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Neurobiological regret and rejoice functions for aversive outcomes

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A decision maker may experience *regret* when a choice he makes results in a more adverse outcome than a different choice would have yielded. Analogously, he may experience *rejoice* when his choice resulted in better outcomes. We used fMRI to investigate the neural correlates of regret and rejoice where payoffs are in terms of a non-monetary medium. Incentives were created using painful outcomes in the form of mild electrical shocks to the foot and the possibility of avoiding them. We hypothesized that the neural response to a painful outcome resulting from an individual's choice would also reflect the degree of regret as measured by the likelihood that alternative choices would have yielded the same adverse outcome. Similarly, when an individual avoids a potential shock, he would experience a degree of rejoice that correlates with the probability he had of receiving the shock. For example, winning a bet when winning was unlikely, even if the outcome is the same, evokes more rejoice than winning when it was highly probable. Our results suggest that activation of a cortical network, consisting of the medial orbitofrontal cortex, left superior frontal cortex, right angular gyrus, and left thalamus, correlates with the degree of regret. A different network, including the rostral anterior cingulate, left hippocampus, left ventral striatum, and brain stem/midbrain correlated with rejoice. The right inferior orbitofrontal cortex, pre-supplementary motor area, anterior cingulate, and posterior cingulate showed similar patterns of activation with both regret and rejoice, suggesting that these regions may be associated with surprise from the realization of relatively unlikely events. Our results suggest that distinct, but overlapping networks are involved in the experiences of regret and rejoice.

Introduction

> *I coulda been a contender. I coulda been somebody, instead of a bum, which is what I am. — Marlon Brando, On the Waterfront (1954)*

An individual feels *regret* when he makes a choice that results in an outcome worse than would have occurred had he made an alternative choice. A feeling of *rejoice* (sometimes referred to as *rejoicing*) occurs when the option chosen yields a more favorable outcome than an alternative decision. Although the feelings of regret and rejoice are part of the human experience, their roles in shaping decisions have been widely debated. The behavioral issue revolves around whether agents hedge their decisions prospectively, anticipating regret and rejoice and taking these potential future emotions into account. In regret theory, for example, regret and rejoice are assumed to be components contributing to the value of a lottery in addition to classical expected utility (Bell, 1982, 1983; Gilovich et al., 1998; Loomes and Sugden, 1982, 1987) and influence prior decisions between risky lotteries. A number of experimental studies have found that regret does influence decision making (Bleichrodt et al., 2007; Cooke et al., 2001; Janis and Mann, 1977; Sorum et al., 2004; Wolfson and Briggs, 2002; Zeelenberg, 1999; Zeelenberg et al., 1996). Furthermore, regret has been invoked to explain decision making that is inconsistent with expected utility theory in many domains outside the laboratory such as healthcare (Smith, 1996) or consumer decisions (Tsiros and Mittal, 2000). Empirical studies have shown that regret can explain empirical patterns in insurance purchases (Braun and Muermann, 2004), where it can account for a preference for low deductibles, financial investment (Dodonova and Khoroshilov, 2005; Muermann et al., 2006) in which it can explain excess volatility and autocorrelation of asset returns, bidding in auctions (Filiz and Ozbay, 2007), in which it can explain bidding higher than risk-neutral Nash equilibrium levels in first price auctions, and the timing of purchase decisions (Cooke et al., 2001), where it captures delays in making purchases.

The widespread existence of behavior consistent with regret raises the issue of whether there exists an underlying neurological activation pattern that is associated with the experience of regret. A few neuroeconomic studies have investigated the neural correlates of regret when payoffs are monetary (Coricelli et al., 2005; Lohrenz et al., 2007). These studies find that activity in the medial orbitofrontal cortex (OFC), anterior cingulate cortex (ACC), and right hippocampus is positively correlated with the magnitude of finan-

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cial regret. Similarly, patients with damage to the OFC neither reported regret nor anticipated negative consequences associated with their actions (Camille et al., 2004). How this modulation propagates backward to the time of decision making remains unknown, but one possibility is through the propagation of fictive error signals, seen, for example, in the ventral striatum (Lohrenz et al., 2007). However, data only exist for monetary outcomes, and so it is unknown whether regret is a general phenomenon that is independent of the medium that generates payoffs.

We conducted an experiment in which we investigated the neural bases of regret and rejoice with a non-monetary medium. Incentives were created using painful outcomes in the form of mild electrical shocks to the foot and the possibility of avoiding them. If an individual's level of utility from the outcome of a decision has a component that depends upon the (expected) outcome that would have resulted from a different decision, the neural response to a painful outcome would also reflect the degree of regret as measured by the difference between the actual payoff and the expected payoff from making an alternative choice. When an individual receives (or avoids) a potential shock, he would experience a degree of regret (or rejoice) that correlates with the likelihood of receiving a shock under different choices. As we report below, we find that there are distinct networks of brain regions whose activity correlates with the degree of regret, rejoice, and both experiences. We use data from participants' self-reported ratings, as well as data on their skin conductance, to further support our finding that differing degrees of regret and rejoice are distinguishable and reflected in physical response measures. We focus here only on regret and rejoice, where outcomes are in part a consequence of one's own decisions, as distinct from disappointment and elation, which result purely from unfavorable realizations of random variables (Loomes and Sugden, 1986; Roese, 1997).

Materials and methods

Subjects

Thirty-six right-handed volunteers (21 females and 15 males; 18 to 38 years of age with a mean of 21.64 years) participated in this study. Due to scanner gradient malfunctions, the data from six subjects were only partially acquired, leaving thirty subjects (17 females and 13 males; 18 to 38 years of age with a mean of 21.3 years) for the data analysis. Written informed consent was obtained from each participant before his session began. The Institutional Review Board of Emory University approved all of the procedures. Each participant was paid USD 40 for her participation.

Experimental procedures

Each session lasted on average approximately one h and consisted of five runs. Each run consisted of 20 trials. Cutaneous electric shocks were administered on the dorsum of the left foot with a Biopac STIM100C stimulator and STIMISOC isolation unit (Biopac Systems, Inc., CA) through shielded, gold electrodes placed 2–4 cm apart. This electrical stimulator was current-controlled and the shock pulse duration was 15 ms. The timing and delivery of shocks were controlled by a custom-designed software application on a laptop through a serial interface.

The shock strengths (in milliamps) were individually tailored to each participant at the beginning of each session. Before subjects were positioned in the fMRI scanner, we measured the maximum shock intensity level they could tolerate by varying the Biopac machine current intensity. The current level was increased until the subject indicated that he could not bear any stronger shock. We then fixed 95% of this maximum shock level as the level they would receive during the session. Each subject underwent a practice run consisting of three trials in order to understand the task instructions.

At the beginning of each trial, subjects were shown a display containing three doors on a screen located inside the scanner (Fig. 1). In each trial, the subject's task was to select one of the doors, which would then be opened. Responses were registered with a fiber optic button-box, placed in the subject's right hand. At the beginning of each trial, the number of doors that contained shocks was indicated at the top of the display. The number ranged from zero to three. The conditions with zero or three shocks served as control conditions with no uncertainty, and we denote these as the no-rejoice and the no-regret conditions respectively. The other two conditions, with shocks behind one or two of the doors, allowed for regret and rejoice to be experienced. The software package, COGENT 2000 (developed by the Functional Imaging Laboratory, University College London), running on MATLAB 7.1 (The MathWorks Inc., MA), was used for the stimulus presentation and response acquisition.

