Available online at www.sciencedirect.com
SciVerse ScienceDirect
www.elsevier.com/locate/brainres
Brain Research

Research Report

An fMRI study on sunk cost effect

Jianmin Zeng[a,b], Qinglin Zhang[a,*], Changming Chen[a], Rongjun Yu[c], Qiyong Gong[d,*]

[a]Faculty of Psychology, Southwest University, Chongqing, No.1 Tiansheng Road, Beibei District, Chongqing City 400715, China
[b]Key Laboratory of Cognition and Personality, Ministry of Education, China
[c]School of Psychology and Center for Studies of Psychological Application, South China Normal University, Guangzhou, China
[d]Huaxi MR Research Center, Department of Radiology, West China Hospital, Sichuan University, No.37 Guoxue Alley, Chengdu City, Sichuan Province 610041, China

ARTICLE INFO

Article history:
Accepted 1 May 2013
Available online 9 May 2013

Keywords:
Sunk cost effect
Escalation of commitment
Decision making
Prospect theory
Neuroeconomics
FMRI

ABSTRACT

Sunk cost effect (also called escalation of commitment, etc) is a pervasive, interesting and famous decision bias, which has been intensively discussed in psychology, economics, management, political science, zoology, etc. To date, little has been known about the neural basis of this phenomenon. We investigated it by using functional magnetic resonance imaging (fMRI) to monitor healthy subjects' brain activities when they made decisions in a task wherein sunk cost and incremental cost were systematically manipulated. *Higher* sunk cost only increased activity of some brain areas (mainly lateral frontal and parietal cortices, which are involved in risk-taking), whereas *lower* incremental cost mainly increased activity of some brain areas (including striatum and medial prefrontal cortex, which are sensitive to rewards). No overlapping brain areas were found to respond to both sunk cost and incremental cost. These results favor certainty effect over self-justification or diminishing sensitivity as account of sunk cost effect.

1. Introduction

Sunk cost effect (also called sunk cost fallacy/bias/error/paradox, escalation of commitment, escalating commitment, throwing good money after bad, knee-deep in big muddy, concorde effect/fallacy, etc) is a pervasive, interesting and famous decision bias. It refers to the following phenomenon: if one has invested more money, time, effort etc (sunk cost) on something, then he is more likely to make further investment (incremental cost) on it. Since sunk cost has been invested and is irrevocable no matter which option one chooses, a traditionally rational decision maker should neglect sunk cost (Thaler, 1980). However, individual, company and even parliament decision makers are actually susceptible to sunk costs. For example, one is more likely to wear a piece of ugly clothing if it has cost him more money; one is more likely to finish watching a boring movie if the ticket cost money than was free; a corporation is more likely to continue a hopeless project if more money has been invested in that project; a congress person may advocate to

*Corresponding authors.
E-mail addresses: james_psych@yeah.net (Q. Zhang), qiyonggong@hmrrc.org.cn (Q. Gong).

0006-8993/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.brainres.2013.05.001

continue a hopeless war because many soldiers have sacrificed in it (Arkes and Blumer, 1985; Sleesman et al., 2012; Staw, 1976; Strough et al., 2008). These examples illustrate that people are more inclined to continue an action when sunk cost is higher. Conversely, some research has reported opposite effect (less when higher) (Heath, 1995). Both cases can be called sunk cost effect since the traditionally rational theory assumes people should neglect sunk cost. This phenomenon exists in not only humans but also non-human animals such as pigeons and rats (Curio, 1987; Macaskill and Hackenberg, 2012; Magalhaes et al., 2012; Navarro and Fantino, 2005; Pattison et al., 2012). Given the phenomenon of sunk cost effect is pervasive in real life and interesting in several disciplines, to study its neural substrate is quite meaningful.

Prospect theory (Kahneman and Tversky, 1979) was used to explain sunk cost effect in the following way (Thaler, 1980): individuals have diminishing sensitivity to losses; the more they have invested (sunk cost), the less painful they fell for additional loss (incremental cost), and the more likely they continue the course. It is important to note that this explanation treats both sunk cost and incremental cost as one thing (loss). If the human brain really treats them in the same way, then the neural correlates of sunk cost and incremental cost should be similar.

Another account of sunk cost effect was self-justification (Brockner, 1992; Staw, 1976): if one abandons continuing the investment, then it seems that he admits the previous investment in his responsibility is wrong; to avoid this bad appearance, he has to continue the investment. In addition, cognitive dissonance was thought to be the psychological root of self-justification (Bazerman et al., 1984). If this account is the case, then the higher the sunk cost is, the more the responsibility and cognitive dissonance is and the more the self-justification is needed. Consequently, when sunk cost is higher, brain areas involved in self-referential processing (such as cortical midline structures) (Northoff et al., 2006), cognitive dissonance (such as anterior cingulate cortex and anterior insula) (van Veen et al., 2009), or responsibility (such as striatum) (Camille et al., 2010) should be more active.

The third account (Arkes and Blumer, 1985) of sunk cost effect is based on another mechanism in prospect theory (Kahneman and Tversky, 1979), named certainty effect. Certainty effect refers that certain gains (losses) are more attractive (disgusting) to people than possible gains (losses), even if their expected values are equal, given the probabilities are not too small. In the case of sunk cost effect, if the subject chooses not to continue the investment, then he faces a certain loss; if he chooses to continue the investment, then he possibly recovers the loss though he also possibly loses more. Therefore, certainty effect drives him to continue the investment. If this is the case, then, the more the sunk cost is, the stronger the certainty effect is (i.e., the stronger the tendency of avoiding the certain loss and choosing the risky option is), and the more risk taking the subject is. Therefore, we can expect, activity of brain areas involved in risk taking (such as lateral frontal and parietal cortices) (Fecteau et al., 2007a, 2007b; Gianotti et al., 2009; Huettel et al., 2006; Knoch et al., 2006; Rao et al., 2008) should correlate with the magnitude of sunk cost.

