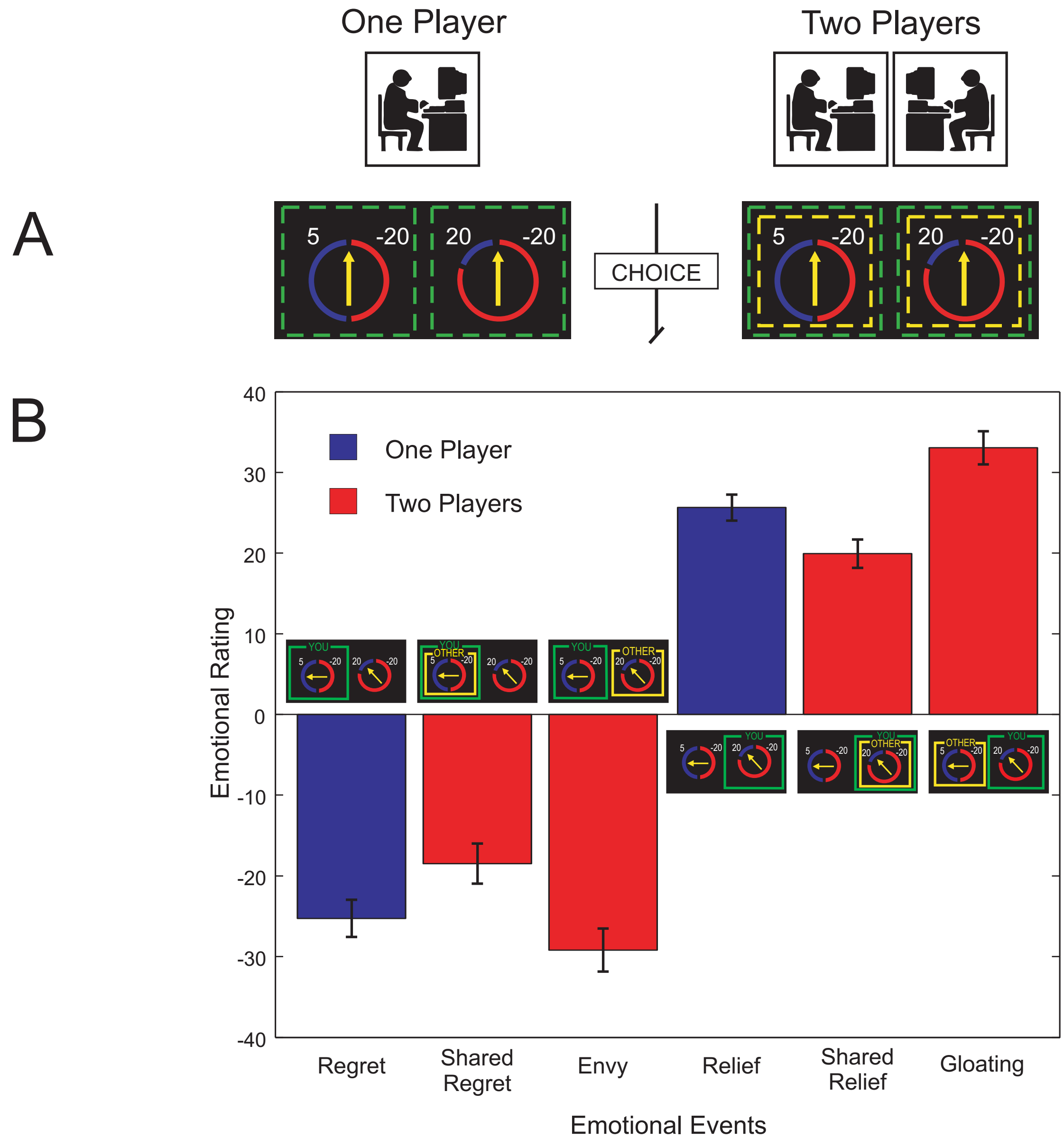

Fig. 3 : (A) Typical single (on the left) and two player trial in Bault et al.. Numbers indicated outcomes, and the probabilities were represented by colored sectors of a circle. Each lottery was surrounded with one dotted square in the case of a one player trial or two dotted squares of different colors in the case of a two player trial.(B) Emotional responses: Average subjective emotional evaluations for different events.The bars represent the average value (± SEM) of the subjective emotional evaluation given by participants in the different events. The pictures around the horizontal axis show the typical screen display seen by participants in the different events.