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# The Interaction of Perceived Control and Gambler's Fallacy in Risky Decision Making: An fMRI Study

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**Abstract:** Limited recent evidence implicates the anterior/posterior cingulate (ACC/PCC) and lateral prefrontal networks as the neural substrates of risky decision-making biases such as illusions of control (IoC) and gambler's fallacy (GF). However, investigation is lacking on the dynamic interactive effect of those biases during decision making. Employing a card-guessing game that independently manipulates trial-by-trial perceived control and gamble outcome among 29 healthy female participants, we observed both IoC- and GF-type behaviors, as well as an interactive effect of previous control and previous outcome, with GF-type behaviors only following computer-selected, but not self-selected, outcomes. Imaging results implicated the ACC and left dorsolateral prefrontal cortex (DLPFC) in agency processing, and the cerebellum and right DLPFC in previous outcome processing, in accordance with past literature. Critically, the right inferior parietal lobule (IPL) exhibited significant betting-related activities to the interaction of previous control and previous outcome, showing more positive signals to previous computer-selected winning versus losing outcomes but the reverse pattern following self-selected outcomes, as well as responding to the interactive effect of control and outcome during feedback. Associations were also found between participants' behavioral sensitivity to the interactive effect of previous control and previous outcome, and right IPL signals, as well as its functional connectivity with neural networks implicated in agency and previous outcome processing. We propose that the right IPL provides the neural substrate for the interaction of perceived control and GF, through coordinating activities in the anterior and posterior cingulate cortices and working conjunctively with lateral PFC and other parietal networks. *Hum Brain Mapp 37:1218–1234, 2016.* 

**Key words:** cingulate cortex; cognitive bias; dorsolateral prefrontal cortex; functional MRI; illusions of control; inferior parietal cortex; precuneus; striatum; ventromedial prefrontal cortex

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## INTRODUCTION

Risky decision-making biases that affect probability evaluation processes, such as illusions of control (IoC) and the gambler's fallacy (GF), have recently attracted attention in neuroscience [Kool et al., 2013; Xue et al., 2011, 2012, 2013]. Such investigations enrich our theoretical understanding of "irrationality" in human decision making [Robson, 2002], as well as carrying clinical implications for understanding and improving the decision-making skills of individuals who are particularly prone to those biases [Hewig et al., 2010].

IoC refer to the belief that an individual can exert influence on the outcome of chance events [Dixon et al., 2007; Ladouceur, 2004; Langer, 1975], which may arise from an inflated estimation of the association between the agent's actions and the favorable outcomes [Thompson et al., 1998]. The GF is the belief that the chances of an event occurring are lowered closely following previous occurrences of that event [Laplace, 1825/1995], leading to increased/decreased risk-taking immediately following losing/winning outcomes [Ariyabuddhiphongs and Phengphol, 2008; Xue et al. 2011]. Both IoC and GF are closely associated with pathological conditions such as gambling addiction [Goodie and Fortune, 2013]. Previous studies investigating the neural basis of IoC have generally implicated the anterior and posterior cingulate cortices (ACC/PCC) [Clark et al., 2009; Kool et al., 2013; Studer et al., 2012] and the dorsolateral prefrontal cortex (DLPFC) [Hare et al., 2009; Studer et al., 2012]. For example, ACC and PCC activities elicited by almost-winning or winning outcomes in gambling games were modulated by active choice [Clark et al., 2009; Kool et al., 2013], and having choices in a roulette game elicited activations in the superior and middle frontal gyri [Studer et al., 2012]. Previous research has also associated GF with activities of the lateral and medial prefrontal networks [Brand et al., 2005; Xue et al., 2011, 2012, 2013]. For instance, Xue et al. (2011) employed a modified cups task and showed that participants generally took more risks, and exhibited greater lateral PFC activities, following losses than following wins, and rostral ACC activities were found to be modulated by previous outcomes in a guessing game [Xue et al., 2013]. The lateral PFC has been previously implicated in self-initiated switching of task behaviors [Dove et al., 2000; Sohn et al., 2000], and it was proposed that the lateral PFC is involved in detecting past recurrence of events in accordance with a "world model," and in signaling the need to deviate from old response patterns to explore more beneficial alternative actions, such as those corresponding to the GF [Daw et al., 2005; Frank et al., 2009; Xue et al., 2011, 2012].

