Experimental Brain Research (2018) 236:679–689
https://doi.org/10.1007/s00221-017-5165-3

RESEARCH ARTICLE

Responsibility modulates the neural correlates of regret during the sequential risk-taking task

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Received: 20 June 2017 / Accepted: 26 December 2017 / Published online: 3 January 2018

Abstract

Responsibility is a necessary prerequisite in the experience of regret. The present fMRI study investigated the modulation of responsibility on the neural correlates of regret during a sequential risk-taking task. Participants were asked to open a series of boxes consecutively and decided when to stop. Each box contained a reward, except for one containing a devil to zero participant's gain in the trial. Once participants stopped, both collected gains and missed chances were revealed. We manipulated responsibility by setting two different contexts. In the Self (high responsibility) context, participants opened boxes and decided when to stop by themselves. In the Computer (low responsibility) context, a computer program opened boxes and decided when to stop for participants. Before each trial, participants were required to decide whether it would be a Self or a Computer context. Behaviorally, participants felt less regret (more relief) for gain outcome and more regret for the loss outcome in the high-responsibility context than low responsibility context. At the neural level, when experiencing a gain, high-responsibility trials were characterized by stronger activation in mPFC, pgACC, mOFC, and striatum with decreasing number of missed chances relative to low responsibility trials. When experiencing a loss, low responsibility trials were associated with stronger activation in dACC and bilateral insula than high-responsibility trials. Conversely, during a loss, high-responsibility trials showed more striatum activity than low responsibility trials. These results highlighted the sensitivity of the frontal region, striatum, and insula to changes in level of responsibility.

Keywords fMRI · Decision making · Responsibility · Striatum · Regret

Introduction

Decision making occurs in situations, where individuals are required to choose one out of many options. In arriving at a deliberative decision, individuals should not only select one option, but reject the alternatives. The outcomes of these alternative options could modulate the evaluation of the obtained outcome. This phenomenon is known as counterfactual thinking (Mandel 2003; Roese 1994, 1997; Zeelenberg et al. 1999). Regret and relief are subjective feelings that result from counterfactual thinking (Boles and Messick 1995; Kelsey and Schepanski 1991; Mellers 2000). Specifically, individuals may experience regret when the obtained outcome is worse than those of the alternative options (Bell 1982; Connolly and Zeelenberg 2002; Markman et al. 1993). Conversely, they may experience relief when the obtained outcome is better than those of the alternative options (Chandrasekhar et al. 2008; Coricelli and Aldo Rustichini 2010; Guttentag and Ferrell 2004).

Lin Li and Zhiyuan Liu contributed equally to this work.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00221-017-5165-3) contains supplementary material, which is available to authorized users.

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The dominant view of the previous studies on regret and relief was that responsibility was a necessary prerequisite in the experience of regret (Connolly et al. 1997; Ordóñez and Connolly 2000; Zeelenberg et al. 1998). Most empirical works related to this view have been done with a paradigm in which participants make choices between two risky gambles (Camille et al. 2010; Coricelli et al. 2005; Nicolle et al. 2011). For instance, in a task involving making choices between two wheels-of-fortune, Coricelli et al. (2005) manipulated responsibility by including "choose" trials, where the decision was made by participants, and "follow" trials, where the decision was made by a computer automatically. The study revealed that people felt no regret in "follow" trials when they had no responsibility for the outcomes. However, this study did not investigate whether regret was affected by different levels of responsibility. In another study, Camille and colleagues (2010) manipulated levels of responsibility by setting two types of trials, in which participants had a second chance to change their decisions or had no such chance. Participants were considered to feel more responsibility if they had a chance to change their decisions. The results revealed that the experience of regret was greater when participants made poor decision on high-responsibility trials.

In addition to simple, stand-alone decisions, individuals are frequently required to make sequential risk decisions in real life, such as deciding when to sell stocks. However, few study has ever investigated whether responsibility modulates regret during a sequential risk-taking task. The main goal of the current study was to address this question. We put forward a different manipulation of responsibility from the previous researches. The essence of our manipulation imitated the procedure of agent-authorizing which occurred more often in everyday sequential risk taking. For instance, clients sometimes ask stockbroker to help them buy and sell shares, and leaders assign underling to help them accomplish a task. In such cases, the outcomes resulting from an agent's decisions are uncertain, yet clients still feel responsible for the outcomes, because the agent is selected by themselves. However, the responsibility is lower than the case when people make decisions from cover to cover.

In the current study, we employed a sequential risk-taking task, which had been successfully used to prompt the emotion of regret (Büchel et al. 2011; Brassen et al. 2012; Liu et al. 2016, 2017), to investigate the modulation of responsibility on regret. During the task, participants were asked to open a series of boxes consecutively and decide when to stop. All except for one box contained a reward (gold); the remaining box contained an adverse stimulus (devil) that caused participants to lose all the gold that had been collected in that trial. When participants decided to stop, the position of the devil was shown, revealing the number of collected gains and missed chances. Participants were paid based on the amount of gold they had at the end of the task. Importantly, we manipulate responsibility by setting two contexts (Self context and Computer context). Before each trial, participants were required to decide whether it would be a Self context or a Computer context. In the Self (high responsibility) context, participants opened boxes and decided when to stop by themselves. In the Computer (low responsibility) context, the computer helped participants to open boxes and decided when to stop. In the low responsibility context, we used the computer instead of another human. The purpose of such manipulation was to avoid contamination by participants' attitude towards another person. Specifically, we tried not to introduce personal trust (in case another person choose a good choice) or blame (in case another person made a bad choice) to our experiment and just focused on levels of responsibility.

