



How the Brain Evaluates and Predicts Monetary Rewards

Giorgio Coricelli

Institut des Sciences Cognitives, CNRS, Bron, France
(e-mail: coricelli@isc.cnrs.fr)

Abstract We study the relations between decision-making and emotions in normal subjects and in patients with brain damage. The experimental task is based on a simple gambling situation. This task allows to characterize a subject's choice behavior in terms of the anticipated and actual emotional impact of a choice, as indexed by physiological responses and subjective ratings. By manipulating the subject's exposure to the outcome of the rejected alternative, fine distinctions could be made between emotions involving disappointment and regret. Normal control subjects report emotional responses consistent with counterfactual reasoning between obtained and non-obtained outcomes; they choose minimizing future regret and learn from their emotional experience. 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.

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1. Introduction

Why do people prefer to buy 'blue chips'?¹

The answer stands in the fact that we would blame more ourselves if we loose money buying shares of unconventional stocks. This follows from the explanation given by Shefrin and Statman (1996) of the stock selection of individual investors: 'To understand how regret applies to stock selection, compare the pur-

¹ The 'blue chips' are the stocks of well-established companies. The term comes from the game of poker where the blue chips are the most expensive chips.

chase of shares of IBM, the most admired company in a recent Fortune survey, with buying stock in a company such as Continental Illinois, the least admired company in the same survey. If you buy Continental Illinois and it goes down in price, you'll blame yourself. 'How could I be so stupid?' you'll say. Choosing it carries much responsibility and high potential for regret. However, if IBM stock drops, you'll look at the misfortune as an act of God. Your choice involves little responsibility and therefore little regret, since IBM is the conventional choice² (pp. 54).

The feeling of responsibility for the consequence of our choice has an important role in decision-making. On one hand we have the tendency to compare factual or imaginative alternatives, engaging in a mental process called counterfactual (Roese and Olson 1995, Byrne 2002), on the other hand, we often 'prefer not to know' the outcome of the option that we have rejected only for the fact that it might be better than the outcome of our choice (Kahneman and Tversky 1982). Counterfactuals amplify (Kahneman and Miller 1986) and in some cases even generate emotional responses (Mellers et al. 1999, Zeelenberg and van Dijk 2004). Humans use strategies to avoid intense negative emotions, and can anticipate the effects of future thinking about 'how would have been better if I had chosen differently', which determines the feeling of regret. Regret is a cognitive-based 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 component (Bell 1995, Loomes and Sugden 1996). 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 et al. 1989), and the decisional process is influenced from the knowledge about the future feedback available.

From a neurobehavioral point of view, an important question concerns the cerebral structures mediating such fundamental human emotions as regret. One potentially critical player is the orbitofrontal cortex, a structure which is connected with the dorsolateral prefrontal regions involved in reasoning and planning, with limbic areas such as the amygdala important for emotion, and

² This explanation is complementary to the effects of the structure of compensation and bonuses which is based on relative performance with respect to the market. It is well known that this structure (presence of benchmark) induces a convergence to a uniform behavior in the market, what we called here the conventional choice, because a loss different from the conventional is penalized.

with other areas providing direct or indirect access to multiple sensory modalities including gustatory, visceral, somatic and visual (Rolls 2000). Studies in non-human primates and neuroimaging experiments in humans show that the orbitofrontal cortex is involved in reward evaluation and comparison (Breiter et al. 2001, Elliot et al. 2003; Tremblay and Shultz, 1999; Dolan 2002). Patients with lesions in this region show poor social and individual decision-making skills and abnormal anticipatory emotional responses (Bechara et al. 1994, Goel 1997, Bechara et al. 2000).

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. In the present study we adopted a decision-theory framework to study the role of specific emotions, such as regret and disappointment, in the process of decision making.

2. Experimental design

We adapted an experimental paradigm inspired from the work of Mellers et al. (1999) to analyze the emotional impact of decisions in terms of disappointment and regret, and test whether the ability to experience these emotions involve the orbitofrontal cortex.