Some previous studies attended to the neural basis of economic investment (Chiu et al., 2008; Lohrenz et al., 2007; Mohr et al., 2010; Shiv et al., 2005). However, they had other focuses rather than explored neural basis of sunk cost effect. Some previous studies examined the neural basis of delay or effort costs (Croxson et al., 2009; Day et al., 2010; Gan et al., 2010; Hillman and Bilkey, 2010; Rudebeck et al., 2006). However, these studies *never* divided cost into sunk cost and incremental cost; the subjects were *usually* non-human animals and so the methods were *usually* lesion or other methods appropriate for non-human subjects. Remarkably, Croxson et al. (2009) used functional magnetic resonance imaging (fMRI) with human participants to study neural basis of effort cost and revealed the following brain areas decreased activation with higher effort cost: bilateral putamen, bilateral supplementary motor area (SMA), left primary motor cortex, left midbrain. In a word, previous research has investigated the neural basis of investment and costs.

However, little research has been devoted to understanding the neural basis of sunk cost effect and testing its alternative explanations in the viewpoint of neuroscience. Therefore, we investigated it by applying fMRI to healthy subjects. We manipulated magnitude of sunk cost and incremental cost systematically and independently in order to identify the neural correlates of each and test the alternative explanations of sunk cost effect.

2. Results

2.1. Behavioral results

If each participant was a rational decision maker, then, when incremental cost became larger, given the total gain was fixed, he should be less inclined to continue to invest (negative effect), and so the number of participants with negative effect should be 25 and that of all the other should be 0. If each participant was a rational decision maker, then he should neglect sunk cost, that is, his decisions should not affected by sunk cost at all (no effect), and so the number of participants with no effect should be 25 and that of all the other should be 0.

To determine whether this is the case, a logistic regression was applied to each participant's data, with his/her behavioral responses (choices) as the dependent variable and sunk cost and incremental cost as the independent variables. Figs. 2 and 3 show the numbers of participants with special effects predicted and observed. All except one participants' choices were negatively affected by incremental cost significantly ($p<.00001$ for each of the 24 participants; $p=.16$ for the one participant), almost same as predicted by the rational model. However, although the rational model predicted no participant should be affected by sunk cost, 19 out of 25 were actually affected significantly ($p<.01$ for each of the 19 participants; the number of participants whose $p<.001$,.0001 or.00001 was 14, 13 or 11). Taken together, for each of most participants, both incremental cost and sunk cost had significant effects on his choice. The former is traditionally rational while the latter is not.

2.2. Neural results

As in most of fMRI studies, we made two levels of analyses: firstly individual level and then group level. In the individual-level analysis, we used sunk cost and incremental cost as

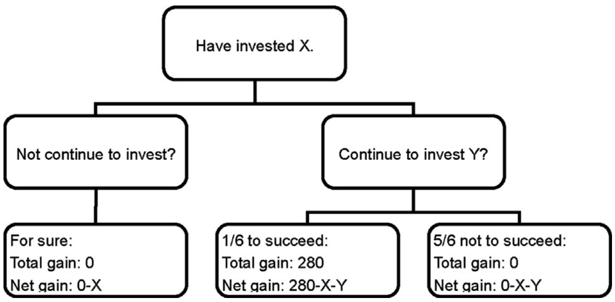

Fig. 1 – General schema of the decision questions. Each participant was instructed to imagine he was a manager of a corporation and so needed to make some investment decisions. In each trial, X (sunk cost) had been invested. Each participant needed to decide whether to further invest Y (incremental cost). If no, then the net gain was 0–X. If yes, then the net gain could be 280–X–Y with probability of 1/6, or 0–X–Y with probability of 5/6. X, Y were respectively substituted with one of sixteen numbers (2, 8, 14… 92) with money unit of ten thousand *yuan* and so made 256 combinations (trials). All other numbers and words were fixed. Each participant was instructed to maximize the net gains: more net gains, more payoff. The figure was a part of the instruction. Our computer procedure (re)instructed each participant until he could pass a test on understanding. In the test, practice and formal experiment, only the content in the top three boxes showed and there were no boxes and lines.

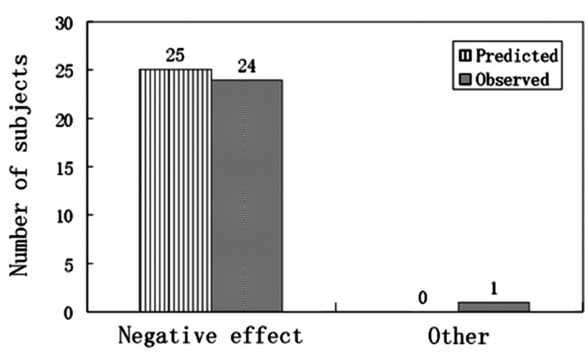

Fig. 2 – Behavioral incremental cost effect. Negative effect: a participant was significantly less inclined to continue to invest when incremental costs became larger. Predicted: predicted by the traditionally rational theory.

regressors to find each participant's each voxel's sensitivity to both costs respectively. In the group-level analysis, each voxel's sensitivity entered into a t-test to determine whether this voxel's sensitivity to sunk or incremental cost is significant in a group-level. See the Method section for more detail.