We predicted that responsibility could modulate the feelings of regret and relief. Behaviorally, we hypothesized that the subjective experience of regret and relief would be enhanced in the Self context relative to the Computer context. At the neural level, the previous studies had identified that striatum was related with reward processing (Apicella et al. 1991; Chandrasekhar et al. 2008; Connolly and Zeelenberg 2002; Coricelli and Aldo Rustichini 2010; Guttentag and Ferrell 2004). Recently, using a sequential risk-taking task, some research showed that striatum participated in regret processing, whose activation decreased along with increasing regret levels (Brassen et al. 2012; Liu et al. 2016). Moreover, the previous research also found that pregenual anterior cingulate cortex (pgACC) and medial prefrontal cortex (mPFC) were involved in reward processing (Haber and Knutson 2010; Izuma et al. 2008; Liu et al. 2016; Rogers et al. 2004). Therefore, with the better outcome, we predicted that stronger activations of striatum, pgACC, and mPFC might be found in the Self context relative to the Computer context. Moreover, we predicted that poor outcome might be related with decreased striatum activation in the Self context other than the Computer context.

Methods

Participants

Eighteen right-handed participants (10 females, aged from 20 to 28 years, $M = 23.67$ years, $SD = 2.33$ years) from the university community with normal or corrected-to-normal vision participated in this experiment. None of the participants had abnormal neurological history. All gave informed consent before scanning. This study was approved by the Ethics Committee of East China Normal University.

Procedure

Before scanning, participants were told that they would play a sequential decision task while undergoing fMRI scanning. At the beginning of each trial, they would be presented with two context options (''Self'' or ''Computer''). They were required to decide whether it would be a Self context or a Computer context by pressing corresponding buttons ('1' for 'Self' and '2' for 'Computer'). Following that, in the Self context, participants opened boxes and decided when to stop by themselves. While in the Computer context, computer helped participants to open boxes and decided when to stop. Participants were also informed that the payment for their participation would be affected by their total gains from both Self and Computer contexts in the task. The actual payment was calculated by subtotaling gains of 30 randomly chosen gain trials at the end of the task.

All participants completed 90 trials in the scanner. On each trial, they first decided whether boxes opened by themselves or not within 2500 ms. Then, an array of eight boxes was presented, where seven boxes contained gold coins and one box contained a devil. The position of the devil was set randomly on each trial. Boxes were opened from left to right one after another. In the Self context, at any stage, participants had 2000 ms to either open the next box or stop and collect the gains acquired so far in that trial by key-press. Opening the box with the devil ended the current trial and all gains from that trial were lost. A jittered interval (ranging from 1800 to 2250 ms) was presented after participants decided to stop or unpacked the devil. Then, the outcome was presented for 3000 ms and highlighted on the screen by a cyan square (in the case of stopping and collecting the gains) or a red square (in the case of unpacking the devil and losing the gains in that trial). The outcome screen also revealed the actual position of the devil, thus informing participants about how many golds they had gained and missed at the same time. Finally, an additional jittered inter-trial interval (ranging from 1500 to 15,500 ms) was introduced. In the Computer context, the computer helped participants to open boxes and decided when to stop. Actually, the strategy of the computer, when opening boxes, was decided by randomly selecting from a database which collected participants' actual performance on each trial of the same risk-taking task in our previous experiments. Specifically, for each trial, our previous work had provided probabilities of different outcomes (i.e., different numbers of boxes being opened, or unpacking devil) that could be achieved by real persons.

In the present experiment, when the computer was making decisions, it would randomly select a specific outcome while considering distribution of probability of all outcomes. This strategy allowed our computer condition to simulate behaviors of an average person. Figure 1 displays two of the possible outcome conditions for a trial.

After scanning, participants were presented with their choices and results from the task completed inside the scanner and were asked to rate how they felt for each trial on a nine-point scale from extreme regret (defined as − 4) to extreme relief (defined as 4).

fMRI data acquisition

Scanning was carried out on a 3T Siemens Trio system at the Functional MRI Lab (East China Normal University, Shanghai). For functional images, 35 slices were acquired using a gradient-echo echo-planar imaging (EPI) sequence (TR = 2200 ms, TE = 30 ms, FOV 10 = 220 mm, matrix size = 64 × 64, slice thickness = 3 mm, gap = 0.3 mm). Before the functional run, a high-resolution structural image was acquired using a T1-weighted, multi-planar reconstruction (MPR) sequence (TR = 1900 ms, TE = 3.42 ms, 192 slices, slice thickness = 1 mm, FOV = 256 mm, matrix size = 256 × 256).