Nevertheless, the IoC and GF have mostly been treated as separate cognitive biases in the context of risky decision making, and research is lacking on how they might interact and jointly determine individuals' behavior. Such gap in research evidence is particularly pertinent as in everyday decision making, those biases tend to co-occur instead of being exclusive to each other [Griffiths, 1994; Strickland et al., 2006]. Existing evidence indicates that GF may depend on the event outcomes being perceived as being caused by inanimate or mechanical processes, which were generally associated with more random sequences of occurrences [Burns and Corpus, 2004], compared with those perceived as having human performance causes [Ayton and Fischer, 2004; Croson and Sundali, 2005; Xue et al., 2013]. These findings suggest a possible connection between GF and IoC [Croson and Sundali, 2005]. For example, people tend to attribute event sequences of greater negative recency (more alternations, consistent with a GF belief) to inanimate or mechanical processes that are under little human control, but sequences of greater positive recency to human performance causes (i.e., the "hot-hand" fallacy) [Ayton and Fischer, 2004]. Thus, whether people would adopt a GF belief might be influenced by their perceived causes of the preceding event(s). In other words, the level of perceived control an individual experiences not only impacts on the current instance of decision making (i.e., IoC), but also sets the condition that determines how the current outcome influences (immediately) future decision making (i.e., the GF vs. the "hand–hand" fallacy) [Gao et al., 2015]. To the authors' knowledge, the only study that has empirically examined the effects of both agency and previous outcome in a risky decision-making paradigm was conducted by Xue et al. [2013], who observed behaviors characteristic of GF—i.e. increased betting following losses, but not wins—in the computer-guess but not the self-guess condition. Also, the left lateral PFC and ACC activities were modulated by the interaction of control and previous outcomes, showing stronger responses to previous losses compared to wins under computer-guess condition, but the reverse pattern under self-guess condition. These findings are consistent with previous studies [Croson and Sundali, 2005] and suggest that GF may only be evoked in the absence of perceived control. However, as each task session consisted of only self-select or computer-select trials in the work by Xue et al. [2013], it is impossible to delineate whether previous outcome interacted with agency in the *previous and/or current* trial in determining the current behavioral and associated neural responses. Such question is particularly relevant to real-life risky contexts, where IoC and GF often interact in a play-by-play, temporally dynamic manner. For example, it might be that individuals rely on information that is provided by immediately previous causal agency when determining whether a GF bias is adopted in the previous outcome, or they might take into account both the previous and current causal agency when assessing the randomness of the situation. Existing evidence is not sufficient for delineating these possibilities.

Existing evidence indicates that the inferior parietal lobule (IPL) may play important roles in risky decision-making. The IPL is interconnected with diverse neural

networks including the lateral PFC, anterior and posterior cingulate, cerebellum, and other superior and inferior parietal regions [Andersen et al., 1990; Clower et al., 2001]. In addition, research utilizing network analysis at system level revealed that the IPL serves as a major cortical "hub" that functions as a relay station for intercommunications between many other brain regions [Bullmore and Sporns, 2009]. As such, the IPL is at an ideal position for integrating and processing information generated at other neural networks, and its functional connectivity patterns with those networks might contribute to an individual's capacity in utilizing converging information during decision-making [Song et al., 2008]. The IPL encodes information about reward probabilities associated with different response options, which is critical for decision-making under uncertainty [Blackwood et al., 2004; Krain et al., 2006; Platt and Glimcher, 1999; Seo et al., 2009], as well as signaling response switching based on outcome history [Bush et al., 2002]. Paulus et al. [2001] showed that IPL activations were associated with response patterns characteristic of GF, and proposed that those networks are critical in supplying alternative strategies based on stored information about previous action–outcome contingencies. Interestingly, the right IPL activity was also modulated by perceived control during decision making and action execution [Farrer et al., 2003; Farrer and Frith, 2002; Studer et al., 2012], raising the possibility that this region provides the neural basis for the potential interactive influence of perceived control and GF. Such role of the IPL likely rests upon its functional connectivities with other frontal and posterior cortical networks under dynamic perceived control and previous outcome conditions, the patterns of which may further determine individuals' risky behaviors in those circumstances. However, current evidence is lacking on the specific response profile of IPL during risky decision making that requires integrative processing of previous causal agency as well as previous outcome in a temporally dynamic manner.