After subjects chose a particular door under a particular task condition, the number of shocks, in the form of red colored shock symbols, remained on top of the three closed doors. A smiley face was shown in trials in which the probability of a shock was zero. After the choice was made, a green arrow was shown on top of the selected door, as shown in the upper left of Fig. 1. After a delay of 6.2–9.8 s after the decision was made, all of the doors were opened. At the same time that the doors were opened, and depending upon whether a shock was associated with the door selected, the subject was either shocked once or not shocked. The red shock symbols on top of the display (i.e., on top of three closed doors) represented the prior probability, and the subjects realized the outcome (shock or no shock) along with the alternative outcomes after anticipating for 6.2–9.8 s. After the doors were opened, subjects were required to rate their experience on a horizontal visual analog scale (VAS). The rating scale ranged from 'very unpleasant' to 'very pleasant.' A hand-held control allowed subjects to move a cursor and to select their desired point on the scale.

The subjects were informed that the doors hiding the shocks could change from trial to trial but were predetermined. They were also informed that the probability of a shock, described as the number of doors hiding shocks, was random and independent of previous trials. Although subjects were not informed of the cumulative frequencies of each condition, over the five runs, there were 20 trials with probability zero of receiving a shock and 20 trials where the probability was 1. There were 30 where the probability was 1/3 and 30 where it was 2/3. The trials were randomly ordered with regard to the probability of a shock present in the trial.

For the analysis, each trial was conceptually divided into four phases: the *decision phase*, the *anticipation of outcome phase*, the *response to outcome phase*, and the *rating phase*. The decision phase was the period of time between when the cue was displayed and door selection. The anticipation phase was the period of time between the door selection and when the outcome was realized. At the response to outcome phase, the subjects experienced the outcome and also observed what would have happened had they chosen differently. Finally, in the rating phase, subjects evaluated their experience on the VAS rating scale. The principal focus of our investigation was the brain response during the response to outcome phase, in which regret and rejoice are experienced.

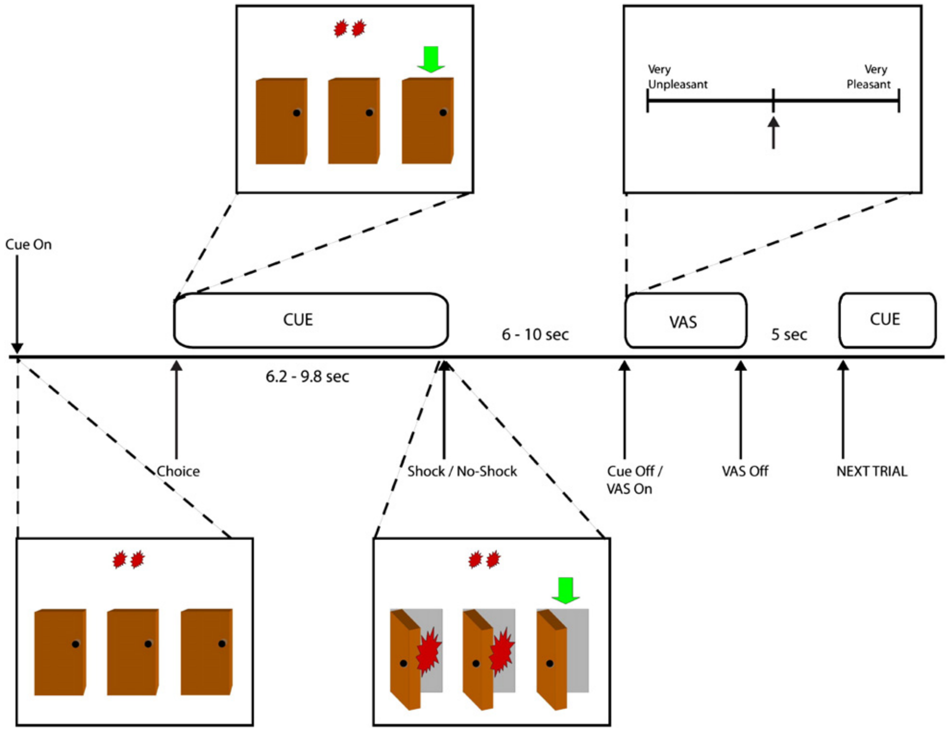

Fig. 1. Experimental trial design. At the beginning of trial (indicated as 'cue on'), subjects were shown three closed doors and an indicator of how many doors have shocks hidden behind them. Subjects chose one of the doors by pressing the corresponding key on a button-box (indicated as 'choice'). After a delay of 6.2–9.8 s, all of the doors were opened and the subject was either shocked or not shocked based on whether or not there was a shock behind the door he selected. After a delay of 6–10 s, a visual analog scale (VAS) appeared (at 'VAS on'). Subjects rated their experience until 'VAS off' and after a delay of 5 s a blank screen was displayed and the next trial began.

The regret level was defined at the response to outcome phase in trials in which a shock occurred and took on one of three levels in each trial (Table 1): highest for the prior probability of receiving the shock of 1/3, followed by 2/3, and then by 1. We will refer to these conditions as the *high*, *low*, and *no regret* conditions, respectively. Rejoice level was registered when a shock was avoided and also took on three levels in the experiment. The highest level was induced with a prior probability of 2/3 of receiving a shock followed by 1/3 and then 0, and the three conditions will be referred to as the high, low, and no rejoice conditions, respectively.

Thus, we assumed that in the response to outcome phase, in trials in which the subjects received a shock, that they would experience more regret when the probability of the shock was 1/3, followed by 2/3, and by 1 (i.e., monotonic). Similarly, in trials in which subjects avoided a shock, they would experience rejoice. The rejoice would be strongest when the prior probability of a shock was 2/3, followed by 1/3, and then by 0. We measured fMRI BOLD responses to categorize the regions involved in the experience of regret, of rejoice, and of both experiences.

Table 1
Conditions in effect during anticipation and response to outcome phases

Anticipation phase (probability of shock)	Response to outcome phase	
	Outcome is a shock	Outcome is no shock
0	N/A	No rejoice
1/3	High regret	Low rejoice
2/3	Low regret	High rejoice
1	No regret	N/A

There are four anticipatory conditions (probabilities 0, 1/3, 2/3, and 1 of receiving a shock) and six response to outcome conditions (no, low, and high regret, as well as no, low, and high rejoice).

fMRI measurements

The MR scanning was performed on a Siemens 3 T Trio whole-body scanner. After the acquisition of a high-resolution T1-weighted scan, the subjects underwent five whole-brain functional (echo-planar imaging, TR = 2350 ms, TE = 30 ms, flip angle = 90, FOV = 192 × 192 mm, 64 × 64 matrix, 3-mm-thick 35 axial slices acquired parallel to anterior–posterior commissural line, and 3 mm^3 cubic voxels) runs (of total 1050–1200 scans), for measurement of the BOLD effect. Head movement was minimized by padding and restraints. To prevent electrical artifacts in the fMRI signal shocks were delivered during a 50 ms pause after each volume, yielding an effective TR = 2400 ms.

fMRI analysis

The data were analyzed using SPM2 (developed by Wellcome Department of Imaging Neuroscience, University College London) with random effects models. Standard preprocessing of functional images was used, which included motion correction, slice timing correction, spatial normalization of all functional images to the MNI template brain in Talairach orientation, and smoothing with a Gaussian 8 mm full width half maximum filter. Each subject's fMRI data was analyzed with a first level general linear model (Friston et al., 1995a,b), and group data were analyzed with a random effects