Data pre-processing and statistical analyses were performed with Statistical Parametric Mapping (SPM8, Wellcome Department of Cognitive Neurology, London). The functional images were corrected for the delay in slice acquisition and were realigned to the first image to correct for inter-scan head movements. The individual T1-weighted, 3D structural image was co-registered to the mean EPI image

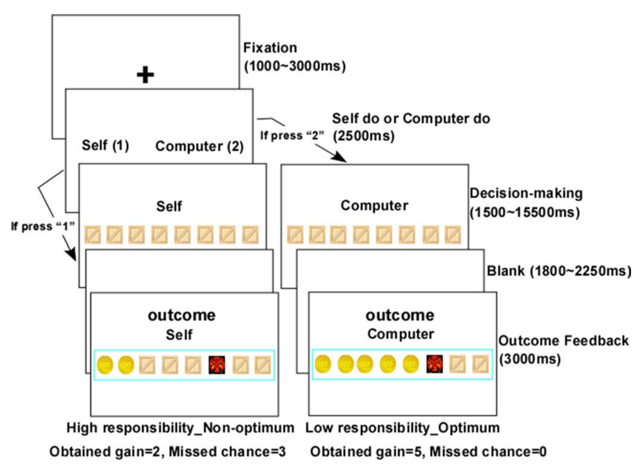

Fig. 1 Two possible conditions were displayed when participants play the task undergoing fMRI scanning. The left part showed that participants decided to open boxes by themselves and stopped after collecting two gold coins. The outcome revealed that they collected two gold coins and missed three chances (i.e., non-optimal outcome) in the current trial. It was Self_Non-optimum condition. The right part showed that participants chose computer to open boxes and computer stopped after collecting five gold coins. The outcome revealed that they collected five gold coins and missed zero chance (i.e., optimal outcome) in the current trial. It was Computer_Optimum condition

generated after realignment. The co-registered structural image was then segmented into gray matter (GM), white matter (WM), and cerebrospinal fluid (CSF) using a unified segmentation algorithm (Ashburner and Friston 2005). The functional images after slice timing and realignment procedures were spatially normalized to the Montreal Neurological Institute (MNI) space (resampled to $2 \times 2 \times 2$ mm^3) using the normalization parameters estimated during unified segmentation and then spatially smoothed with a Gaussian kernel of 8 mm full-width half-maximum (FWHM).

fMRI data analyses

Parametric analyses were performed to assess how brain activities were modulated by obtained gain, missed chance and lost coin during Computer or Self context. Four types of conditions were defined: (i) Computer_Gain, trials in which participants chose computer to open boxes for themselves and computer did not unpack the devil; (ii) Self_Gain, trials in which participants chose to open boxes by themselves and they did not unpack the devil; (iii) Computer_Loss, trials in which participants chose computer to open boxes for themselves and computer unpacked the devil; and (iv) Self_ Loss, trials in which participants chose to open boxes by themselves and they unpacked the devil. Both of obtained gain and missed chance were used as the parametric regressors in Computer_Gain and Self_Gain conditions, respectively. The number of lost gold coins was used as the parametric regressors in both Computer_Loss and Self_ Loss conditions. The resulting subject-specific estimates of the parametric regressors at each voxel were then entered into a second-level one sample *t* test.

Then, we conducted the general linear model to investigate how responsibility affected the neural responses to the Outcome (Devil, Non-optimum, and Optimum) (Brassen et al. 2012; Liu et al. 2016). At the first-level analyses, six types of conditions were defined according to Context (Computer vs. Self) and Outcome (Devil, Non-optimum, and Optimum): (i) Self_Optimum, trials in which participants chose to open boxes by themselves and they got the largest possible gain (zero missed chances); (ii) Self_Non-optimum trials in which participants chose to open boxes by themselves and they missed some chances; (iii) Self_Devil, trials in which participants chose to open boxes by themselves and they unpacked the devil; (iv) Computer_Optimum, trials in which participants chose computer to open boxes for themselves and computer got the largest possible gain; (v) Computer_Non-optimum, trials in which participants chose computer to open boxes for themselves and computer missed some chances; and (vi) Computer_Devil, trials in which participants chose computer to open boxes for themselves and computer unpacked the devil. A general linear model analysis created six contrast images for each participant summarizing differences of interest. The six first-level contrast images from each participant were then analyzed at the second level employing a random-effects model (flexible factorial design in SPM8).

For all analyses, at the first level, all the conditions were time-locked to the presentation of the outcome of final decision with a duration of 3 s, convolved with a canonical hemodynamic response function (HRF). Additional covariates of no interest were created for movement-related variance and decision-making phase. High-pass temporal filtering with a cutoff of 128 s was also applied in the models. A cluster-level threshold of $p < .05$ (FWE) and a voxel-level threshold of $p < .001$ (uncorrected) were used to define activations.

Results

Behavioral results

Before data analyses, we checked the average number of trials for each condition across participants (Table 1). Moreover, the average number of lost coins, obtained gain, and missed chances in both contexts were calculated. Paired *t* test showed no significant difference in the average number of lost coins, obtained gain and missed chances between two contexts (Table 2).