The present study focuses principally on investigating the interactive influence of IoC and GF, employing a risky decision-making task that independently manipulates perceived control and outcome history on a dynamic, trial-by-trial basis, with the amount of wagering as the dependent measure [Persaud et al., 2007]. We hypothesized that participants would wager more when they perceived greater self-control, or following losing rather than winning outcomes. Critically, the previous causal agency would modulate the effect of previous outcome, such that increased betting would occur after loss compared with after win only if the preceding outcome was computer-selected rather than self-selected. The current agency would further interact with previous agency and previous outcome in determining participants' wagering. Perceived greater self-control would lead to increased activities in the cingulate and lateral PFC, and previous outcomes would also modulate neural activities in the lateral PFC. Importantly, we expected previous outcomes to have differential effect on IPL betting-related neural signals depending on whether those outcomes were generated by self- or other-controlled selections. Such interactive effect of perceived control and outcome would also be evident in IPL signals during feedback processing. A related hypothesis was that the IPL would exhibit different functional connectivities with other brain networks implicated for processing agency, during betting following outcomes resulting from either self- or computer-controlled choices, particularly among individuals exhibiting greater behavioral sensitivity to the interactive effect of previous control and previous outcome.

## MATERIALS AND METHODS

### Participants

Ethical approval was granted by the Eastern China Normal University. Twenty-nine Chinese female undergraduate and graduate students were recruited (age = 19–28 years). The inclusion of young female participants in our study helped to minimize potential confounding effects of gender and age, which were previously found to modulate risk-taking tendency [Byrnes et al., 1999]. All participants were free of any history of major physical illness and neurological or psychological conditions such as substance dependence disorders, psychotic disorders, and affective disorders. No participants reported any past or present gambling problems as assessed with the National Opinion Research Center (NORC) diagnostic screen for gambling problems [Gerstein et al., 1999]. All participants had normal or corrected-to-normal vision and were right-handed as assessed with the Edinburgh Handedness Inventory [Oldfield, 1971].

All participants gave written informed consent for participation. The imaging data of three participants were subsequently excluded due to excessive movement in the MRI scanner (>1 voxel in the *X*, *Y*, or *Z* direction), leaving twenty-six participants in imaging data analysis.

### Experimental Task

The participant played a card-guessing game involving betting on success in matching the cards selected on two occasions (Fig. 1). The game consisted of self-selected and computer-selected conditions. During the self-selected condition, the participant was first presented with three cards (the 2 of spades, the 4 of hearts, and the 6 of clubs) aligned horizontally, and was prompted to select one by pressing the corresponding button. Following a jittered inter-stimulus-interval (ISI) of 3 sec (range = 2–4 sec, Poisson-distributed), the second selection phase was delivered, which required the participant to choose the card that she selected in the first instance from among the same three cards as before, which had nevertheless been spatially shuffled and "faced down." Participants were explicitly