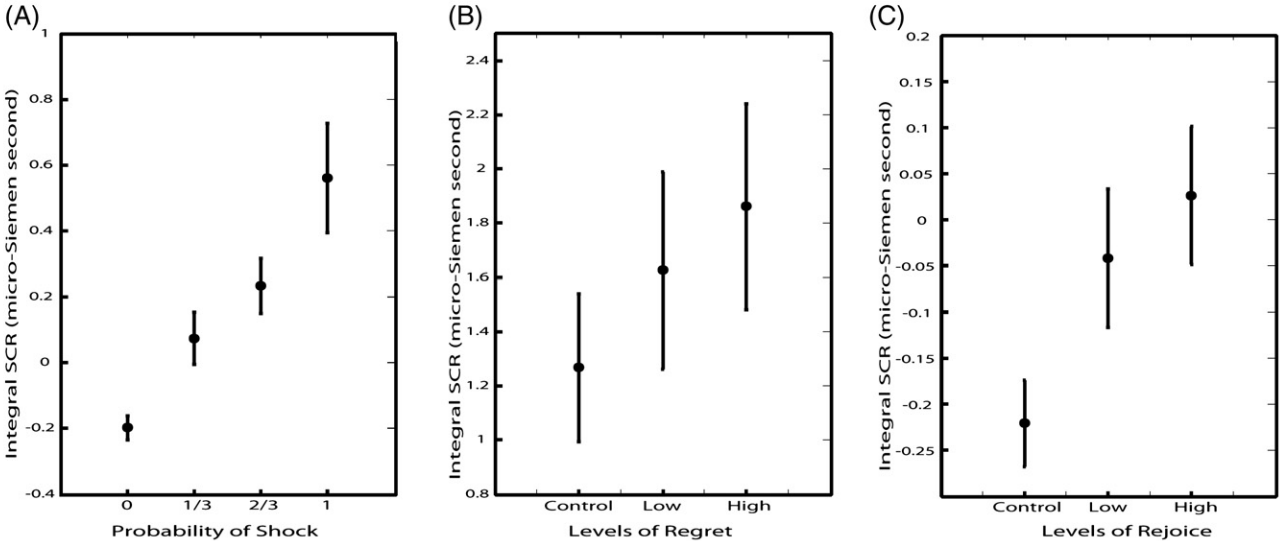

Fig. 2. (A) The left panel displays the skin conductance responses (SCR) during the anticipation phase for the four probabilities of getting a shock. (B) The middle panel contains the SCR arousals for the no, low, and high regret conditions in the response to outcome phase. (C) The third panel shows the SCR responses for the no, low, and high rejoice conditions at the response to outcome phase. Error bars indicate the between-subject standard errors of the mean.

model at the second level (Friston et al., 1999). In the first level of analysis, the design matrix was constructed for all five runs with effects for the Decision (variable duration event), Anticipation (4 levels as variable duration event), Response to Outcome (6 conditions as impulse events), and rating phases (variable duration event). We included six motion parameters for each run as regressors in order to control for the effects related to head motion. At the second level, contrast images corresponding to each 'response to outcome' effect on a subject-wise basis were entered into a 2×3 within-subjects ANOVA (Henson and Penny, 2005) using the outcome (shock or no shock) and the three levels (high, low, no) as independent variables. For some of the subjects at the first level analysis, all of the six 'response to outcome' conditions were not present in a run (depending on a subject's door selection in the one-shock and two-shock conditions). Fifteen out of thirty subjects contained all the 'response to outcome' conditions in all the runs, eleven subjects contained all the 'response to outcome' conditions in four of the runs, and four subjects contained all the 'response to outcome' conditions in three of the runs. Because of this, it was not possible to construct balanced contrasts in the first level analysis for some of the subjects. Instead, we constructed a 2×3 within-subjects ANOVA model at the second level. Thus, taking the average across runs for the 6 'response to outcome' conditions and performing the ANOVA at the 2nd level were more efficient. This second level model also allowed us to plot the brain activity (beta values) profile across all of the outcome conditions relative to the control conditions. The second level within-subjects ANOVA design matrix in SPM (suggested in Henson and Penny, 2005) contained separate columns for the main effects, interactions, constant term, and subject effects. Using this type of model, we constructed a 2×3 within-subjects ANOVA at the second level with a main effect for shock, main effect for levels, interaction effects (for regret and rejoice), constant term, and subject specific terms.

The main effect of outcome yielded two contrasts: the network activated from receiving a shock and the one activated from the avoidance of a shock. The main effect for levels represented the degree of regret or rejoice experienced in comparison with the control condition. The control conditions were a certain shock (no regret) in the case of regret and a certain avoidance of a shock in the case of rejoice (no rejoice). The two interaction terms of interest were (a) receiving a shock interacted with the probability of it being received and (b) avoiding a shock interacted with the probability of it being received. The interaction terms were used to identify brain regions that encoded the magnitude of regret and rejoice, respectively. From the two interaction contrasts, 6 mm spherical regions of interest (ROI) over local maxima were drawn and the beta values for each of the six Response to Outcome conditions were extracted from each subject. Subsequent analyses on the regret and rejoice functions were performed outside SPM.

We constructed another second level within-subjects ANOVA model using the anticipation phase subject-wise contrast images

Table 2
Brain regions that activated in response to regret

Brain area		BA	Coordinates (mm)			*T* score
Precuneus	R	7	9	−81	51	5.16
	L	7	−6	−63	66	4.84
Middle occipital cortex	L	19	−30	−81	39	5.04
Angular gyrus	R	39	45	−72	36	4.47
Thalamus	L		−6	−27	12	4.44
Inferior temporal cortex	L	37	−54	−66	−18	4.40
Superior frontal cortex	L	6	−21	6	66	4.13
Medial orbitofrontal cortex	R	11	3	54	−24	4.10
	L	11	−9	60	−6	3.83
		11	0	60	−9	3.54
Paracentral gyrus	R	4	3	−21	72	4.10
Precentral gyrus	R	6	21	−18	75	4.07

Stereotaxic MNI coordinates of significant BOLD signals for the interaction term (where shock related components decrease from *high to low to no regret* conditions and the no shock related components increase from *high to low to no rejoice* conditions) obtained from the 2×3 ANOVA constructed by entering the two effects (shock and no shock) and the three levels of regret and rejoice at the second level SPM analysis. These activations were obtained with uncorrected $p<0.001$, number of voxels ≥ 10.

related to the four levels of prior shock probabilities. We refer to each of these ex ante probabilities as a condition in the anticipation phase and more specifically as the probability of 0, 1/3, 2/3, and 1 conditions. The brain responses during the anticipation phase correlating with the prior probability of shock were presented to evaluate the assertion that the neural correlates in the anticipation phase and response to outcome involve the same brain regions. We performed a non-sphericity correction at the second level analysis for both the ‘response to outcome’ and anticipation phase within-subject ANOVA models to account for any correlations among the contrast images from each subject.

SCR measurements

Skin conductance responses (SCR) were acquired in the fMRI scanner with a Biopac MP 150 digital converter (Biopac Systems