When sunk cost increased, several brain areas *increased* but no brain regions decreased activation significantly (Fig. 4 Red Color, and Table 1), mainly including: bilateral middle and superior frontal cortices, left superior and inferior parietal cortices.

When incremental cost increased, many brain areas *decreased* but one increased activation significantly (Fig. 4 Green Color, and Table 2), mainly including: medial superior

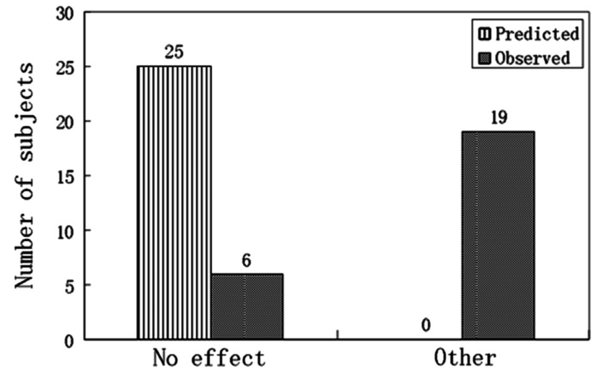

Fig. 3 – Behavioral sunk cost effect. No effect: a participant's choices were not affected by sunk costs significantly. Predicted: predicted by the traditionally rational theory.

frontal cortex (a part of medial prefrontal cortex), left superior frontal cortex, left caudate (a part of striatum), left precentral cortex (the one increasing activation), middle cingulate cortices, left middle and superior temporal cortices, right middle temporal cortex, left middle occipital cortex, left angular, and right lingual cortex.

The first trend to observe is that increasing sunk cost *only activated* some brain areas significantly whereas increasing incremental cost *mainly deactivated* some brain areas significantly. Interestingly their neural effects had basically opposite directions. A question is whether there was any brain area responding to the magnitudes of both sunk cost and incremental cost significantly. With a common region analysis, the study found no such overlap (Fig. 4). Taken together, neural correlates of sunk cost and incremental cost were largely different in both directions and areas, suggesting the human brain processes these two kinds of costs quite differently.

3. Discussion

3.1. *Brain areas sensitive to sunk cost*

We found that increasing sunk cost was associated with increased activation in lateral frontal and parietal cortices, which are involved in risk-taking.

Huettel et al. (2006) found that risk-taking behavior could predict the activation of the posterior parietal cortex whereas ambiguity-taking behavior could predict the activation within the lateral prefrontal cortex (ambiguity referred to uncertainty with unknown probabilities). Knoch et al. (2006) used low-frequency, repetitive transcranial magnetic stimulation to temporarily stimulate the function of dorsolateral prefrontal cortex (DLPFC) of subjects; afterwards, they measured subjects' risk-attitudes in decisions. They found subjects became riskier in decisions after stimulation of the right DLPFC. Rao et al. (2008) found that (voluntary) risk taking was associated with activation in dorsal lateral prefrontal cortex etc. With resting-state electroencephalography, Gianotti et al. (2009) found that the activity in the right prefrontal cortex predicted subjects' risk-taking behavior.