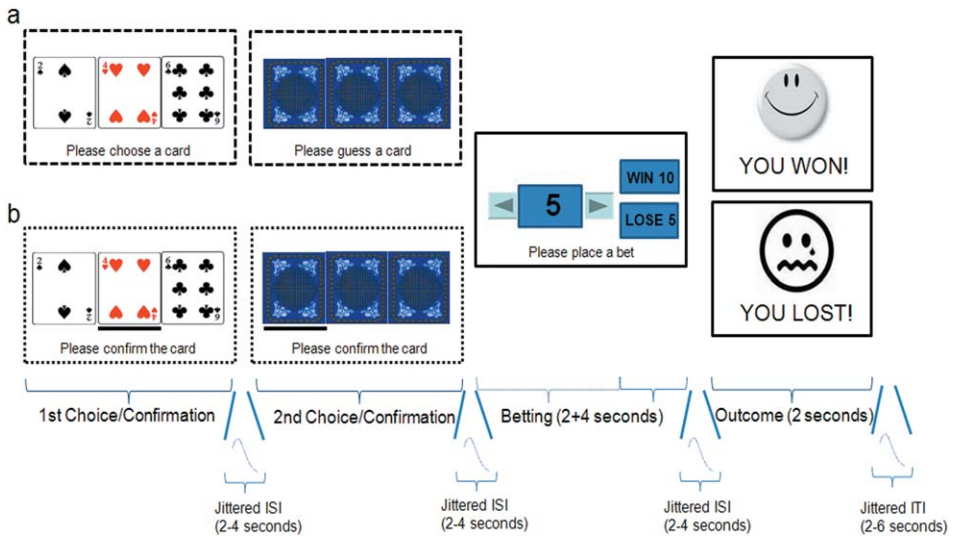


**Figure 1.**

The card-guessing game. In the self-selected condition (**a**), participants were first presented with three cards, from which they would select one. They would then try to pick the card that they just selected from the same three cards, which were nevertheless spatially shuffled and "faced down." After both selections and before the outcome, participants were asked to place bets on their success of matching the cards. Stakes ranged from 5 to 50 credits, with participants gaining double the stake if winning and losing the stake if losing. The starting values of the stake were randomized within both the self-selected and computer-selected conditions, in the range of 5–50. Participants were not allowed to behaviorally adjust the stake within the first 2 sec of the betting phase. Following those 2 sec, they had 4 sec to adjust the stake to the desired amount by pressing one of two buttons to increase or decrease the stake. Winning or losing outcomes were then delivered for 2 sec. Jittered ISI with mean of 3 sec were delivered between the first and second card selections, between the second card selection and betting, and between betting and outcome. ITI were also jittered with a mean of 4 sec. The timeline and stake schedule of the computer-selected condition (**b**) were identical to those of the self-selected condition, with the only difference that the computer made both card selections in pseudo-random manners (as indicated to the participant by the black underline). The participant merely needed to select that card to confirm the computer's choice. Each of the self-chosen and computer-chosen conditions delivered 10 winning outcomes and 20 losing outcomes, arranged in pseudo-random sequences. Not shown in the figure, the choice made by either the participant or the computer in each trial was displayed on the top of the screen to reduce the participant's working-memory load.

instructed that as a result of the spatial shuffling, the position of each card could either change or remain the same. To reduce the participant's working memory load, her choice in the first phase was displayed at the top left of screen (e.g., "You chose the 4 of hearts"). Following another jittered ISI (mean = 3 sec, range = 2–4 sec, Poisson-distributed), the participant was presented with an adjustable initial stake (5, 10, 20, 30, 40, or 50, randomized across trials in both self-selected and computer-selected conditions), as well as the corresponding winning and losing amounts for that stake. The participant would always gain double the stake in case of winning, or lose the exact amount of stake otherwise. Both the participant's first (e.g., 4 of hearts) and second selections (e.g., the left card) were displayed at the top of screen during betting. The participant was not allowed to adjust the stake during the first 2 sec of the betting phase, but was instructed instead to elaborate on how much to bet mentally. The text "Please place your bet" then appeared at the bottom of the screen, signaling the participant that she could start increasing or decreasing the stake within the range of 5–50 by pressing one of two buttons in a 4-sec interval. The betting phase was followed by a third jittered ISI of 3 sec (range = 2–4 sec, Poisson-distributed) before the winning or losing outcome was revealed, which lasted for 2 sec. The next trial commenced after a jittered inter-trial-interval (ITI) of 4 sec (range = 2–6 sec, Poisson-distributed).

The computer-selected condition was similar to the self-selected condition, except that both card selections were performed by the computer, not by the participant (Fig. 1). In each of the two selection phases, the card selected by the computer was underlined by a black horizontal line, and the participant merely needed to select that card to confirm the computer's choice. For each of the two card selections, the computer made the selections pseudo-randomly, with the only constraint that all three cards were selected for an equal number of times in total (i.e., 10

times). The timeline, stake schedule, motor demands, and stimulus presentation of the computer-selected trials were otherwise identical to those of the self-selected trials. Participants were instructed that in the computer-selected trials, the computer would "*automatically select a card for you, so you do not get to decide on which card to select*." We did not explicitly instruct the participants that the computer would select the cards randomly, following a large body of previous research studying risky decision-making biases such as the IoC which adopted similar practices [e.g., Clark et al., 2009; Dixon et al., 2007; Langer, 1975]. Rather, the agency manipulation was inherent in the task conditions, such that participants could make their own card selections in one condition but not in the other [Wagenaar and Keren, 1988]. Given previous research indicating that people generally perceive events with mechanical or inanimate causal agencies as following random sequences of occurrences [Burns and Corpus, 2004], we expected participants to perceive the event sequences associated with the computer-selected condition as, at least relatively, random.