Table 1 Average trial number of each condition across participants (mean ± SD, range)

	Optimum	Non-optimum	Devil	Total
Self	8.4 ± 2.4 (4,13)	22.4 ± 6.4 (12,36)	23.4 ± 4.4 (9,37)	54.2 ± 6.8
Computer	8.3 ± 1.7 (5,10)	18.0 ± 4.5 (9,26)	9.5 ± 2.2 (5,13)	35.8 ± 6.8

Table 2 Average number of lost coins, obtained gain and missed chances in the Self and Computer contexts (mean ± SD)

	Self	Computer	*t*	*p*
The average number of lost coins	2.25 ± 0.47	2.04 ± 0.56	1.30	0.21
The average number of obtained gain	4.15 ± 0.59	4.03 ± 0.24	0.99	0.34
The average number of missed chances	1.46 ± 0.37	1.51 ± 0.24	0.41	0.69

To investigate how responsibility affected the emotional ratings of outcomes. A 2 (Context: Computer vs. Self) × 3 (Outcome: Optimum, Non-optimum and Devil) repeated measures ANOVA on emotional ratings was conducted. Significant main effects of Context and Outcome (both Fs > 10.08, both ps < .01) were observed. A significant interaction between Context and Outcome was also found ($F(2, 34) = 27.26$, $p < .01$). Paired t tests revealed that emotional ratings for Optimum and Non-optimum outcomes in the Self context were higher than those in Computer context (ts > 3.71, ps < .01). Moreover, emotional ratings for Devil outcome in the Self context were lower than that in the Computer context ($t(17) = 4.69$, $p < .01$) (Fig. 2).

In Gain trials (trials in which participants did not unpack the devil and gained golds), we ran a mixed regression based on emotional ratings across participants. In the stepwise regression analysis, obtained gain, missed chance, context (Self or Computer), the interaction between context and obtained gain and the interaction between context and obtained gain were defined as predictors. Finally, obtained gain ($\beta = 0.18$, $t = 9.25$, $p < .01$), missed chance ($\beta = -1.31$, $t = -23.40$, $p < .01$), context ($\beta = 0.08$, $t = 4.65$, $p < .01$), and the interaction of missed chance and context ($\beta = 0.55$, $t = 9.99$, $p < .01$) entered the regression equation.

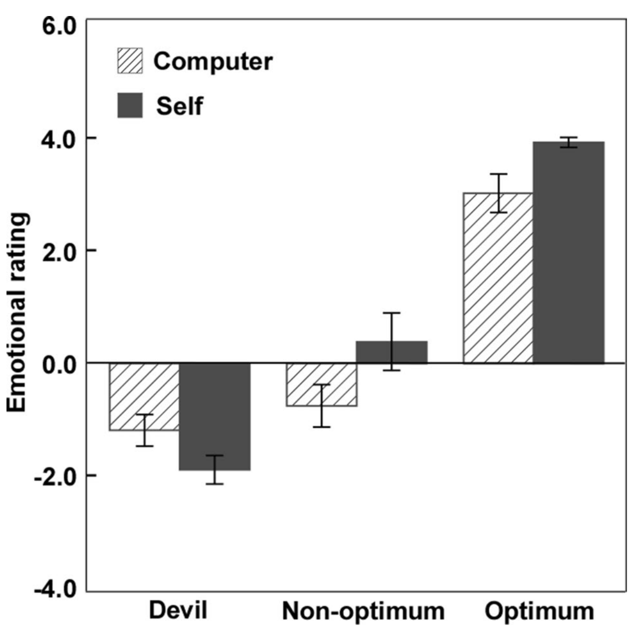

Fig. 2 Behavioral results. The Context (Computer vs. Self) × Outcome (Optimum, Non-optimum, and Devil) repeated measures ANOVA on emotional ratings showed significant main effects (both Fs > 10.08, both ps < .01) and significant interaction [$F(2, 34) = 27.26$, $p < .01$]. Paired t tests revealed that emotional ratings for Optimum and Non-optimum outcomes in the Self context were higher than those in the Computer context (ts > 3.71, ps < .01). Moreover, emotional ratings for Devil outcome in the Self context were lower than that in the Computer context ($t(17) = 4.69$, $p < .01$)

The post-hoc analysis of covariance showed the coefficient of missed chance in Self context was significantly larger than that in Computer context ($F(1, 1005) = 99.80$, $p < .01$).

In addition, we also ran a mixed regression based on emotional ratings across participants in Loss trials (when participants unpacked the devil and lost the collected golds). In the stepwise regression analysis, lost gain, context (Self or Computer), the interaction between context and lost gain were defined as predictors. Finally, lost gain ($\beta = -0.76$, $t = -30.87$, $p < .01$), context ($\beta = 0.183$, $t = 7.42$, $p < .01$), and the interaction of lost gain and context ($\beta = 0.15$, $t = 6.14$, $p < .01$) entered the regression equation. The post-hoc analysis of covariance showed the coefficient of missed chance in Self context was significantly larger than that in Computer context ($F(1, 606) = 37.74$, $p < .01$).

fMRI results

Parametric analyses in gain trials

In Gain trials, both obtained gain and missed chance were used as the parametric regressors in Self and Computer contexts, respectively. In the Computer context, subgenual anterior cingulate cortex (sgACC, MNI 6 36 − 4; − 4 36 0) showed increased activation with decreasing number of missed chances (Fig. 3a; Table 3). Moreover, in the Self context, medial prefrontal cortex (mPFC, MNI −4 58 14), right medial orbitofrontal cortex (mOFC, MNI 10 56 0), pregenual anterior cingulate cortex (pgACC, MNI 12 44 14), and right putamen (MNI 24 18 4) showed increased activations with decreasing number of missed chances (Fig. 3b; Table 3). No region showed significant activation with increasing number of missed chances in both Self and Computer contexts. In addition, no region showed significant activation with increasing or decreasing number of obtained gains in both Self and Computer contexts.