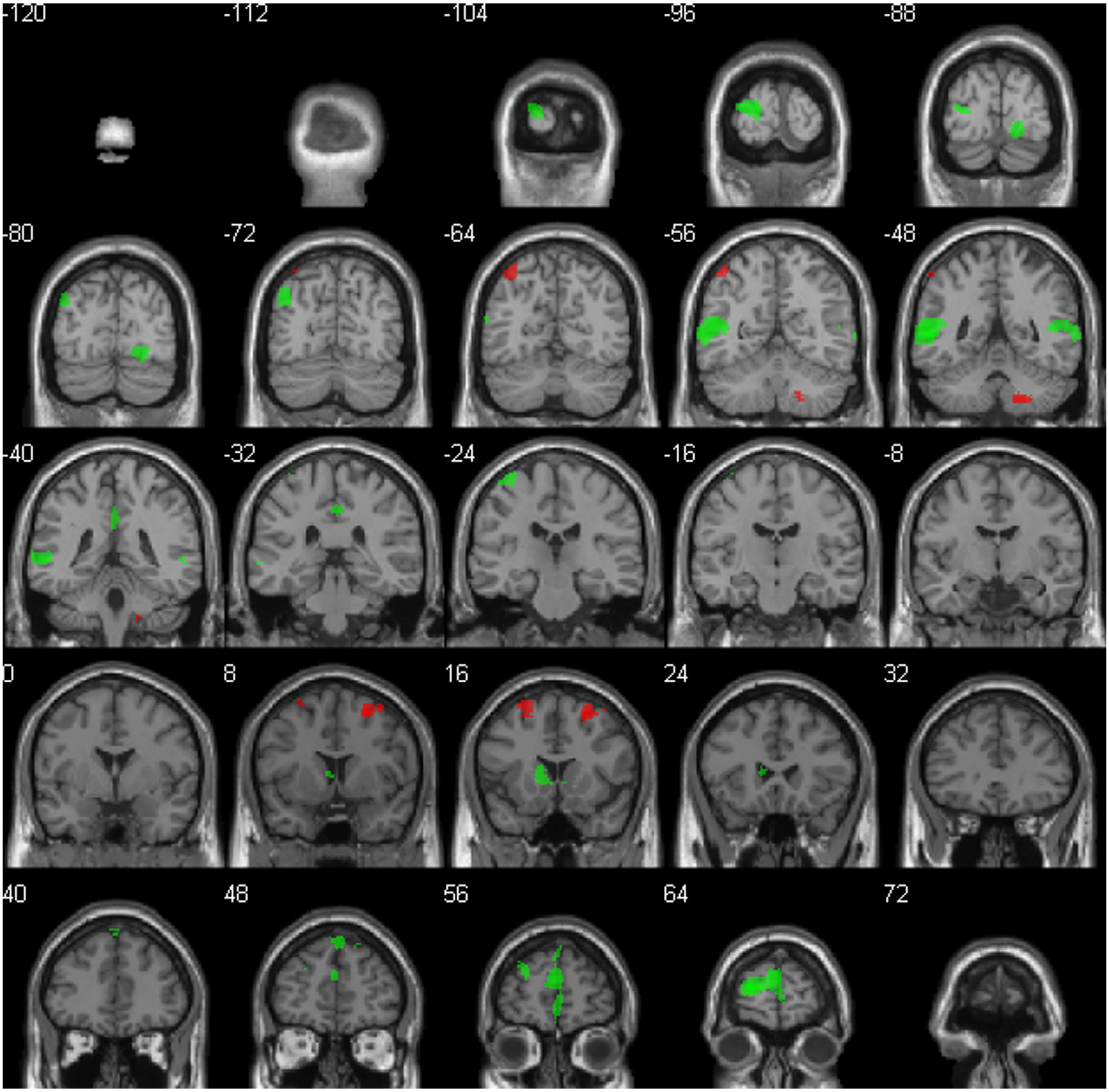

Fig. 4 – Neural sunk and incremental cost effects, projected on the single participant's structural template included in SPM8. Red: Brain areas sensitive to sunk cost magnitude (corrected at cluster level $p<.05$); all *increasing* activation with higher sunk cost. Green: Brain areas sensitive to incremental cost magnitude (corrected at cluster level $p<.05$); all (except the precentral area) *decreasing* activation with higher incremental cost.

Table 1 – Brain areas sensitive to the sunk cost (corrected at cluster level $p<.05$).

Brain area	Peak MNI coordinate (x, y, z)	Peak T value	Number of voxels
Frontal_Mid_L and Frontal_Sup_L	−24, 16, 64	3.7006	143
Frontal_Sup_R and Frontal_Mid_R	26, 12, 56	5.313	276
Parietal_Inf_L and Parietal_Sup_L	−40, −68, 56	3.9397	227
Cerebelum_9_R and Cerebelum_8_R	18, −44, −48	4.5617	183

In a word, previous studies revealed that the lateral frontal and parietal cortices are involved in risk-taking. In our experiment, the activity of these brain regions correlated with sunk cost, suggesting sunk cost effect closely related to risk taking.

3.2. *Brain areas sensitive to incremental cost*

When incremental cost decreased, the possible net gain of the risky option increased, given the gross gain was fixed.

Table 2 – Brain areas sensitive to the incremental cost (corrected at cluster level $p<.05$).

Brain area	Peak MNI coordinate (x, y, z)	Peak T value	Number of voxels
Frontal_Sup_Medial_L and Frontal_Sup_L and Frontal_Sup_Medial_R	−20, 66, 12	−5.4671	1312
Caudate_L	−14, 18, 8	−3.8893	214
Temporal_Mid_L and Temporal_Sup_L	−58, −50, 8	−5.0028	1185
Temporal_Mid_R	46, −50, 12	−4.0824	340
Precentral_L	−40, −30, 70	4.0352	125
Cingulate_Mid_R and Cingulate_Mid_L	2, −32, 42	−3.4708	135
Lingual_R	22, −80, −10	−3.7809	303
Occipital_Mid_L	−30, −92, 10	−4.9764	456
Occipital_Mid_L and Angular_L	−40, −72, 36	−4.2795	230

Therefore we could expect some areas involved in reward processing increased activity with decreasing incremental cost. Actually, we observed increasing activity in striatum and medial prefrontal cortex when incremental cost decreased. Previous studies have shown that the striatum is sensitive to the expectation or detection of rewards (Elliott et al., 2000; Green et al., 2011; Knutson et al., 2000; Schultz et al., 2000; Zeng et al., 2012, 2013). The medial prefrontal cortices' role in processing rewards has also been well established (Carlson et al., 2011; Oberg et al., 2011; Pratt and Mizumori, 2001; Richardson and Gratton, 1998; Rogers et al., 2004; Trzcinska and Bielajew, 1998; Tzschentke, 2000; Wise, 2000).

When incremental cost decreased, subjects became more inclined to choose the “continue to invest” option, which is much more complicated than the other option. Consequently they needed to think and view more to figure out each possible net gain and loss and their probabilities. Consequently, brain areas involved in vision, calculation and even language could become more active when incremental cost decreased. Actually we found the activity in temporal, angular and occipital cortices increased with decreasing incremental cost. Temporal cortices play a role in language processing (Binder et al., 2000; Haitova et al., 2012; Hein and Knight, 2008; Karnath, 2001). Occipital lobules were generally believed to play roles in visual processing. The left angular cortex is thought to play important roles in language and number processing (Binder et al., 1997; Dehaene et al., 2003; Husain et al., 2012; Price, 2000).