The task contained a total of 60 trials divided equally between the self- and computer-selected conditions (i.e., 30 trials in each condition). Self- and computer-selected trials were presented to participants in alternating blocks of 3, with half of the participants receiving self-selected trials and the other half receiving computer-selected trials when starting the task. While this mini-block task setup may be somewhat atypical when event-related design is adopted, where trials belonging to different conditions are more often delivered in random or pseudo-random sequences, we adopted such setup for three reasons. First, using (pseudo)random trial sequences would mean that individual participants would receive the trials of different task conditions in different sequential arrangements, which would add extra between-subjects variances to our data that may confound the effects of interest. Second, researchers are often not able to control the trial sequences if the trials are delivered in a (pseudo)random manner. As a consequence, some participants may, by chance, receive low numbers of self-selected/computer-selected alternations, which is undesirable for the evaluation of the effects involving the interaction of current and previous control. Our task design, on the contrary, ensures that each participant would receive nineteen agency alternations. Third, frequent switching between experimental conditions (in our case, between self-selected and computer-selected trials) can elicit behavioral [Wylie and Allport, 2000] and neural effects [Dove et al., 2000; Sohn et al., 2000] by itself. In order to reduce such switching effect, we adopted the mini-block setup so as to ensure that the number of agency alternations in each participant was below twenty times. Each condition delivered 10 winning and 20 losing outcomes in a pseudo-random sequence, which contingency matched the perceived win/loss contingency from the task presentation (given 1 card was selected among 3 cards in each of the card-selection phases). Lower rates of winning versus losing outcomes were also frequently implemented by previous studies employing gambling-related paradigms [e.g., Clark et al., 2009; Shao et al., 2013]. The participant was informed that the amount of real money rewarded for completing the task would depend on her performance relative to that of other participants.

## Procedure

Following a pre-task screening (see section "Participants"), participants were given instructions on the card-guessing game. Participants then completed a practice task outside the scanner, which consisted of three self-selected and three computer-selected trials. After scanning, the participant filled in a post-game questionnaire that included questions about the game, such as "*When the computer chose the cards, what was the chance of winning*?" and "*How many times do you think you won when you chose the cards?*" as well as a 7-point Likert-scale question assessing the internal or external locus of control (LoC) [Rotter, 1966]: "*In general, would you describe yourself as a person with EXTERNAL locus of control (i.e. one who attributes successes or failures to external factors such as luck and other people, and believes things are governed more by external powers rather than yourself) or INTERNAL locus of control (i.e. one who attributes successes and failures to internal factors such as personal efforts, mental power or determination, and believes things are governed more by internal rather than external factors)?*" The participant was then debriefed, thanked, and paid according to her actual earnings during the task in comparison to those of other participants who had completed the task in the current study or in previous pilot work.

## Behavioral Data Analysis

The stakes that participants placed on individual trials were subjected to a random-intercept linear regression model implemented in MLwIN [Rasbash et al., 2009; Centre for Multilevel Modelling, University of Bristol, UK), which assumed that the mean stakes placed by individual participants may vary in a normally distributed way. Our behavioral data satisfied this assumption as Kolmogorov–Smirnov normality testing showed that participants' mean stakes followed a normal distribution ($P > 0.1$). The model has a hierarchical structure of two levels, with the first level being the different trials within individual participants and the second level being participants [Rasbash et al., 2009]. The first stage of analysis assessed the main effects of control (self-selected coded as 0.5 vs. computer-selected coded as $-0.5$ on a given trial), the outcome of the immediately previous trial (win coded as 0.67 vs. loss coded as $-0.33$), the stake placed on the previous trial, and the number of accumulated winning outcomes up to a given trial. In the second stage, the

interactive effects of the previous outcome and both the previous (i.e., self- or computer-selected on the immediately previous trial) and current control were assessed separately. Please note that all individual dependent and independent variables entered into the first- and second-stage models, including the discrete ones, were mean-centered e.g. winning outcomes were coded as 0.67 and losing outcomes as −0.33 as there were twice as many losing outcomes as winning outcomes. In order to examine whether the potentiating effect of previous losing outcome on stake was due to GF or loss-chasing [O'Connor and Dickerson, 2003], we repeated the above linear regression analysis incorporating the extra variable of accumulated total score, which represented participants' accumulated loss (or win) since the beginning of task, as well as including the interaction of previous outcome and each of the following variables: (1) previous stake; (2) accumulated total win number, and (3) accumulated total score. The results of these analyses are included in Supporting Information—Additional behavioral analyses.