Parametric analyses in loss trials

In Loss trials, the number of lost gold coins was used as the parametric regressor in both Self and Computer contexts. In the Computer context, dorsal anterior cingulate cortex (dACC, MNI −6 32 30; 12 28 30) and insula (MNI 38 26 −2; − 42 14 4) showed increased activations with increasing lost gold coins (Fig. 4; Table 4). However, no region showed significant activation with increasing lost gold coins in the Self context. In addition, no region showed significant activation with decreasing lost gold coins in both Self and Computer contexts.

Assuming that each participant might have a normal expectation on the location of devil, which could be represented by the average gains from each gain trial in the Self context, we suggested that in the Computer context, a devil

Fig. 3 Parametric analyses in Gain trials. **a** SgACC (MNI 6 36 − 4; − 4 36 0) showed increased activation with decreasing number of missed chances in the Computer context. **b** mPFC (MNI − 4 58 14), mOFC (MNI 10 56 0), pgACC (MNI 12 44 14), and right putamen (MNI 24 18 4) showed increased activations with decreasing number of missed chances in the Self context

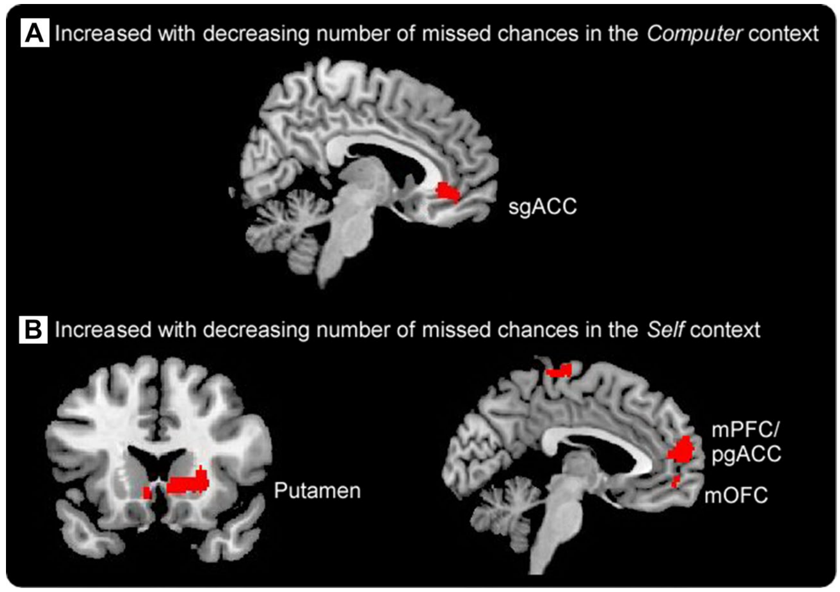

Table 3 Parametric analyses in gain trials

	Region	Peak activation			*t* Value	Voxels
		X	*Y*	*Z*		
Increased with decreasing number of missed chances in the computer context						
L	Linual Gyrus	− 14	− 74	− 6	6.94	3147
R	Middle Occipital Gyrus	28	− 94	14	7.38	2146
R	sgACC	6	36	− 4	7.29	1506
L	sg*ACC*	− 4	36	0	6.33	
R	Precentral Gyrus	36	− 12	68	5.45	478
Increased with increasing number of missed chances in the Computer context						
No region						
Increased with decreasing number of missed chances in the self context						
L	mPFC	− 4	58	14	5.86	1001
R	*mOFC*	10	56	0	5.82	
R	*pgACC*	12	44	14	4.53	
R	Middle occipital gyrus	30	− 92	12	6.54	542
L	Superior occipital gyrus	− 14	− 98	12	5.02	418
L	Paracentral lobule	− 6	− 28	70	5.13	353
R	Inferior occipital gyrus	40	− 82	− 12	4.53	230
R	MCC	8	− 30	38	4.35	226
R	Putamen	24	18	4	4.79	223
Increased with increasing number of missed chances in the self context						
No region						

Coordinates (mm) are in MNI space

L left hemisphere, *R* right hemisphere

All the clusters survived FWE correction ($p<.05$) for multiple comparisons at the cluster level, with a voxel-level threshold corresponding to $p<.001$, uncorrected

positioned beyond expectation might involve with more error signals detection and increased activation levels in ACC and insula. To test such suggestion, we calculated for each participant the average number of boxes being opened in the Self context resulting in gain outcomes. In addition, this number was then used as the cut-point to divide all loss trials from the same participant in the Computer context into two subcategories: those 'normal' loss trials with devils