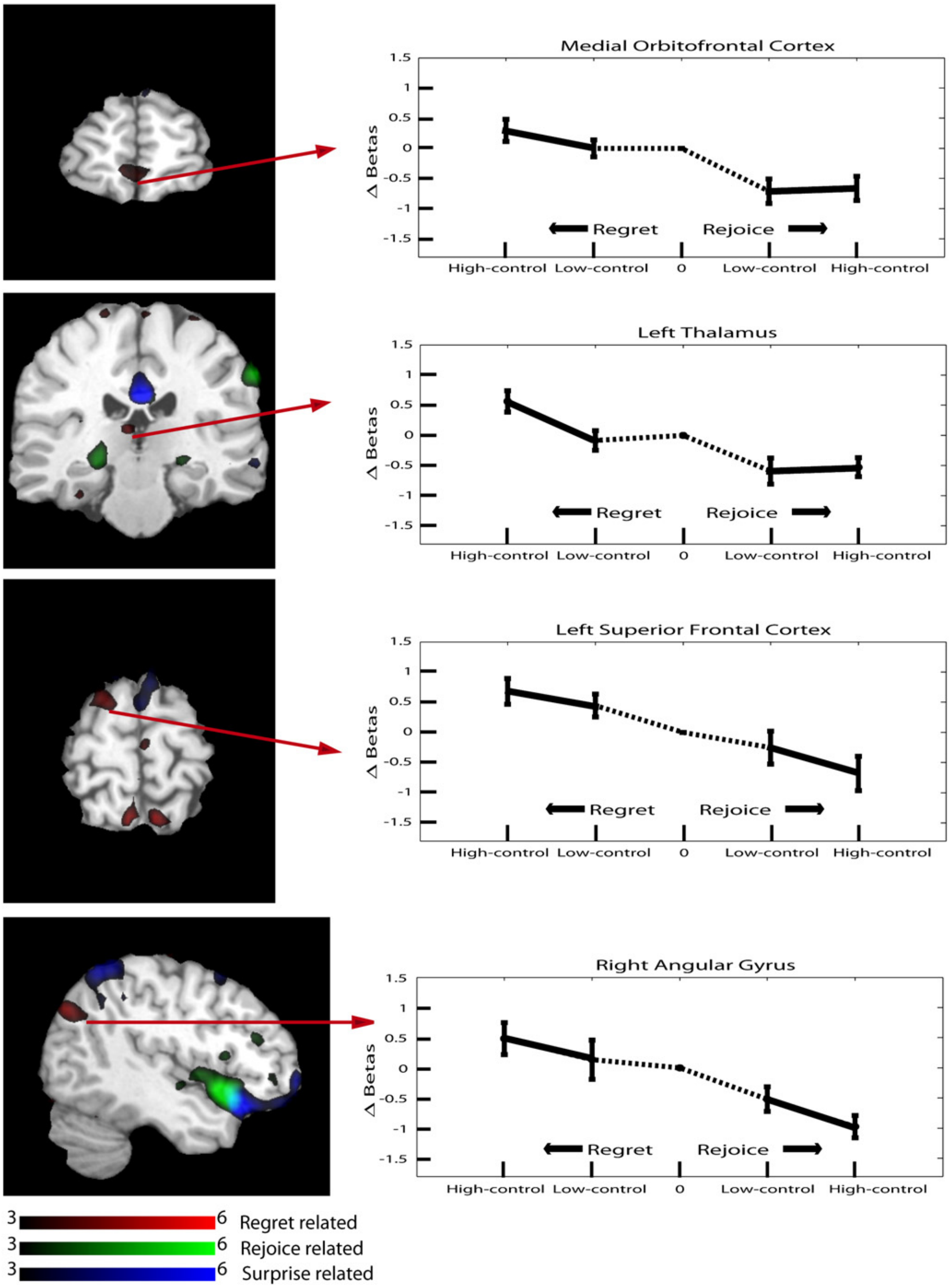

Fig. 3. Brain regions associated with regret. The activations corresponding to regret related (red), rejoice related (green), and surprise related (blue) are shown. The beta value of differences of high and low degree regret/rejoice conditions with control conditions (no regret/rejoice conditions) is plotted. The regret-related brain regions were: medial orbitofrontal cortex [MNI coordinate: (−9, 60, −6)], left thalamus [MNI coordinate, (−6, −27, 12)], left superior frontal cortex [MNI coordinate: (−18, 6, 69)], and angular gyrus [MNI coordinate: (45, −72, 36)].

Inc., CA) and AcqKnowledge 3.7.3 recording software. A TTL-generator box was interfaced to the serial port of the experimental computer (the laptop running COGENT), allowing for the generation of digital timestamps for each stimulus on the Biopac channel recordings. The SCR data were sampled at 125 Hz, and a 1 Hz low-pass filter and 0.05 Hz high-pass filter were applied to the data during acquisition.

SCR analysis

SCRs were measured in both the Anticipation and the response to outcome phases in each trial. The SCR data were first detrended and the artifacts due to scanning were removed using a two-stage filtering process. The scanner produced artifacts in the SCR data in the form of high amplitude spikes of short duration. These artifacts were subsequently filtered out in MATLAB 7.1 using a moving average filter and an automatic de-noising wavelet filter (Donoho, 1995). The moving average filter computed the absolute value of the difference between a given data point (t) and the previous point ($t-1$), and if the resulting value was greater than 0.01 μS, then t was replaced by $((t-1)+(t+5))/2$. This filter removed the spikes due to the scanner. A one-dimensional de-noising wavelet filter was used to de-noise the SCR signal along with recovering its short duration variations (‘wden’ function of the wavelet toolbox) with ‘sqtwolog’ universal threshold of symlet type ‘sym8’ with the decomposition level 10 in the second stage filtering process.

To measure arousal during the anticipation phase, integral SCRs were computed for a 7-second window following the beginning of each trial, and these were analyzed for each level of risk (probability of shock). Similarly, the arousal levels in the response to outcome phase were measured by integrating the SCR for 7 s following the outcome, whether it was a shock or no shock.

VAS ratings

The VAS ratings were a self-reported evaluation of subjects' experiences in all six possible outcome conditions (two outcomes, shock and no shock: and three prior probabilities for the outcome, 1/3, 2/3, and 1). We performed a repeated-measures ANOVA on the rating values to look for significant differences between the outcome conditions. The ratings were normalized by assigning cardinal values uniformly to the VAS scale and dividing the number associated with each rating by the same individual's average rating in the no regret condition (if the realization was a shock) or the no rejoice condition (if the realization was no shock) by the same individual.

Results

Decisions

There was strong evidence that subjects perceived the locations of the shocks as random because their choices were uniformly distributed across the three doors. Repeated-measures ANOVA for the one-shock and two-shock conditions (the ones in which the choice was consequential) showed no significant difference [Greenhouse–Geisser (G–G) corrected $F(1.724,49.986)=0.009$, $p=0.984$] in the number of times each door was picked. Thus, subjects were not biased to one door during selection. The choices also appeared to be nearly independent of the prior history of outcomes. Subjects switched their door selection 62% of the time from one trial to the next when the previous trial outcome was a shock and switched 68% of the time when the previous trial outcome was no shock. Random decision making would yield an incidence of door switching of 67%; the switching observed here was not significantly different from random choice for trials preceded by no shock [$t(29)=0.747$, $p=0.461$] but was significantly smaller [$t(29)=-2.841$, $p=0.008$] for trials preceded by a shock. The decision time was significantly shorter when a shock was impossible or certain than when it was uncertain, indicating that subjects actively decided which door to pick when there was a possibility of avoiding a shock. The mean decision time values for individuals facing shock probabilities of 0, 1/3, 2/3, and 1 were 1.903, 2.504, 2.488, and 2.130, respectively. A repeated-measures ANOVA on decision times for the four shock probabilities as within-subject factors revealed a significant main effect [$F(3,87)=20.295$, $p<0.001$]. Furthermore, pair-wise comparison of decision times among the four factors yielded no significant difference [$p=0.830$] between the 1/3 and 2/3 probability conditions but significant differences [$p<0.001$] between the control conditions (probabilities of 0 and 1) and the conditions of interest (1/3 and 2/3 probability).

Participant self-reports

At the end of each trial, individuals rated the experience of the trial on a scale from *very unpleasant* to *very pleasant*. The results indicated that participants experienced different levels of regret, as well as different levels of rejoice, in a pattern consistent with our earlier assumptions. High regret trials were viewed as more unpleasant than low regret, which in turn was more unpleasant than no regret. High rejoice trials were rated more pleasant than low regret followed by no regret. Shocks were rated as more unpleasant, the less likely they were to be received, and avoidance of a shock was

Table 3
Brain regions that activated with rejoice

Brain area		BA	Coordinates (mm)			*T* score
Anterior insula	R		45	15	−12	6.70
	R		39	−15	−6	3.84
	L		−45	6	−6	4.37
	L		−30	−21	15	3.79
Lingual gyrus	R	17/18	15	−84	3	5.92
Ventral striatum (putamen)	L		−18	9	−9	5.39
	R		18	9	−9	4.35
Supramarginal gyrus	R		63	−27	42	5.25
Calcarine	L	17	−12	−87	0	4.95
Anterior cingulate cortex (rostral)	R	24/25	3	36	3	4.66
Hippocampus	L		−21	−27	−3	4.61
Caudate	R		12	15	0	4.35
Superior medial frontal cortex	L	9/8	−9	36	48	4.29
Midbrain/brain stem	R		3	−15	−12	4.23
Middle temporal cortex	R	37	33	−60	−12	3.67
Middle frontal cortex	R	46	48	45	24	3.63