In order to test whether the observed effects due to control, previous outcome, and the current/previous control × previous outcome interaction were dependent on the mini-block nature of trial sequence (i.e., the position in the block at which trials occurred), we repeated the linear regression analysis incorporating the extra variables of switching index (i.e., whether a given trial is a "switching trial," or the first trial in each mini-block) and block-position index (i.e., first, second, or third trial in a block), and assessed whether these variables modulated the effects of interest. The results of these analyses are also included in Supporting Information—Additional behavioral analyses.

We additionally performed similar linear regression analyses on individual participants' reaction times (RTs) when selecting among the "faced-up" cards (card selection 1) and when selecting among the "faced-down" cards (card selection 2), in order to assess whether those RTs were influenced by the factors of control, previous outcome, and the interactive effects of current and previous control as well as previous outcome. As we were not primarily interested in participants' behavioral measures during the card-selection phases, results of these analyses are included in Supporting Information—Additional behavioral analyses.

We also correlated individual participants' standardized beta co-efficient values, which reflected the influence of control on their stakes, with their rating responses to the post-game questionnaire (see section "Procedure"). The statistical thresholds for the behavioral analyses were set at $P < 0.05$, two-tailed.

## Image Acquisition and Analysis

Functional magnetic resonance image (fMRI) data were acquired with a 3-Tesla Siemens scanner equipped with a standard 12-channel head coil. A total of 798 volumes were collected as $3 \times 3 \times 4$ mm$^3$ T2*-weighted echo-planar images (slice number/TR/TE/flip angle = 33/2,000 ms/30 ms/90°, matrix = $64 \times 64$, FOV = $192 \times 192$ mm$^2$) along the anterior–posterior plane. Anatomical images were acquired with a T1-weighted spin-echo pulse sequence with spatial resolution of $0.5 \times 0.5 \times 1$ mm$^3$. Image preprocessing was carried out using the SPM 8 software (Wellcome Trust Centre for Neuroimaging, UCL, UK). Functional images were corrected for slice acquisition timing and realigned to the first image of the scan session to correct for head-motion artifacts. The functional images were co-registered to high-resolution T1 images at the participant level and normalized to the Montreal Neurological Institute (MNI) template (resolution = $3 \times 3 \times 3$ mm$^3$) using unified segmentation T1 images. Each volume was then smoothed with a Gaussian filter (full-width-half-maximum = 6 mm) and high-pass filtered at 128 seconds (or 0.008 Hz).

Events of interest were convolved with a canonical hemodynamic-response-function (HRF) for the modeling of blood-oxygen-level-dependent (BOLD) signals. Analysis of brain signals elicited during betting (i.e., the first 2 sec of the betting phase, see Fig. 1) employed a general linear model (GLM) with a full-factorial design involving within-subjects factors of control (self-selection vs. computer-selection on a given trial), previous control (self-selection vs. computer-selection on the immediately previous trial), and previous outcome (win vs. loss on the immediately previous trial). Analysis of BOLD signals elicited during the outcome phase (with a duration of 2 sec) employed a GLM with a full-factorial design involving within-subjects factors of control (self-selection vs. computer-selection) and outcome (win vs. loss). The stakes that a participant placed on a given trial were entered as a parametric modulator in the outcome phase. We ensured that no multi-collinearity issue was present in our data by running multi-collinearity checks among individual participants using SPSS v. 20 (IBM Corp.), and no evidence of multi-collinearity was observed for any of the participants (all tolerance values >0.87). At the participant level, individual event contrasts of interest (i.e., those related to the main effects of control, previous outcome, and the interactive effect of previous control and previous outcome during betting, and those related to the main effect of control, and the control × outcome interactive effect during feedback) were computed. At the group level, contrasts of *a priori* interest were evaluated with one-sample *t*-tests. For completeness of the GLM, the main effect of previous control, as well as the control × previous control, control × previous outcome, and the control × previous control × previous outcome interactive effects on betting-related signals were also analyzed. These effects are not central to our research hypotheses and were included in Supporting Information Table S1 without further discussions.