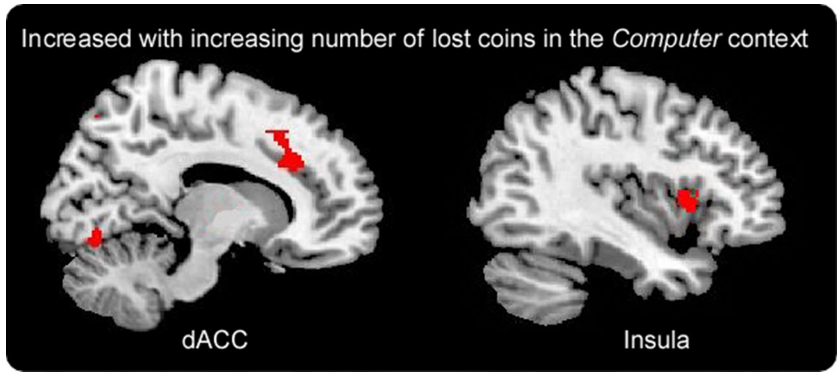

Fig. 4 Parametric analyses in Loss trials. In the Computer context, dACC (MNI −6 32 30; 12 28 30) and insula (MNI 38 26 −2; − 42 14 4) showed increased activations with increasing lost gold coins

Table 4 Parametric analyses in loss trials

	Region	Peak activation			*t* Value	Voxels
		X	*Y*	*Z*		
Increased with increasing number of lost gold coins in the Computer context						
L	dACC	− 6	32	30	4.88	514
R	*dACC*	12	28	30	4.80	
L	*mACC*	10	22	42	4.26	
R	Insula lobe	38	26	− 2	6.10	377
L	Insula lobe	− 42	14	4	6.78	291
Increased with decreasing number of lost gold coins in the Computer context						
No region						
Increased with increasing number of lost gold coins in the Self context						
No region						
Increased with decreasing number of lost gold coins in the Self context						
No region						

Coordinates (mm) are in MNI space

L left hemisphere, *R* right hemisphere

All the clusters survived FWE correction ($p < .05$) for multiple comparisons at the cluster level, with a voxel-level threshold corresponding to $p < .001$, uncorrected

located in relatively earlier positions, and those ‘unexpected’ loss trials with devils located beyond the cut-point. In line with parametric analyses, stronger activations of dACC and insula were found in ‘unexpected’ loss trials than in ‘normal’ loss trials (Table 5).

Context × Outcome interaction

The F-contrast of Context (Self vs. Computer) × Outcome (Devil, Non-optimum and Optimum) interaction revealed significant activation in dmPFC (MNI −6 30 56; 8 36 56) (Fig. 5a; Table 6). dmPFC activation identified in the interaction showed significant difference among different outcomes in the Self context but not in the Computer context. Specifically, the activities in dmPFC were greater for Optimum outcome than both Non-optimum and Devil outcomes in the Self context (ts > 4.839, ps < 0.01 with sequential Bonferroni correction).

The activation of right putamen (MNI 18 14 −8) was also observed in the F-contrast of Context × Outcome interaction (Fig. 5b; Table 6), which overlapped with activated putamen in parametric analyses. Then, parameter estimates across right putamen were extracted. As shown in Fig. 5b, no significant difference was found between Self and Computer contexts in both Non-optimum and Optimum outcome. Only in the Devil outcome, the activities in right putamen were significantly greater for the Computer context than Self context [$t(17) = 5.649$, $p < .01$ with sequential Bonferroni correction].

We also conducted the ROI analyses, the results in ROI analyses were in line with the results in whole-brain analyses (Fig. S1, see supplementary materials). Moreover, one participant with less than five trials in Self_Optimum condition was found. We removed this participant and reanalyzed the fMRI data. The F-contrast of Context (Computer vs. Self) × Outcome (Optimum, Non-optimum and Devil)

Table 5 Contrast between 'unexpected' loss trials and 'normal' loss trials in Computer context

	Region	Peak activation			t Value	Voxels
		X	Y	Z		
Unexpected–normal						
L	SupraMarginal gyrus	– 54	– 46	30	6.26	810
L	Inferior frontal gyrus	– 50	12	0	4.55	757
L	*Insula lobe*	– 38	20	– 2	4.39	
R	Inferior frontal gyrus	42	22	– 12	4.27	625
R	*Insula lobe*	34	20	12	3.85	
R	dACC	10	20	28	5.19	329
L	*dACC*	– 6	26	22	3.77	
L	mCC	– 6	– 10	34	3.75	296
Normal-unexpected						
No region						

Coordinates (mm) are in MNI space

L left hemisphere, *R* right hemisphere

All the clusters survived FWE correction ($p<.05$) for multiple comparisons at the cluster level, with a voxel-level threshold corresponding to $p<.001$, uncorrected