Interestingly, activation of the left precentral cortex showed positive correlation with incremental cost, even though all the other activated areas showed negative. This area was well-known as motion area. In our experiment, when incremental costs were large, both options were quite unpleasant to the participants: to definitely get a net loss, or to spend a large cost to get a possibility of recovering sunk cost. In this situation, the participants felt more difficult to make the final determination, and such a difficult determination might accompany with heavy key-pressing as we experienced in daily life, and so activated the precentral cortex more strongly. Actually, in the experiment, the participants were arranged to respond with their right hands, which corresponded to the left precentral cortex. The above explanation also accords with this arrangement.

3.3. *Theoretic implication*

As stated in the Introduction section, a popular explanation of sunk cost effect is, individuals have diminishing sensitivity to losses. According to this explanation, the more individuals have lost (sunk cost), the less painful they fell for a fixed additional loss (incremental cost), and the more likely they continue the course. Accordingly we can expect neural regions sensitive to sunk cost and incremental cost should be similar. However, our neuroimaging results show that brain activity involved in processing sunk cost and incremental cost differed in both areas and directions. Our findings question the neural reality of the above theoretic explanation of sunk cost effect and suggest that distinct brain regions are engaged in processing these two types of costs.

Another explanation of sunk cost effect is self-justification. This explanation implies, the more the sunk cost is, the more is the activity of brain areas sensitive to self (cortical midline structures), responsibility (striatum), or cognitive dissonance (anterior cingulate cortex and anterior insula). However, as revealed in the section Neural results, the brain regions sensitive to sunk cost were mainly lateral frontal and parietal cortices, totally different from the above brain regions predicted by self-justification account of sunk cost effect. Therefore, our finding also does not support this explanation.

The third explanation comes from certainty effect proposed by prospect theory. This explanation says, between a certain loss and a possible (risky) loss, given their expected values are equal and the probability is not too small, people are likely to reject the certain loss (not continuing the investment) and choose the risky loss (continuing the investment). This explanation implies, the larger the sunk cost is, the more risk-taking a subject is, and the more is the activity of brain areas involved in risk-taking (bilateral frontal and parietal cortices). The neural results support this explanation.

4. Conclusion

This study showed that larger sunk cost induced stronger activity in lateral frontal and parietal cortices, which are involved in risk-taking; smaller incremental cost induced stronger activity in striatum and medial prefrontal cortices, which are sensitive to rewards. No overlapping brain areas were found to respond to both sunk cost and incremental cost. These results favor certainty effect over self-justification or diminishing sensitivity as account of sunk cost effect.

5. Experimental procedure

5.1. *Participants*

We recruited 27 participants via a posted advertisement in a university campus. All were university students and right-handed. Their mean age was 21.96 with a range of 20–24. Two participants were excluded from analysis because of image scanning problem. This left 25 valid participants. Thirteen of them were females. This experiment was approved by the Administration Committee of Psychological Research of our university. Informed consents were obtained from all the participants. They did not have a history of serious body or mental illness that might recur during the experiment. They did not have implanted metal in their bodies and passed the strict check of metal wearing before entering the scanning room.

5.2. *Main procedure*

5.2.1. *Phase 1: instruction [outside the scanner]*

Each participant was instructed to imagine he was a manager of a corporation and so needed to make some investment decisions as shown in Fig. 1 and described in its caption. Three out of all trials would be randomly chosen after he finished the whole experiment to determine his net total gain, which would then be transformed into real payoff according to a transforming table, which had the following properties: higher net total gain, higher payoff; 80 *yuan* for the best performance and −20 *yuan* for the worst performance; the latter means 20 *yuan* would be subtracted from his participation payoff. (We intentionally enlarged the range of the payoffs so as to encourage the participants to make decisions seriously). When his net total gain was negative, his decision payoff could be negative, zero or positive, depending on the special value of his net total gain. The special structure of the transforming table was not shown to the participant until the end of the experiment. This was to ensure participants did not adopt some special decision criteria according to the special structure of the table. In a randomly selected decision question, according to the experimental setting as shown in Fig. 1, if he had chosen "not continue to invest", then his net gain was 0–X; if he had chosen "continue to invest", then his net gain was determined by drawing a card from 6 cards in which 1 card was the target card—if the drawn card was the target card, then the net gain was 280–X–Y; otherwise, 0–X–Y. He had additional participation payoff of 40 *yuan*. So, his total payoff could be 120–20 *yuan* in theory. The actual maximum, minimum and average payoff turned out to be 100, 30 and 50.8 *yuan*. As a reference, these participants' average monthly living expenditure (not including school and accommodation fee) was 613 *yuan*. All words in the experiment were in Chinese.

5.2.2. *Note for the paper readers: schema used in phase 2 to 3 (brief schema hereafter)*

As stated in Fig. 1, the full figure was a part of the instruction. In the test, practice and formal experiment, only the content in the top three boxes showed and there were no lines and boxes. That was the following (except that the actual background was black and the actual characters were white). This was for simplifying the content in the screen. All the three sentences were presented together at the same time.

Have invested X

Not continue to invest? Continue to invest Y?

5.2.3. *Phase 2: test and practice [outside the scanner]*

Firstly, the computer asked each participant several questions so as to check whether he had understood the decision situation. If he did not pass the test, the procedure would go back to the instruction; if he did, then it would go to the practice described as follows.