Stereotaxic MNI coordinates of significant BOLD signals for the interaction term (where no shock related components decrease from the *high to low to no rejoice* conditions and the shock related components increase from the *high to low to no regret* conditions) obtained from the 2×3 ANOVA constructed by entering the two experimental effects (shock and no shock) and the three levels of regret and rejoice at the second level SPM analysis. These activations were obtained with uncorrected $p<0.001$, number of voxels ≥ 10.

rated more favorably, the more likely the shock had been. Repeated-measures ANOVA on the normalized ratings where subjects experienced a shock outcome, with factors for regret level (no, low, and high) and fMRI run (1,2,3,4,5) as within-subject factors, indicated a significant main effect for level [Greenhouse–Geisser (G–G) corrected $F(1.265,20.236)=5.091$, $p=0.028$], but not for the main effect of fMRI run [G–G corrected $F(2.948,47.161)=0.363$, $p=0.777$] or the interaction between level and fMRI run [G–G corrected $F(3.707,59.316)=0.389$, $p=0.802$]. Further analysis revealed that this effect was monotonically increasing from no to low to high level of regret [$F(1,16)=5.266$, $p=0.036$]. Thus, when receiving a shock, participants reported a worse experience with a greater degree of regret. Similarly, repeated-measures ANOVA on the normalized ratings for the trials where no shock was administered using the level of rejoice (no, low, and high) and runs (1,2,3,4,5) as within-subject factors resulted in a significant main effect for level [G–G corrected $F(1.085,20.611)=6.084$, $p=0.02$], but not for fMRI run [G–G corrected $F(3.001,57.024)=0.872$, $p=0.461$] or the interaction between rejoice level and run [G–G corrected $F(4.185,79.512)=0.657$, $p=0.630$]. Further analysis

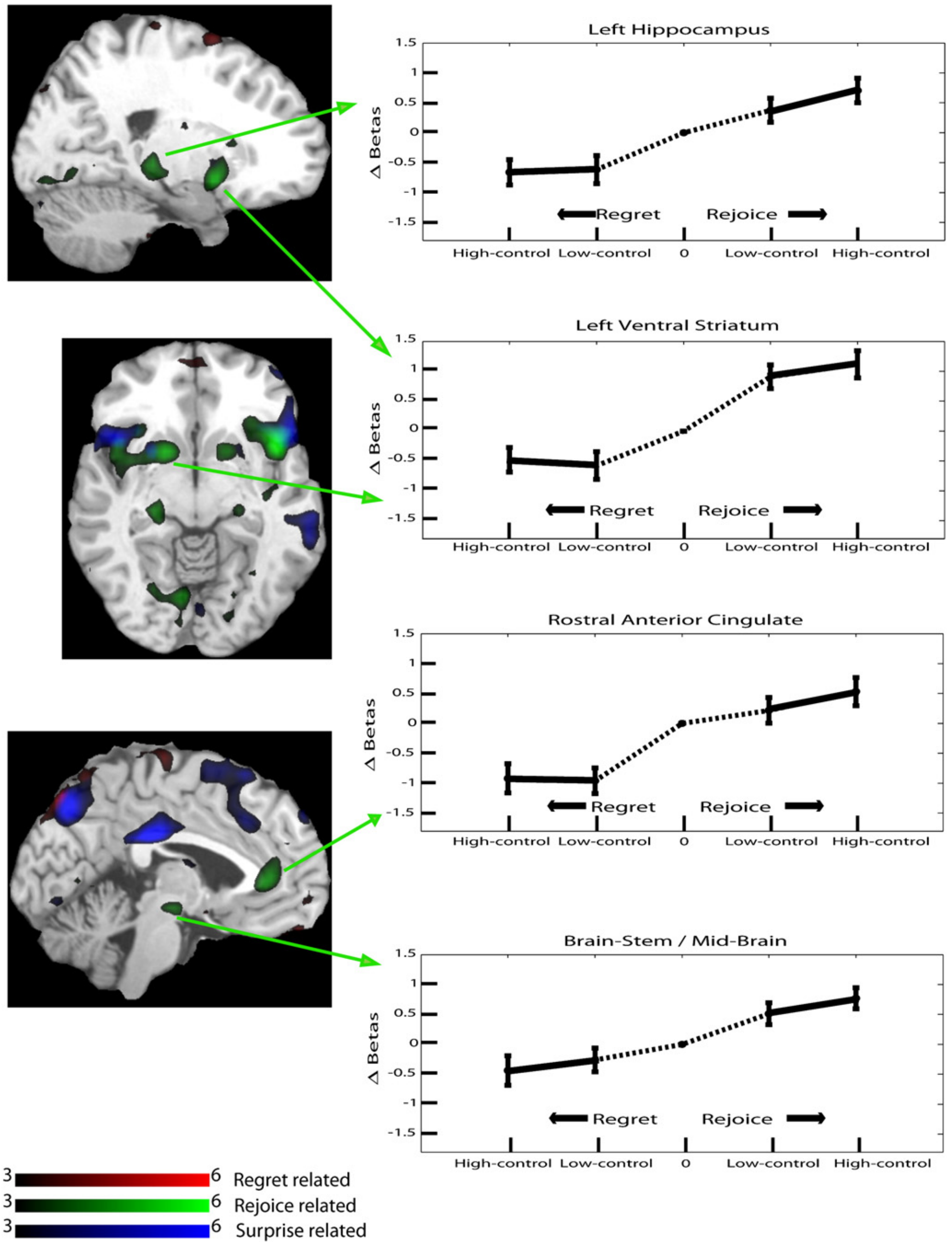

Fig. 4. Brain regions activated with the experience of rejoice along with the plots of differences of betas. The activations corresponding to rejoice related (green), regret related (red), and surprise related (blue) are shown. The rejoice-related brain regions were: left hippocampus [MNI coordinate: (−21, −27, −3)], left ventral striatum [MNI coordinate: (−18, 9, −9)], rostral anterior cingulate [MNI coordinate: (3, 36, 3)], and midbrain/brain stem [MNI coordinate: (3, −15, −12)].

revealed significantly increasing linear [$F(1,19)=5.324$, $p=0.032$] and quadratic [$F(1,19)=19.703$, $p<0.001$] increasing trends over the three rejoice levels (no to low to high).

Skin conductance response (SCR) results

The SCRs were also sensitive to the level of regret or rejoice. The integrated SCR during the decision making phase of each trial showed a significant main effect for probability of receiving a shock [$F(3,87)=13.630$, $p<0.001$], and further analysis indicated a linearly increasing relationship with the probability of receiving a shock in the trial [$F(1,29)=16.251$, $p<0.001$] (Fig. 2). When the outcomes were revealed and the participant received a shock, the integrated SCRs displayed a significant main effect for the prior probability of a shock [Greenhouse–Geisser (G–G) corrected $F(1.679,48.690)=8.450$, $p=0.001$]. Furthermore, the response displayed a significant linear increasing (from no to high regret) trend [$F(1,29)=11.702$, $p=0.002$]. When participants avoided a shock, there was also a significant main effect for rejoice level [$F(2,58)=5.452$, $p=0.007$] with a significant linearly increasing trend from no to high rejoice [$F(1,29)=6.561$, $p=0.016$].

fMRI results

Analysis of the fMRI data indicated that individuals experienced a different pattern of brain responses associated with regret and rejoice, and these responses correlated with the degree of the two experiences. A within-subjects ANOVA of the fMRI activation revealed that several regions activated with an intensity modulated by the level of regret (obtained from the interaction term where receiving a shock interacted with the ex ante probability of it being received). A region was classified as related to regret if it exhibited decreasing activity profile from higher regret to higher rejoice conditions. The regret-related brain regions included the left thalamus, left middle occipital cortex, left inferior temporal cortex, right angular gyrus, left precuneus, left superior frontal cortex, and medial orbitofrontal cortex (Table 2). Activation in the medial orbitofrontal cortex, the left thalamus, the left superior frontal cortex, and the right angular gyrus was greater in high regret than in no regret, as well as greater in no rejoice than in high rejoice, and these areas are illustrated in Fig. 3.