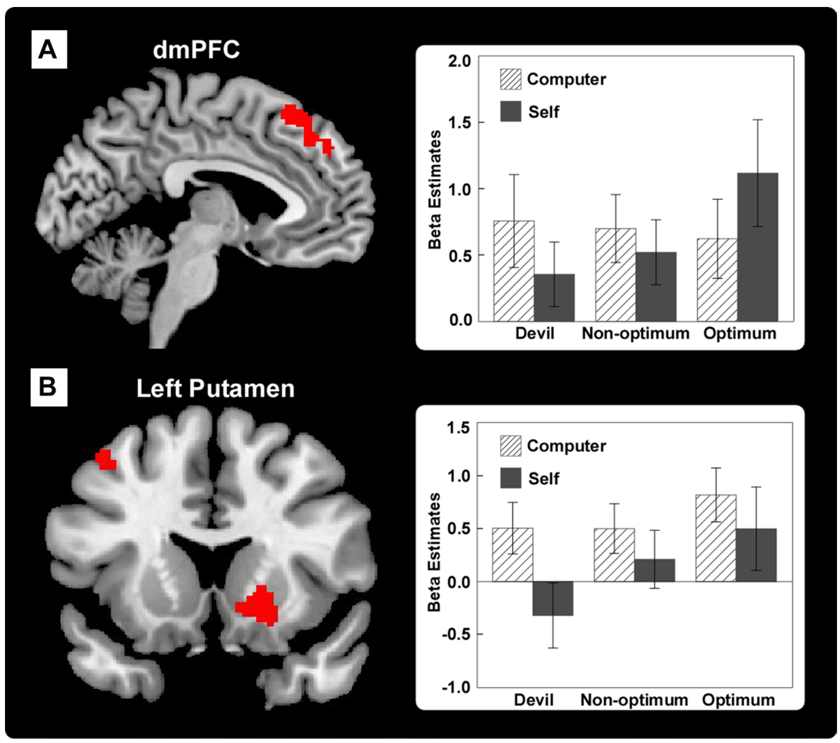

Fig. 5 F-contrast of Context (Self vs. Computer) × Outcome (Devil, Non-optimum and Optimum) interaction. The results revealed significant activation in dmPFC (MNI −6 30 56; 8 36 56) and right putamen (MNI 18 14 −8). **a** Activities in dmPFC were greater for Optimum outcome than both Non-optimum and Devil outcomes in the Self context ($ts>4.839$, $ps<0.01$ with sequential Bonferroni correction). **b** Only in the Devil outcome, the activities in putamen were significantly greater for the Computer context than Self context ($t(17)=5.649$, $p<.01$ with sequential Bonferroni correction)

showed the same basic regions, such as dmPFC and putamen (Table S1, see supplementary materials).

Discussion

In the present study, we employed a modified sequential risk-taking task (Büchel et al. 2011; Brassen et al. 2012) to investigate the modulation of responsibility on regret. Behaviorally, the results revealed emotional ratings for Optimum and Non-optimum outcomes were higher in the Self context (high-responsibility context) compared to the Computer context (low responsibility context). Moreover, emotional ratings for the loss (devil) outcome were lower in the high-responsibility context than the low responsibility context. At the neural level, increased activations of mPFC, mOFC, pgACC, and striatum were found with decreasing number of missed chances in general across different Gain

Table 6 F-contrast of Context (Computer vs. Self) × Outcome (Optimum, Non-optimum, and Devil)

	Region	Peak activation			*F* Value	Voxels
		X	*Y*	*Z*		
L	Fusiform Gyrus	− 26	− 76	− 8	22.34	1751
R	Inferior Occipital Gyrus	38	− 76	− 10	19.76	1038
L	dmPFC	− 6	30	56	15.55	763
R	*dmPFC*	8	36	56	12.73	
L	Superior Parietal Lobule	− 26	− 56	48	19.20	639
R	Middle Temporal Gyrus	62	− 20	− 14	13.19	426
R	Putamen	18	14	− 8	22.93	365

Coordinates (mm) are in MNI space

L left hemisphere, *R* right hemisphere

All the clusters survived FWE correction ($p<.05$) for multiple comparisons at the cluster level, with a voxel-level threshold corresponding to $p<.001$, uncorrected

trials in the high-responsibility context. However, in the low responsibility context, only increased sgACC activation was observed with decreasing number of missed chances. Moreover, in Loss trials, dACC and bilateral insula showed increased activations with increasing number of lost gold coins in the low responsibility context. Besides, striatum showed lower activation for loss outcome in high-responsibility context relative to low responsibility context.

In line with our hypothesis, participants felt less regret (more relief) for high-responsibility context than low responsibility context in Gain trials. Moreover, they felt more regret (less relief) for the devil outcome in the high-responsibility context than the low responsibility context. The previous studies revealed that responsibility was a necessary prerequisite in the experience of regret (Connolly et al. 1997; Ordóñez and Connolly 2000; Zeelenberg et al. 1998). Using the paradigm in which participants make choices between two risky gambles, numerous studies have found that the higher subjective responsibility was, the stronger feeling of regret for negative outcome would be reported (Camille et al. 2010; Nicolle et al. 2011). Consistent with the previous research, the current study also showed that participants felt more regret for the loss outcome in the high-responsibility context than in the low responsibility context during a sequential risk-taking task. Moreover, the results revealed participants felt more relief for gain (Optimum and Non-optimum) outcomes in the high-responsibility context than low responsibility context.