X, Y in the Brief Schema were respectively substituted with some numbers between 2 and 92 with money unit of ten thousand *yuan*. For each decision question, each participant needed to indicate his preference by pressing one of the two keys by right index or middle finger. Previous to each decision question, there was a black screen with a white cross in the center lasting 2–6 s (mean=4 s), which served as a reminder and jittered inter-stimulus interval.

The practice had two stages. In the first stage, a participant could take his time to make the decision. In the second stage, each decision question displayed 4 s; he had to make the decision in that duration. This could avoid the total scanning time was too long to be endured by the participants. This limited time also encouraged participants to make decision on the basis of intuition rather than calculation. This also ensured the response time was similar across trials and participants, and so made both individual and group statistics more reasonable in this aspect.

One may notice that the statuses of X (sunk cost) and Y (incremental cost) are not the same in the above decision situation. Nevertheless, this difference is intrinsic between the two kinds of costs: if we cancel this status difference in the two kinds of costs, then they are no longer sunk cost and incremental cost. Therefore, this status difference is not a shortcoming but a necessity for this experiment.

5.2.4. *Phase 3: formal experiment [inside the scanner]*

X, Y in the Brief Schema were respectively substituted with one of sixteen numbers (2, 8, 14…, 92) with money unit of ten thousand *yuan*. This made $16 \times 16 = 256$ combinations; each combination made a trial. In each trial, the procedure was completely same as that of the second stage in the practice. There was a short break after every 43 or 42 trials; this broke the 256 trials into 6 runs. At the beginning of each run, there was an additional 4-second black screen, images scanned during which would be discarded to allow for T1 equilibrium effects. The X, Y combinations were distributed as even as possible between runs. In each run, they were in a random sequence. All participants received the same sequences.

5.3. *fMRI data acquisition*

The visual material was presented to the participants by a mirror attached to a head coil. An fMRI-compatible response device was used for recording participants' responses. Blood-oxygenation-level-dependent (BOLD) signals were measured with a T2*-weighted echo-planar imaging (EPI) sequence using Siemens Trio Tim 3.0T with the following scanning parameters. Repetition Time (TR): 2000 ms. Echo Time (TE): 30 ms. Flip angle: 90°. Voxel size: 3.75 mm × 3.75 mm × 5 mm. Matrix: 64 × 64 × 30. Order of acquisition of slices: interleaved (from top to bottom.)

5.4. *fMRI data analysis*

5.4.1. *Preprocessing*

The fMRI data analysis was implemented with SPM8 software package (http://www.fil.ion.ucl.ac.uk/spm/). The images were reoriented so as to reduce the deviation of their origins and orientations from the standard template. They were then motion corrected, and nonlinearly transformed into the standard MNI coordinates. These normalized images were then re-sliced into 2 mm × 2 mm × 2 mm, and smoothed with 8 mm as the full-width at half maximum of the Gaussian smoothing kernel. Following suggestion from SPM8 manual, we did not directly correct slice-acquisition time differences.

5.4.2. *Individual statistics*

For a participant's data, each run was entered as a session in SPM8. In each session, we had single condition with two parameters (regressors): sunk cost, incremental cost; we also had non-interesting regressors: parameters from realignment; the high-pass filter was 128. An informed basis set with time and dispersion derivatives was used. The serial correlations were AR(1). Applying this routine created some beta images. For example, each run (session) had one beta image of the 1st basis function for sunk cost, and so six runs had six beta images of such a kind. Averaging these six beta images resulted in a contrast image of the 1st basis function for sunk cost. (This is equivalent to setting 1/6 as weight for each corresponding regressor in each run in the contrast manager in SPM8.) Similarly, we can get a contrast image of the 1st basis function for incremental cost.

5.4.3. *Group statistics*

A one-sample t-test was applied to 25 participants' contrast images of the 1st basis function for sunk cost or incremental cost separately. For correction of multiple comparisons, the cluster extent threshold method (Slotnick et al., 2003) was used. Applying both voxel $p<.005$ and cluster extent >106 in a T-map, we got corrected $p<.05$. Aware that the amygdalae are small structures whose (de)activation could be overlooked by the above method, we also tried a loosen criterion (changing cluster extent to be 0) for the amygalae, but found neither activation nor deactivation of the amygdalae for either of sunk cost and incremental cost.

Funding sources

This study was supported by the National Natural Science Foundation of China (a grant awarded to Jianmin Zeng in 2013), the National Natural Science Foundation of China (Grant No. 81030027), and Major Program of National Social Science Foundation of China (No. 11&ZD088).

Acknowledgments

The initial data analyzing and first draft writing was done when JZ visited Faculty of Economics, University of Cambridge, following invitation from Prof. Aldo Rustichini. JZ extremely appreciates his invitation and Prof. Rik Henson's important guidance in the fMRI data analysis. Nevertheless, the authors are wholly responsible for any possible issue in this paper.

REFERENCES

Arkes, H.R., Blumer, C., 1985. The psychology of sunk cost. Organ. Behav. Hum. Decis. Processes 35, 124–140.

Bazerman, M.H., Giuliano, T., Appelman, A., 1984. Escalation of commitment in individual and group decision-making. Organizational Behav. Hum. Perform. 33, 141–152.

Binder, J.R., Frost, J.A., Hammeke, T.A., Cox, R.W., Rao, S.M., Prieto, T., 1997. Human brain language areas identified by functional magnetic resonance imaging. J. Neurosci. 17, 353–362.

Binder, J.R., Frost, J.A., Hammeke, T.A., Bellgowan, P.S.F., Springer, J.A., Kaufman, J.N., Possing, E.T., 2000. Human temporal lobe activation by speech and nonspeech sounds. Cereb. Cortex 10, 512–528.