Normal subjects and patients with orbitofrontal cortex lesions were presented with a choice between two risky gambles involving a monetary reward. We tested three groups of subjects: (1) healthy normal control subjects ($N=18$, 13 females, 5 males, mean age 43.7; mean education level, 14.2, range 7–22) without neurological history; (2) orbital prefrontal patients ($N=5$) with focal lesions in the orbitofrontal cortex; (3) three control patients with lesions located in the posterior part of the cingulate cortex (BA, 23) in one case, in the dorsolateral prefrontal cortex (BA 8) in another case, and in the frontal operculum and part of the median prefrontal region (BA 44, 45, 9) in a third case. All 8 patients performed in the normal range in global cognitive test (Mattis Scale and WAIS-III) and all of them (orbitofrontal and control patients) showed impairments in tasks sensitive to frontal lobe dysfunction

On each trial of the experiment, the subject viewed two gambles where different probabilities of financial gain or loss were represented by colored sectors of a circle. Once selected, the chosen gamble was highlighted on the screen by a square. A rotating arrow then appeared in the center of the gamble circle, stopping after a variable timing. The outcome of the selected gamble, indicated by the resting position of the arrow, resulted in financial gain or loss for the subject. There were two kinds of trials; for 30 trials the outcome (and spinning arrow) was apparent only in the selected gamble (partial-feedback condition). In the other 30 trials,

spinning arrow and outcome of both the selected and unselected gambles were visible to the subject (complete-feedback condition). Complete-feedback trials enabled the subject to judge not only the financial consequence of their decision, but also the corresponding outcome that the subject would have achieved had they selected the other option.

Each individual gamble presented paired combinations of 200, 50, –50 and –200 points and represented one of three levels of outcome probability (0.2, 0.5 and 0.8). Shortly after the arrow(s) stopped rotating, an emotional rating scale appeared below the two wheels. The subject used this scale to express how sad or how happy he/she felt by putting a mark on the scale. The emotional scale ranges from –50 (extremely sad) to +50 (extremely happy). Skin conductance response (SCR), a physiological marker of emotion, was also recorded.

We tested several predictions, namely that: (1) the experienced emotion will be determined by the contrast between the obtained and unobtained outcome, rather than by the absolute value of the obtained outcome; (2) the same obtained outcome will lead to different experienced emotions depending on whether feedback about the outcome of the unchosen option is also available; (3) as compared to normal subjects, the emotion experienced by patients with orbitofrontal lesions will show weak effects of feedback about the outcome of the unchosen option; (4) advantageous choice strategy will develop as a result of the ability to take into account the outcome of the unchosen option.

3. Results

The subjective emotions experienced in this gambling task depend on the values of the obtained outcomes and unobtained outcome. Other things being equal, subjects express more pleasant emotions when the obtained value is positive than when it is negative. The effect of the unobtained outcome strongly modulates that of the obtained outcome. In the partial feedback condition, *disappointment* is expressed in the perception of losses being more unpleasant and gains less pleasant if the unobtained outcome from the same gamble wins 200 instead of losing 200 (see Table 1; Wilcoxon signed-rank test, $Z = -3.703$, $P < 0.001$, for –50 obtained; $Z = -3.637$, $P < 0.001$, for +50 obtained).

The emotional reaction is modulated more strongly in the complete feedback condition. Losing 50 when the unchosen alternative wins 200 induces a strong negative feeling, while the same outcome is perceived as indifferent when the other gamble loses more (see Table 2; Wilcoxon signed-rank test, $Z = -3.237$, $P = 0.0012$). Even a gain of 50 can produce unhappiness if the other option wins more (Wilcoxon signed-rank test, $Z = -3.680$, $P < 0.001$), whereas it produces a pleasant sensation when the other gamble loses.

Table 1 Average emotional rating for all possible combination of obtained/unobtained outcome in partial feedback condition for normal subjects and orbitofrontal patients.

Obtained	Unobtained	Normal subjects (N=18)		OFC (N=5)	
		Mean	sd	Mean	sd
-200	-50	-30.41	15.29	-27.50	22.22
-200	50	-31.26	15.07	-28.83	16.93
-50	-200	3.23	6.73	-5.85	11.01
-50	50	-12.40	10.66	-14.25	15.45
-50	200	-18.13	9.60	-19.93	8.36
50	-200	22.43	10.31	16.47	6.72
50	200	6.81	10.88	6.77	13.37
50	-50	16.70	8.22	17.00	7.04
200	-50	35.09	12.44	36.00	17.37
200	50	35.68	13.04	36.00	14.24

Table 2 Average emotional rating for all possible combination of obtained/unobtained outcome (the outcome of the unchosen gamble) in complete feedback condition for normal subjects and orbitofrontal patients.