A different network of brain regions was modulated by the level of rejoice. This network consisted of the bilateral ventral striatum, right caudate, left hippocampus, midbrain/brain stem, right supramarginal gyrus, right lingual gyrus, left calcarine, bilateral anterior insula, rostral anterior cingulate cortex, and the superior medial frontal cortex (Table 3). These rejoice-related brain regions showed decreasing activity from higher rejoice to higher regret conditions. A subset of these regions also displayed greater activation with the highest level of rejoice than under no rejoice, as well as greater activation under no regret than the high regret. The subset consisted of the left hippocampus, left ventral striatum, rostral anterior cingulate, and midbrain (Fig. 4).

Different brain regions exhibited activation levels that increased with *both* the levels of regret and rejoice (Table 4). Using the contrast obtained from the main effect of levels, this pattern of activation was suggestive of a function related to “surprise.” The right inferior orbitofrontal cortex, pre-supplementary motor area, dorsal anterior cingulate, and the posterior cingulate all displayed this type of pattern (Fig. 5). They activated more strongly, the lower the prior likelihood of the outcome that was eventually realized, whether the outcome was a shock or no shock. The right amygdala (identified from the main effect of levels) displayed a pattern of activity that did not fit into any of the above classifications. It had greater activation when the *possibility* of a shock existed. That is, it activated identically under every condition except for the one in which there was zero probability of a shock, in which it exhibited a lower level of activation (Fig. 6).

Table 4
Regions that activated with both regret and rejoice

Brain area		BA	Coordinates (mm)			*T* score
Inferior orbitofrontal cortex	R	47	48	21	−18	8.26
	R	47	51	39	−15	5.23
	L	47	−48	18	−12	6.15
Precuneus	L	7	−6	−75	45	7.14
Posterior cingulate cortex	R	23	3	−30	27	7.11
Inferior parietal cortex	R	40	42	−54	57	5.50
	L	40	−42	−54	57	4.51
Anterior cingulate cortex (dorsal)	L	24	−3	24	36	5.40
Middle temporal cortex	R	21	63	−39	−6	5.29
Pre-supplementary motor area	R	6	6	24	63	5.20
Amygdala	R		24	6	−15	4.71
Precentral gyrus	R	6/44	51	12	42	4.50
Thalamus	R		9	−3	12	4.14
Cerebellum	L		−42	−66	−27	4.13

Stereotaxic MNI coordinates of significant BOLD signals for the main effect of degree obtained from the 2×3 ANOVA constructed by entering the two effects and three levels at the second level SPM analysis. These activations were obtained with uncorrected $p<0.001$, number of voxels ≥ 10.

During the anticipation phase, another network of regions exhibited increasing activation as the prior probability of receiving a shock increased. Activation in the dorsal anterior cingulate, supplementary motor area, right superior parietal cortex, bilateral superior temporal pole, bilateral somatosensory area (SII), bilateral insula, bilateral precentral gyrus, bilateral thalamus, left cerebellum, bilateral posterior cingulate gyrus, bilateral middle frontal cortex, and right inferior temporal cortex (Table 5; Fig. 7) was greater during the anticipation phase, the higher the probability of a shock. Except for the dorsal anterior cingulate, thalamus, and insula, the regions in this group did not display a similar monotonic pattern of activation in the response to outcome phase.

Discussion

Regret, like Marlon Brando’s character exhibited, influences how one experiences an outcome that results from one’s decisions. Choose poorly and regret it; choose wisely and rejoice. The most common formulation of regret and rejoice is as a result of counterfactual thinking, in which a realized outcome is compared with “what might have been” (Boles and Messick, 1995; Inman et al., 1997; Kelsey and Schepanski, 1991; Mellers, 2000; Ritov and Baron, 1995; Roese and Olson, 1995; Zeelenberg, 1999). Although a growing body of experimental work supports the existence of the commonsense notions of regret and rejoice, a number of questions remain as to how such a comparative algorithm is implemented both cognitively and neurobiologically in the brain. For example, what is the neurobiological signature of rejoice? Is what is commonly associated with regret actually the registering of surprise? One approach is to examine decisions that individuals make. Under the assumption that individuals make decisions to maximize their

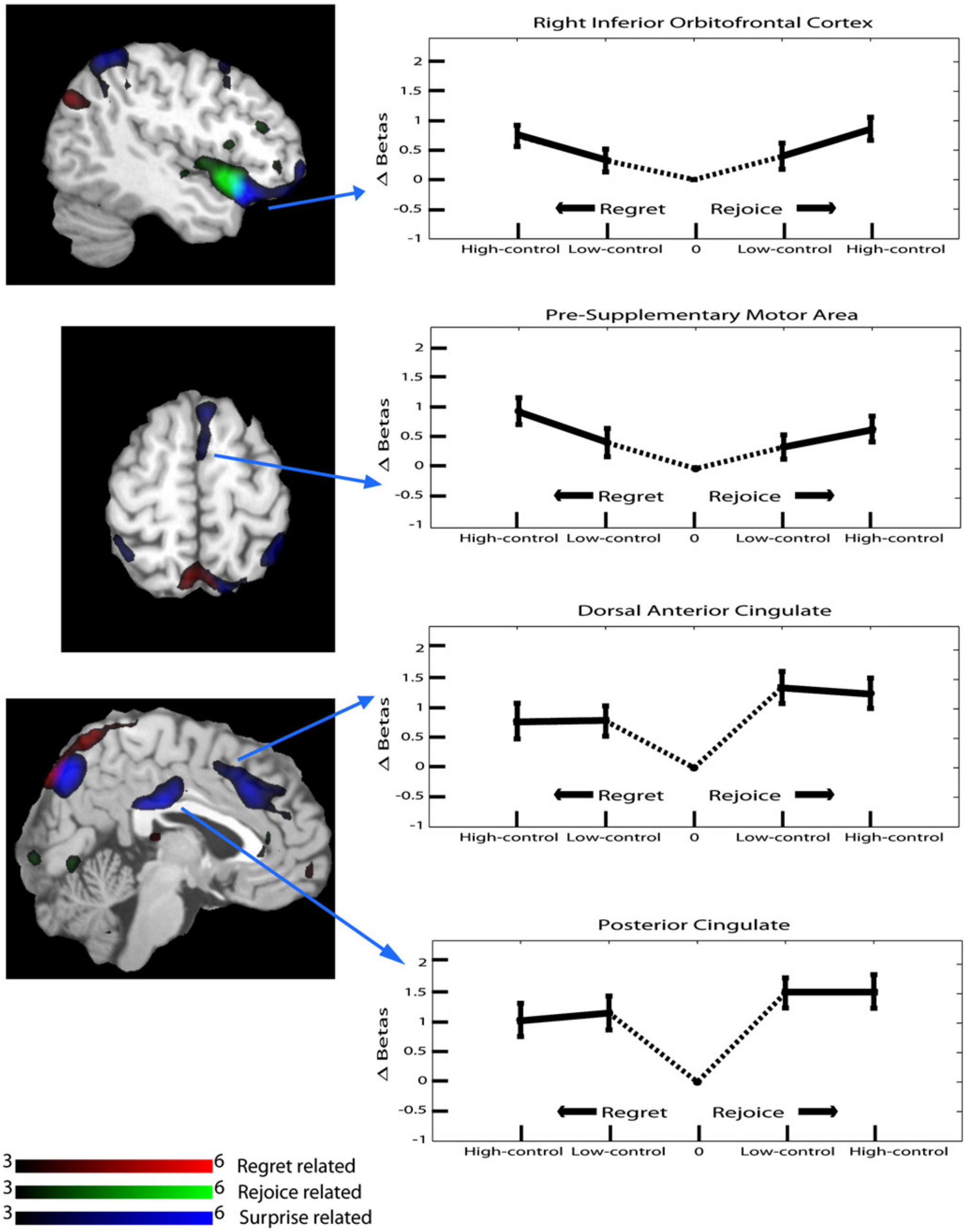

Fig. 5. Brain regions modulated similarly across two degrees of regret and rejoice along with the differences of betas (blue). The activations corresponding to surprise regret related (red) and rejoice related (green) are also shown. The areas displaying similar profiles for both regret and rejoice were: right inferior orbitofrontal cortex [MNI coordinate: (51, 39, −15)], pre-supplementary motor area [MNI coordinate: (6, 24, 63)], dorsal anterior cingulate [MNI coordinate: (−3, 24, 36)], and posterior cingulate [MNI coordinate: (3, −30, 27)].