Brockner, J., 1992. The escalation of commitment to a failing course of action—toward theoretical progress. Acad. Manage. Rev. 17, 39–61.

Camille, N., Pironti, V.A., Dodds, C.M., Aitken, M.R.F., Robbins, T.W., Clark, L., 2010. Striatal sensitivity to personal responsibility in a regret-based decision-making task. Cogn. Affect. Behav. Neurosci. 10, 460–469.

Carlson, J.M., Foti, D., Mujica-Parodi, L.R., Harmon-Jones, E., Hajcak, G., 2011. Ventral striatal and medial prefrontal BOLD activation is correlated with reward-related electrocortical activity: a combined ERP and fMRI study. Neuroimage 57, 1608–1616.

Chiu, P.H., Lohrenz, T.M., Montague, P.R., 2008. Smokers' brains compute, but ignore, a fictive error signal in a sequential investment task. Nat. Neurosci. 11, 514–520.

Croxson, P.L., Walton, M.E., O'Reilly, J.X., Behrens, T.E.J., Rushworth, M.F.S., 2009. Effort-based cost-benefit valuation and the human brain. J. Neurosci. 29, 4531–4541.

Curio, E., 1987. Animal decision-making and the concorde fallacy. Trends Ecol. Evol. 2, 148–152.

Day, J.J., Jones, J.L., Wightman, R.M., Carelli, R.M., 2010. Phasic nucleus accumbens dopamine release encodes effort- and delay-related costs. Biol. Psychiatry 68, 306–309.

Dehaene, S., Piazza, M., Pinel, P., Cohen, L., 2003. Three parietal circuits for number processing. Cogn. Neuropsychol. 20, 487–506.

Elliott, R., Friston, K.J., Dolan, R.J., 2000. Dissociable neural responses in human reward systems. J. Neurosci. 20, 6159–6165.

Fecteau, S., Knoch, D., Fregni, F., Sultani, N., Boggio, P., Pascual-Leone, A., 2007a. Diminishing risk-taking behavior by modulating activity in the prefrontal cortex: a direct current stimulation study. J. Neurosci. 27, 12500–12505.

Fecteau, S., Pascual-Leone, A., Zald, D.H., Liguori, P., Theoret, H., Boggio, P.S., Fregni, F., 2007b. Activation of prefrontal cortex by transcranial direct current stimulation reduces appetite for risk during ambiguous decision making. J. Neurosci. 27, 6212–6218.

Gan, J.O., Walton, M.E., Phillips, P.E.M., 2010. Dissociable cost and benefit encoding of future rewards by mesolimbic dopamine. Nat. Neurosci. 13, 25–27.