Obtained	Unobtained	Normal subjects (N=18)		OFC (N=5)	
		Mean	sd	Mean	sd
-200	-200	-22.22	18.63	-33.50	14.85
-200	-50	-29.47	14.75	-31.60	15.29
-200	50	-39.38	14.44	-30.00	34.64
-200	200	-39.17	11.27	-7.50	10.61
-50	-200	0.38	9.75	-13.83	10.96
-50	-50	-10.56	14.64	-17.00	21.61
-50	50	-11.65	12.54	-10.92	11.55
-50	200	-29.42	19.10	-10.56	4.19
50	-200	22.85	12.33	11.08	9.05
50	-50	19.09	8.64	16.58	6.13
50	50	10.56	15.39	11.75	11.54
50	200	-7.41	23.80	7.58	10.11
200	-200	36.25	14.99	26.75	20.49
200	-50	35.61	14.76	31.94	18.34
200	50	33.17	15.70	31.25	14.90
200	200	33.97	15.48	42.00	15.25

Direct comparisons between the two conditions show different levels of emotional involvement under complete and partial feedback. Emotional ratings for a given outcome obtained in the face of a more favorable outcome of 200 for the unchosen gamble are more negative than in the face of an unobtained outcome of 200 for the chosen gamble (Wilcoxon signed-rank tests, $P < 0.001$, for both -50 and $+50$ obtained outcomes). This is the signature of *regret*: an unpleasant emotion triggered by knowledge of the rejected alternative's outcome.

SCR increases when learning the outcome of the gamble. Importantly, the distinction between disappointment and regret expressed by subjective mood ratings is confirmed by the physiological index of emotional reactivity, since viewing the outcome of the rejected alternative enhances the SCR as compared to viewing only the outcome of the chosen gamble (paired t -test, $t = -2.124$, $P = 0.0406$, two-tailed). This effect is particularly pronounced when losing as compared to winning 50, suggesting that regret potentiates more strongly an already negative emotion ($t = -2.007$, $P = 0.031$).

A very different pattern of results was observed in patients with orbitofrontal lesions. Like normal subjects, they are generally happier when winning than when losing (Wilcoxon signed-rank test, $Z = -3.296$, $P < 0.001$), and their SCR demonstrates clear emotional arousal when learning the outcome of the gamble. The disappointment effect, i.e. the effect of the unobtained outcome, is present but not as contrasted as that seen in normals. When losing, they are somewhat sadder if the unobtained outcome was a large gain than if it was a greater loss (Wilcoxon signed-rank test, $Z = -1.671$, $P = 0.094$, for -50 obtained). When winning, the effect of the unobtained outcome was not significant (Wilcoxon signed-rank test, $Z = -1.483$, $P = 0.138$, for 50 obtained). This suggests that they were somewhat able to reason counterfactually on the chosen gamble. However, the emotions expressed by these patients are not modulated at all by feedback on the outcome of the unchosen gamble, and they seem to experience no regret whatsoever. Sadness expressed at losing 50 is not more intense if the rejected alternative wins 200 nor is the joy felt at winning 50 tarnished by seeing that the gain would have been larger had the alternative gamble been selected. It should be stressed that the absence of a regret effect cannot be explained by a less differentiated emotional expression or by a reluctance to use the extremes of the rating scales, since patients, like normal subjects, were shown to use the full range of the emotional rating scale with the larger values of obtained outcomes (i.e. -200 and 200). SCR data confirm that lack of emotional reaction of the orbitofrontal patients to the outcome of the rejected gamble. As will be seen below, the differences between normal subjects and orbitofrontal patients in the emotional impact of the consequence of their choices are accompanied by differences in the choice strategy adopted by each group.

Three control patients with frontal lesions sparing the orbital area partici-

pated in the experiment. Emotional ratings show the effects of the unobtained outcome in both the partial and complete feedback condition, indicating that they responded with disappointment and regret in a manner comparable to normal subjects, clearly showing the selectivity of the effects to the orbital region within the frontal lobe.

Now we address the question: Do subjects choose anticipating negative emotions?