In the current study, significant striatum activation was found as related to the Optimum outcome. Specifically, the previous studies that employed similar sequential risk-taking tasks had also found increased levels of striatum activity with the Optimum outcome. Moreover, the previous research had observed that striatum was involved in reward processing (Apicella et al. 1991; Chandrasekhar et al. 2008; Connolly and Zeelenberg 2002; Coricelli and Aldo Rustichini 2010; Guttentag and Ferrell 2004). Greater striatum activation for the Optimum outcome confirmed the reward-related role of the striatum. Some research also revealed that striatum participated in regret processing, whose activation decreased along with increasing regret levels (Brassen et al. 2012; Liu et al. 2016). Besides, striatum showed decreased activation for the loss outcome in the high-responsibility context than the low responsibility context. Such neural results were consistent with our behavioral results that participants experienced more regret for the loss outcome in the high-responsibility context than the low responsibility context. Such results extended the previous finding by confirming that the activation of striatum was not only involved with the status of being responsible or not, but also sensitive to changing level of responsibility.

Increased activations of mPFC, pgACC, Mofc, and striatum were found with decreasing number of missed chances in general across different gain outcomes in the high-responsibility context. We suggested that increased activations in mPFC, pgACC, mOFC, and striatum along with optimal output reflect their roles in a 'reward system' which has been repeatedly identified during decisions involving rewards (Haber and Knutson 2010; Izuma et al. 2008; Liu et al. 2016; Rogers et al. 2004). The current findings on mPFC, pgACC, mOFC, and striatum were also in line with our previous findings that these regions were associated with optimal outcome. Moreover, in the low responsibility context, increased sgACC activation was observed with decreasing number of missed chances. We did not found mPFC and pgACC in the Computer context. The previous studies showed that brain region of mPFC played a key role in self-processing. Increased activation of mPFC with outcome getting better in the Self context might also reflect its role in guiding a perspective of self (Humphreys and Sui 2016). These results highlighted the sensitivity of the mPFC, pgACC, mOFC and striatum to the effects of responsibility.

Interestingly, during such a sequential risk-taking task, dACC and insula showed increased activations with increasing number of lost gold coin in the low responsibility context but not high-responsibility context. The previous studies revealed that dACC and insula were not only related to error signals, but also served as two key regions of the salience network (Chang and Sanfey 2013; Civai et al. 2012; Güroğlu et al. 2010; Seeley et al. 2007; Xiang et al. 2013). We considered the reason why dACC and insula were found by parametric analysis in the low responsibility context lies in the error detection function related to these brain regions. It is reasonable to assume that the average number of boxes being opened by each participant in the high-responsibility context resulting in gain outcomes might indicate the participant's normal expectation on the location of the devil. Then, for each participant, any loss outcome in the low responsibility context with a devil positioned beyond this expectation (e.g., devil appeared behind the average number of boxes being opened in the high-responsibility context) might involve with more error detection process (Wu et al. 2016). To test such a suggestion, we calculated for each participant the average number of boxes being opened in the high-responsibility context resulting in gain outcomes. In addition, this number was then used as the cut-point to divide all loss trials from the same participant in the low responsibility context into two subcategories: those 'normal' loss trials with devils located in relatively earlier positions, and those 'unexpected' loss trials with devils located beyond the cut-point. In line with our suggestion that dACC and insula play a role in error detection, stronger activations of dACC and insula were found in 'unexpected' loss trials (devil located in relatively later positions) than in 'normal' loss trials (devil located in relatively earlier positions).

Conclusion

The current study suggested that regret was modulated by different levels of responsibility. Behaviorally, participants felt more regret for loss (Devil) outcome and more relief for gain (Optimum and Non-optimum) outcome in the high-responsibility context than low responsibility context. At a neural level, the current study reported increased activations of different brain regions along with the outcomes getting better in high vs. low responsibility context. Specifically, increased activations of mPFC, mOFC, pgACC, and striatum were related with better outcomes in the high-responsibility context, while increased sgACC activation was observed with the outcome getting better in the low responsibility context. In Loss trials, dACC and bilateral insula showed increased activations with increasing loses in the low responsibility context. Besides, for loss (devil) outcome, striatum showed lower activation in the high-responsibility context relative to low responsibility context.

Limitation

The number of trials in the two contexts was determined by participants. In the current study, the number of trials in Self context was larger than that in Computer context. Therefore, the fMRI analyses might have different power in the two contexts. Moreover, we did not set a no responsibility context, so we could not generalize our conclusion from the no responsibility context to the high level of responsibility context. The check of responsibility manipulation was carried out by the return visit investigation, during which participants reported higher responsibility for Self context relative to Computer context. This might bring another limitation that participants did not provide a real-time rating of their sense of responsibility during the task. Adding such a measure to future works might be able to directly tie the sense of responsibility in the moment to neural function. In addition, using the sequential risk-taking task, the previous studies revealed that reward-related region, such as striatum, took part in the processing of regret, whose activation decreased with increasing regret level. However, during such a task, the feeling of regret was induced by lost money or missed money. In our future works, we will conduct the study in which we could investigate the neural basis of regret with a non-monetary medium.

Acknowledgements This work was supported by the National Natural Science Foundation of China [31271090; 71371180]; the National Education Research Project of China [CBA160186]; and the Key Program of the National Social Science Foundation of China [14AZD106].

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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