Gianotti, L.R., Knoch, D., Faber, P.L., Lehmann, D., Pascual-Marqui, R.D., Diezi, C., Schoch, C., Eisenegger, C., Fehr, E., 2009. Tonic activity level in the right prefrontal cortex predicts individuals' risk taking. Psychol. Sci. 20, 33–38.
Green, E., Jacobson, A., Haase, L., Murphy, C., 2011. Reduced nucleus accumbens and caudate nucleus activation to a pleasant taste is associated with obesity in older adults. Brain Res. 1386, 109–117.
Haitova, P., Marecek, R., Mikl, M., Zelinkova, J., Brazdil, M., 2012. Superior temporal sulcus and its functions. Cesk. Slov. Neurol. Neurochir. 75, 154–158.
Heath, C., 1995. Escalation and de-escalation of commitment in response to sunk costs—the role of budgeting in mental accounting. Organ. Behav. Hum. Decis. Processes 62, 38–54.
Hein, G., Knight, R.T., 2008. Superior temporal sulcus—it's my area: or is it?. J. Cogn. Neurosci. 20, 2125–2136.
Hillman, K.L., Bilkey, D.K., 2010. Neurons in the rat anterior cingulate cortex dynamically encode cost-benefit in a spatial decision-making task. J. Neurosci. 30, 7705–7713.
Huettel, S.A., Stowe, C.J., Gordon, E.M., Warner, B.T., Platt, M.L., 2006. Neural signatures of economic preferences for risk and ambiguity. Neuron 49, 765–775.
Husain, F.T., Patkin, D.J., Kim, J., Braun, A.R., Horwitz, B., 2012. Dissociating neural correlates of meaningful emblems from meaningless gestures in deaf signers and hearing non-signers. Brain Res. 1478, 24–35.
Kahneman, D., Tversky, A., 1979. Prospect theory—an analysis of decision under risk. Econometrica 47, 263–291.
Karnath, H.O., 2001. New insights into the functions of the superior temporal cortex. Nat. Rev. Neurosci. 2, 568–576.
Knoch, D., Gianotti, L.R.R., Pascual-Leone, A., Treyer, V., Regard, M., Hohmann, M., Brugger, P., 2006. Disruption of right prefrontal cortex by low-frequency repetitive transcranial magnetic stimulation induces risk-taking behavior. J. Neurosci. 26, 6469–6472.
Knutson, B., Westdorp, A., Kaiser, E., Hommer, D., 2000. FMRI visualization of brain activity during a monetary incentive delay task. Neuroimage 12, 20–27.
Lohrenz, T., McCabe, K., Camerer, C.F., Montague, P.R., 2007. Neural signature of fictive learning signals in a sequential investment task. Proc. Nat. Acad. Sci. USA 104, 9493–9498.
Macaskill, A.C., Hackenberg, T.D., 2012. The sunk cost effect with pigeons: some determinants of decisions about persistence. J. Exp. Anal. Behav. 97, 85–100.
Magalhaes, P., White, K.G., Stewart, T., Beeby, E., van der Vliet, W., 2012. Suboptimal choice in nonhuman animals: rats commit the sunk cost error. Learn. Behav. 40, 195–206.
Mohr, P.N.C., Biele, G., Krugel, L.K., Li, S.C., Heekeren, H.R., 2010. Neural foundations of risk-return trade-off in investment decisions. Neuroimage 49, 2556–2563.
Navarro, A.D., Fantino, E., 2005. The sunk cost effect in pigeons and humans. J. Exp. Anal. Behav. 83, 1–13.
Northoff, G., Heinzel, A., Greck, M., Bennpohl, F., Dobrowolny, H., Panksepp, J., 2006. Self-referential processing in our brain—a meta-analysis of imaging studies on the self. Neuroimage 31, 440–457.
Oberg, S.A.K., Christie, G.J., Tata, M.S., 2011. Problem gamblers exhibit reward hypersensitivity in medial frontal cortex during gambling. Neuropsychologia 49, 3768–3775.
Pattison, K.F., Zentall, T.R., Watanabe, S., 2012. Sunk cost: pigeons (Columba livia), too, show bias to complete a task rather than shift to another. J. Comp. Psychol. 126, 1–9.
Pratt, W.E., Mizumori, S.J.Y., 2001. Neurons in rat medial prefrontal cortex show anticipatory rate changes to predictable differential rewards in a spatial memory task. Behav. Brain Res. 123, 165–183.
Price, C.J., 2000. The anatomy of language: contributions from functional neuroimaging. J. Anat. 197, 335–359.
Rao, H., Korczykowski, M., Pluta, J., Hoang, A., Detre, J.A., 2008. Neural correlates of voluntary and involuntary risk taking in the human brain: an fMRI Study of the Balloon Analog Risk Task (BART). Neuroimage 42, 902–910.
Richardson, N.R., Gratton, A., 1998. Changes in medial prefrontal cortical dopamine levels associated with response-contingent food reward: an electrochemical study in rat. J. Neurosci. 18, 9130–9138.
Rogers, R.D., Ramnani, N., Mackay, C., Wilson, J.L., Jezzard, P., Carter, C.S., Smith, S.M., 2004. Distinct portions of anterior cingulate cortex and medial prefrontal cortex are activated by reward processing in separable phases of decision-making cognition. Biol. Psychiatry 55, 594–602.
Rudebeck, P.H., Walton, M.E., Smyth, A.N., Bannerman, D.M., Rushworth, M.F.S., 2006. Separate neural pathways process different decision costs. Nat. Neurosci. 9, 1161–1168.
Schultz, W., Tremblay, L., Hollerman, J.R., 2000. Reward processing in primate orbitofrontal cortex and basal ganglia. Cereb. Cortex 10, 272–283.
Shiv, B., Loewenstein, G., Bechara, A., Damasio, H., Damasio, A.R., 2005. Investment behavior and the negative side of emotion. Psychol. Sci. 16, 435–439.
Sleesman, D.J., Conlon, D.E., McNamara, G., Miles, J.E., 2012. Cleaning up the big muddy: a meta-analytic review of the determinants of escalation of commitment. Acad. Manage. J. 55, 541–562.
Slotnick, S.D., Moo, L.R., Segal, J.B., Hart, J., 2003. Distinct prefrontal cortex activity associated with item memory and source memory for visual shapes. Cognit. Brain Res. 17, 75–82.
Staw, B.M., 1976. Knee-deep in big muddy—study of escalating commitment to a chosen course of action. Organ. Behav. Hum. Perform. 16, 27–44.
Strough, J., Mehta, C.M., McFall, J.P., Schuller, K.L., 2008. Are older adults less subject to the sunk-cost fallacy than younger adults?. Psychol. Sci. 19, 650–652.
Thaler, R., 1980. Toward a positive theory of consumer choice. J. Econ. Behav. Organ. 1, 39–60.
Trzcinska, M., Bielajew, C., 1998. Functional connections between medial prefrontal cortex and caudate-putamen in brain-stimulation reward of rats. Behav. Neurosci. 112, 1177–1186.
Tzschentke, T.M., 2000. The medial prefrontal cortex as a part of the brain reward system. Amino Acids 19, 211–219.
van Veen, V., Krug, M.K., Schooler, J.W., Carter, C.S., 2009. Neural activity predicts attitude change in cognitive dissonance. Nat. Neurosci. 12, 1469–1474.
Wise, R.A., 2000. Interactions between medial prefrontal cortex and meso-limbic components of brain reward circuitry. In cognition, emotion and autonomic responses: the integrative role of the prefrontal cortex and limbic structures. In: Uylings, H.B.M., VanEden, C.G., DeBruin, J.P.C., Feenstra, M.G.P., Pennartz, C.M.A. (Eds.), Progress in Brain Research, vol. 126. Elsevier Science Bv, Amsterdam, pp. 255–262.
Zeng, J., Wang, Y., Zhang, Q., 2012. An ERP study on decisions between attractive females and money. PLoS ONE 7: e45945.
Zeng, J., Zou, Y., Zhang, Q., 2013. Social competition factor influences the neural response to rewards: an ERP study. Brain Res. 1501, 12–20.