utility, the anticipation of regret or rejoice might change their evaluation of different lotteries, and in turn, their choices (Bell, 1982; Loomes and Sugden, 1982). Brain imaging, however, provides another method to study whether utility functions are modulated by regret and rejoice, and we focus specifically on whether regret is experienced as a separate cognitive function apart from the decision-free value of the outcome itself (the value that would be attained if the outcome was forced upon the individual so that there was no choice).

Although regret and rejoice have been studied empirically with monetary outcomes, no data exist for comparable experiences with non-monetary paradigms. Although there is no reason to suspect that regret and rejoice should not exist for things other than money, it is possible that the neural mechanisms that accompany them might depend on the specific modality of the outcome. Our data show clearly that the participants experienced electric shocks differently when the ex ante probability of receiving the shock differed. The self-reported ratings of the experience show that a shock was experienced as worse, the less likely it was. This suggests that regret is the proper interpretation to give to the neural activation patterns that appear after a shock, if the activation increases with the lower the probability the shock was to be

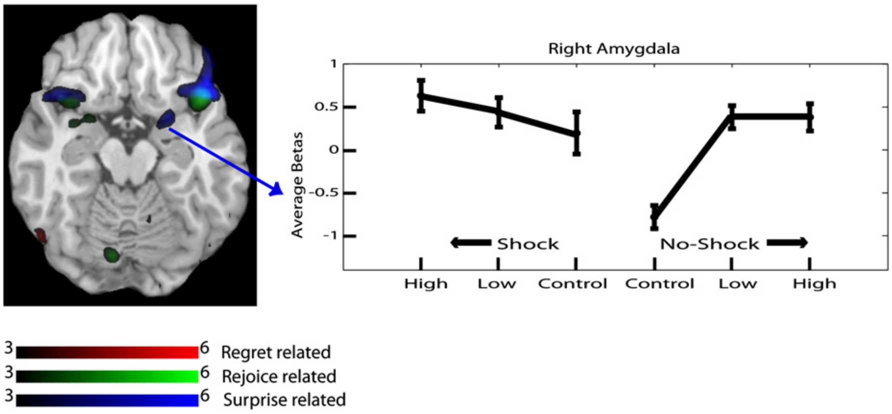

Fig. 6. Brain region activated by the possibility of a shock. The right amygdala [MNI coordinate: (24, 6, −15)] was found to be activated if and only if an aversive outcome was possible.

received. Similarly, making a decision that avoided a shock yielded more favorable self-reported evaluations of the experience when the shock was more likely beforehand. This indicates that individuals experienced rejoice at beating relatively unfavorable odds. In both the case of receiving a shock and avoiding it, the measures of the subjective experience of the outcome yielded values 20–35% greater than when the participant selected the only door with that outcome compared to trials in which all doors yielded the same outcome.

Because the shocks were hidden randomly behind the doors, there was, in fact, no optimal strategy for decision making. Based on this, it might be argued that the participants did not perceive that they were making meaningful decisions. However, both the distribution of choices of each door and the reaction times showed that the participants were, in fact, thinking about which door to choose. There was no significant difference in the number of times each door was chosen, indicating that the participants were not simply picking the same door each time. Moreover, the one-third and two-thirds conditions, which were the only conditions in which different outcomes could result for different decisions, showed significantly greater decision times than the control conditions of probabilities 0 and 1 for receipt of a shock.

Table 5
Regions activated with the linear increase of probability of shock in the anticipation phase

Brain area		BA	Coordinates (mm)			*T* score
Anterior cingulate (dorsal)	L	24/32	−3	9	39	9.32
Supplementary motor area	R	6	9	−9	75	8.13
Superior parietal cortex	R	5/7	15	−48	72	7.19
Superior temporal pole	R	21/38	60	3	0	6.74
	L	21/38	−57	3	0	5.45
Somatosensory area (SII)	R	2/42	57	−27	27	5.52
	L	2/42	−63	−24	21	5.46
Thalamus	R		9	−21	3	5.00
	L		−6	−24	−9	4.92
Precentral gyrus	R	6	45	−3	45	4.98
	L	6	−51	−3	45	3.75
Middle frontal cortex	L	46/9	−36	48	36	4.67
	R	46	27	36	24	3.76
Anterior insula	R		33	24	6	5.00
			45	6	6	4.62
	L		−39	18	6	4.49
Cerebellum	L		−21	−60	−27	4.49
	L		−9	−42	−30	4.14
Posterior cingulate gyrus	R	31	15	−30	42	4.36
Postcentral gyrus	L	5/1	−18	−45	72	3.82

Stereotaxic MNI coordinates of significant BOLD activations from the linear contrast of the shock probabilities: 0, 1/3, 2/3, 1 at the second level SPM ANOVA analysis. The activations were obtained with uncorrected $p<0.001$, number of voxels ≥ 10.

The SCR results yield some insight into the physiological nature of regret and rejoice. First, during the anticipation stage, there was a nearly linear relationship between the integrated SCR and the probability of receiving a shock. This is consistent with a large body of data linking the magnitude of the SCR with arousal state that finds that the more likely an adverse outcome, the greater the arousal (Bradley et al., 2001, 2005; Kobayashi et al., 2007). At the time of the realization of the outcome, we found that both the degrees of regret and rejoice were monotonically associated with greater SCRs. Thus, receiving a shock when it was relatively unlikely was more arousing than receiving one when the outcome was already known. Due to the generally much smaller SCRs associated with the avoidance of a shock than with the receipt of a shock, the magnitude of effect of rejoice on the SCR, although significant, was smaller than that of regret. But the similarity of the shape of the relationships with both regret and rejoice suggests that physiological arousal was not the final common pathway of a signed regret function. SCR behaved more like a surprise function, taking on higher values, the less likely, ex ante, the realized outcome.

The fMRI results did, however, reveal different but overlapping networks that were associated with regret and rejoice. We observed networks with three different relationships to regret/rejoice: (1) a monotonically increasing function from maximal rejoice to maximal regret; (2) the opposite, i.e., a monotonically decreasing function from maximal rejoice to maximal regret; and (3) a "surprise" function that increased with the degree of both regret and rejoice. Although regret theory, as originally proposed by Loomes and Sugden (1982) and Bell (1982), did not explicitly assume the existence of distinct and separate regret and rejoice functions, the neural evidence suggests that the separate neural networks underlie the two forces.