In order to determine the influence of anticipated emotions of disappointment and regret on the decision process, we tested a model of choice incorporating these emotional variables as well as the expected values of the two gambles. The outcome structure of the experiment was defined so that the two gambles always differed in their expected values, but the gamble with the highest expected value was less advantageous (i.e. won less often) on average than the one with the lowest expected value. This was done in order to ensure that subject would experience negative emotions on a sufficient number of trials. Under these conditions, subjects could learn to choose advantageously by anticipating future emotional reactions and trying to avoid negative emotions.

The analysis of the choice between the two gambles can be carried out by comparing the probability of choosing each of them. Given that $\Pr(g_{1it}) = 1 - \Pr(g_{2it})$, where $\Pr(g_1)$ and $\Pr(g_2)$ are the probability of choosing gamble 1 and gamble 2, respectively; we can proceed defining the probability of choosing g_1 , in terms of the three factors affecting the choice: anticipated disappointment (d), anticipated regret (r), and expected value (e).

We call x_1 and y_1 the highest and the lowest outcome of gamble one (g_1); and x_2 and y_2 the highest and the lowest outcome of gamble two (g_2). The probability of x_1 is p and the probability of y_1 is $(1-p)$; while, the probability of x_2 is q , and the probability of y_2 is $(1-q)$. The probability of choosing gamble one is:

$$\Pr(g_{1it}) = 1 - \Pr(g_{2it}) = F[d_{it}, r_{it}, e_{it}] \quad (1)$$

Where $i = individual$, $t = time$. The function $F[\theta]$ denotes the function $\exp(\theta)/[1 + \exp(\theta)]$. The variables d and r , as described in equation (2) and (3), indicate the processes of minimizing future disappointment and future regret, respectively. While, e indicates the results of maximizing expected values.

$$d = [|y_2 - x_2|(1-q)] - [|y_1 - x_1|(1-p)] \quad (2)$$

$$r = [|y_2 - x_1| - |y_1 - x_2|] \quad (3)$$

$$e = EV(g_1) - EV(g_2) = [px_1 + (1-p)y_1] - [qx_2 + (1-q)y_2] \quad (4)$$

Table 3 Regression analysis. Panel logit procedure with individual random effects. Data from complete feedback condition

Normal control subjects ($N=18$)

Variable name	Coefficient	Std error	z	$P > z $
Constant	-0.219	0.146	-1.50	0.133
d	-0.002	0.002	-0.82	0.411
r	0.008	0.002	4.94	0.00
e	0.026	0.004	6.66	0.00

Log likelihood = 211.68; Wald chi = 128.23; $P < 0.0001$

Orbitofrontal patients ($N=5$)

Variable name	Coefficient	Std error	z	$P > z $
Constant	-0.409	0.178	-2.29	0.022
d	-0.003	0.003	-0.98	0.328
r	0.002	0.002	0.96	0.336
e	0.023	0.005	4.62	0.000

Log likelihood = -116.60; Wald chi (3) = 54.89; $P < 0.0001$

Subjects would choose g_1 , minimizing disappointment (equation 2), if the difference in absolute value between the lowest and the highest possible outcome in g_2 , weighted by the probability of the lowest outcome, is larger than the same weighted difference in g_1 . The process of anticipating regret is described by the minimization of the difference between the lowest and the highest outcome across gambles (equation 3). Finally, subjects would choose g_1 if its expected value is higher than the one of g_2 (equation 4).

Results from a regression analysis (Table 3) using the data from complete feedback trials, when the subjects might anticipate both future disappointment and future regret, show that they chose maximizing expected values ($P < 0.001$) and minimizing future regret ($P < 0.001$). Anticipating disappointment would have corresponded with a risk avoidance behavior. The absence of this behavior indicates the hierarchical relationship between risk and regret. Indeed, the subjects chose minimizing regret independently of the risk component of the choice.

Thus, the experience of regret has a major impact on the process of choice, inducing the subjects to chose avoiding the feeling of this highly negative emotion.

4. Discussion

In contrast with the standard theory in decision-making, our results show that 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.

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.

Evidence in cognitive neuroscience shows that patients with focal lesions in 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 lose their jobs, 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 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 with 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 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 sub-

ject'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 can be evaluated. As shown by the model of choice, the feeling of responsibility for the negative result, i.e. regret, reinforces the decisional learning process.

The orbitofrontal cortex integrates cognitive and emotional components of the entire process of decision-making; its incorrect functioning determines the inability to generate specific emotions like regret, which has a fundamental role in regulating behavioral strategies in individual and social context.

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