For trials in which the subject picked a door with a shock behind it, and in which one or both of the remaining doors did not contain a shock, we observed an increase of activity in several cortical and thalamic regions relative to when a shock was certain. To qualify as

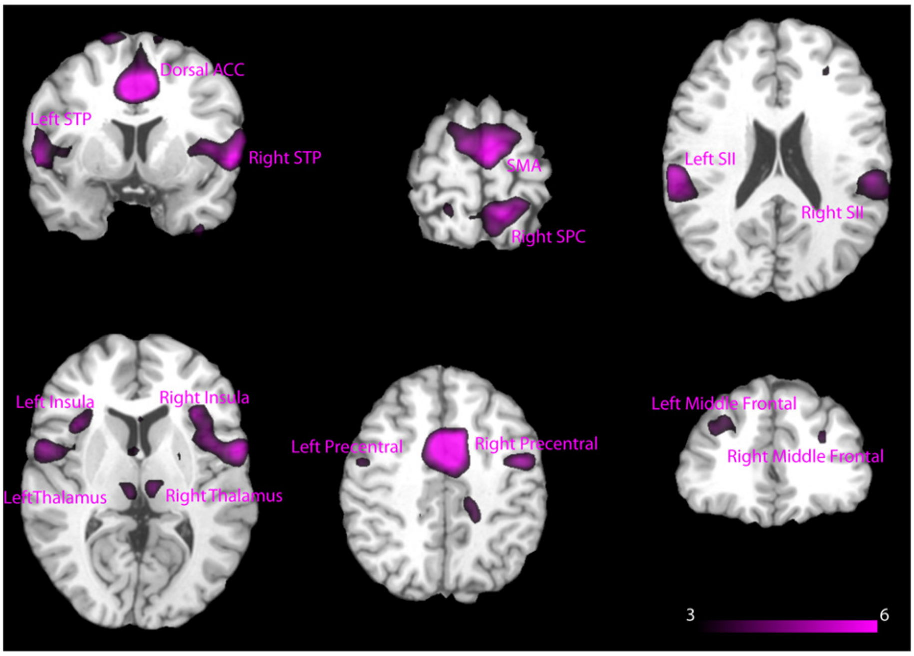

Fig. 7. Brain regions modulated by the probability of a shock in the anticipation phase. The significantly activated brain regions were dorsal anterior cingulate (ACC), supplementary motor area (SMA), right superior parietal cortex (SPC), bilateral superior temporal pole (STP), bilateral somatosensory area (SII), bilateral insula, bilateral precentral gyrus, bilateral thalamus, and bilateral middle frontal cortex represented in the are shown (purple).

a regret-related area, these regions were required to show monotonically increasing activity from probability 1 trials to 1/3 probability trials. With probability 1 of a shock, there was no possibility of regret, whereas the 1/3 (high-regret) condition offered the most opportunity for regret. Areas showing the strongest relationship included visual processing regions (middle occipital cortex and precuneus), which most likely reflected a shift in visual attention that scaled with the number of alternative outcomes. The thalamus, also associated with visual attention (Kastner and Pinsk, 2004), showed a similar increase in both higher regret and higher rejoice conditions. The other areas associated with regret but not with rejoice included the right angular gyrus, left superior frontal cortex, and the medial orbitofrontal cortex. In a previous study of regret using monetary outcomes, the medial orbitofrontal cortex was implicated in the experience of regret (Coricelli et al., 2005). This study also found the presence of regret to activate the inferior parietal lobule, a region that partially overlapped the area of regret-related activity we observed in the angular gyrus. Another recent study of positive and negative monetary reward found a similar pattern of activation in the orbitofrontal cortex when the outcome was worse than anticipated and striatum when better (Liu et al., 2007). It is, therefore, indicative that the activation of some of the regret-related regions, notably the OFC, is robust, with respect to a completely different incentive medium – electrical shocks – and the creation of regret through variation in ex ante probability instead of magnitude of alternative outcomes.

Avoidance of a shock, leading to the experience of a degree of rejoice, was associated with a distinct network from regret. Surprisingly, the bilateral anterior insula showed the strongest relationship to the degree of rejoice. Although the insula has been linked with painful outcomes (Berns et al., 2006; Brooks and Tracey, 2005; Koyama et al., 2005; Peyron et al., 2002; Ploghaus et al., 1999), its anterior extensions have been characterized as relating to the anticipated emotional state of something potentially painful (Craig, 2003). Thus, its role in rejoice here may reflect an activity state that tracks the ex ante probability of receiving a shock. More specific to the positive valence of avoiding a shock was the increasing rejoice-related activity of the left hippocampus and bilateral ventral striatum. The striatum, in particular, is generally accepted as playing a key role in reward prediction errors (Berns et al., 2001; McClure et al., 2003; Montague et al., 2006; O'Doherty et al., 2004, 2003; Pagnoni et al., 2002; Schultz et al., 1997; Yacubian et al., 2006). Because we manipulated regret/rejoice through probability, the more likely the anticipated shock, the greater the reward prediction error when it was avoided. The fact that we observed increasing striatal activity with rejoice only, and not decreasing activity with regret, suggests that the ventral striatum may be involved in only one side of the regret/rejoice continuum. This finding is consistent with a recent study using financial markets which found that this same region computed only positive "fictive error" and not negative ones (Lohrenz et al., 2007). Thus, our finding can be viewed as an extension of this result to non-monetary outcomes.

It is interesting to note that brain regions related to regret and near the striatum, namely the medial orbitofrontal cortex and rostral anterior cingulate cortex, exhibited reverse patterns of activation profiles. The medial orbitofrontal cortex has been implicated previously in studies of regret (Coricelli et al., 2005; Liu et al., 2007), while the rostral anterior cingulate has been previously implicated in emotional and error processing (Bush et al., 2000). Thus the rostral anterior cingulate area which is caudal to medial orbitofrontal cortex may be responsible for the emotional processes related to rejoicing (i.e., pleasure related) and suggests the possibility of a rostral–caudal gradient of different aspects of processing regret similar to that seen in the caudate for reward prediction errors (Haruno and Kawato, 2006).

It is possible that the 'response to outcome' we observed due to the anticipation for an outcome (based on the prior probability) could have included an element of prediction error. However, prediction error applies in the context of reinforcement learning, and in our experiment there were no statistical associations to learn. None of the doors was preferentially associated with a particular outcome state. Our behavioral results also show that there was no preferred strategy for picking doors. But our observation that the shocks were experienced worse under the maximal regret condition suggests that there could be a signal at the outcome different than a prediction error signal (which would not be expected to change subjective utility). Instead, our results may come under the class of 'fictive error' signals (recently formulated by Montague and colleagues, Lohrenz et al., 2007). Our results also show that the anticipation-related brain regions are not the same as the 'response to outcome.' Thus, we believe that the regret/rejoice findings at the outcome are due to the counterfactual process of what would have happened had a different door been chosen (as opposed to a more conventional error signal of the difference between expectation and outcome).

"Surprise" is a reflection of the ex ante probability of a particular outcome. The lower the probability, the more surprising the event when it occurs. In our experiment, we manipulated regret through such a probability manipulation, but because there were only two possible outcomes, the probability of not receiving a shock was complimentary to the probability of receiving one. Thus, brain regions that showed increasing relationships to *both* the degree of regret and rejoice were designated surprise-related regions. This was a substantially more expansive network than either the pure regret or rejoice ones. Of note, the lateral orbitofrontal cortex was the region most strongly activated by surprise. Although this region was implicated in a previous study of regret (Coricelli et al., 2005), it may actually be registering surprise, an interpretation that could not be made with the design of Coricelli et al. (2005). This region has more commonly been associated with aversive outcomes and losses (Hosokawa et al., 2007; O'Doherty et al., 2001; Rolls, 2000; Ursu and Carter, 2005). Its activation with both regret and rejoice in our study may reflect a specialization for the processing of potentially aversive outcomes, whether realized or not. Many of the surprise-related regions we observed, including the posterior cingulate, ACC, and precuneus, have been linked to selective attention (Crottaz-Herbette and Menon, 2006; Hahn et al., 2006; Hopfinger et al., 2000; Posner and Petersen, 1990; Small et al., 2003), and their activation in our study suggests a potentially augmenting effect of both regret and rejoice. In other words, the emotional response to either form of counterfactual comparison may require more attention to alternative outcomes. Without this attention, it is possible that regret and rejoice are not experienced.

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