In order to further characterize the BOLD signals in the brain areas that exhibited significant activations to the contrasts of interest, we extracted percent signal change (PSC)

values from those regions specifically as regions of interest (ROIs), and assessed the effects of individual participants' behavioral sensitivity to control, previous outcome, or previous control × previous outcome, as indicated by their corresponding $\beta$ values from behavioral analyses, on the PSC values. To this end, we constructed repeated-measures ANOVA models in SPSS incorporating the same within-subjects factors for the betting and outcome phases as described above, but this time with the behavioral $\beta$ values entered as additional between-subjects covariate of interest. Results of these analyses are presented alongside the contrasts-of-interest analyses. Such ROI analyses aimed to link participants' neural responses, as revealed by the event contrast analyses, with their behavioral patterns, thus aiding the interpretation of the behavioral significance of those neural signals. As such the ROI analyses should be considered separately from the whole-brain covariate analyses (see below). In order to reduce the total number of tests conducted, we only assessed the associations between those neural and behavioral responses that were elicited by the same task effect. For example, the effect of control $\beta$ values during betting was assessed only on brain signals elicited by the control effect, but not on those elicited by the previous outcome or previous control × previous outcome effect.

We also performed another GLM analyses which additionally incorporated the two card selection phases, each of which was modeled with 8 regressors corresponding to the 2 (self-selection vs. computer-selection) × 2 (previous self-selection vs. previous computer-selection) × 2 (previous win vs. previous loss) within-subjects factorial design. The onset times for these regressors were set as the times when the card selection screens were displayed, and the durations were set as participants' RTs for card selections. Event contrasts of *a priori* interest (i.e., those related to the effect of control, previous outcome, and previous control × previous outcome) were evaluated at both the first (participant) and the second (group) levels. As we were not primarily interested in neural signals during the card-selection phases, results of these analyses and the relevant discussions are included in Supporting Information—Additional imaging analyses and discussion (also see Supporting Information Table S2).

In order to test whether the neural effect of the previous control × previous outcome interaction, which was the primary focus of our study, was dependent on the mini-block trial arrangement of our task paradigm, we performed a control GLM analysis at the participant level, including individual trials' block-position index (see section "Behavioral data analysis") as a condition-specific parametric modulator. The modulatory influence of this index was then evaluated at the group level. Results of these analyses are also included in Supporting Information—Additional imaging analyses and discussion.

Furthermore, we tested whether the influence of control, previous outcome, and previous control × previous outcome on participants' betting behaviors and on their BOLD signals during the betting and feedback phases were associated with each other. This was done by entering individual participants' standardized $\beta$, extracted from the behavioral analyses (see section "Behavioral data analysis"), as group-level covariates, and assessing their influences on BOLD signals elicited by event contrasts of *a priori* interest, at a *whole-brain* level. The association between participants' LoC scores and their BOLD signals was also assessed. As in the ROI analyses (see above), we only examined the effects of behavioral covariates on neural activities elicited by task event contrasts that have *a priori* associations with the covariates. This approach greatly limited the total number of covariate analyses that were performed, and kept the expected number of false positives to be well below 1 for both the betting and the outcome phases.

Whole-brain activation threshold was set at $P < 0.005$ at peak level and $P < 0.05$ at cluster level, corresponding to a cluster size of 90 or more, in accordance with the Monte Carlo simulation performed by AlphaSim implemented in REST v.1.8 [Song et al., 2011]. Where follow-up analyses were required for elucidating on the effects of task event contrasts and/or behavioral covariates on BOLD signals, PSC values were extracted from significant activation clusters using the MarsbaR toolbox (http://marsbar.sourceforge.net/faq.html).

Finally, we carried out generalized psycho-physiological interactive (gPPI) analysis [McLaren et al., 2012] to elucidate the functional connectivity associated with key task-event contrasts (i.e., those concerning the previous control × previous outcome effect) during betting. The gPPI approach extends from the traditional PPI analysis method, and is applicable when the task paradigm consists of more than two conditions [McLaren et al., 2012]. We extracted BOLD signals (first eigenvariate) from the ROI obtained from the regional analysis on the interactive effect of previous control and previous outcome, which signals were then adjusted for removing nuisance covariates (i.e., motion regressors) and were mean-corrected. The resulted signals constituted the physiological term of the PPI analysis. Each of the betting and outcome task regressors was then separately convolved with the HRF to form the psychological terms. Next, the extracted BOLD signals were deconvolved to obtain an estimate of the neural activity, which were then multiplied by each of the task regressors separately before convolution to form the PPI regressors. The activation threshold for the exploratory whole-brain gPPI analysis was set at $P < 0.005$ at peak level, uncorrected.

## RESULTS

### Behavioral Analysis

Participants placed significantly larger stakes if they selected both cards compared to if the computer selected

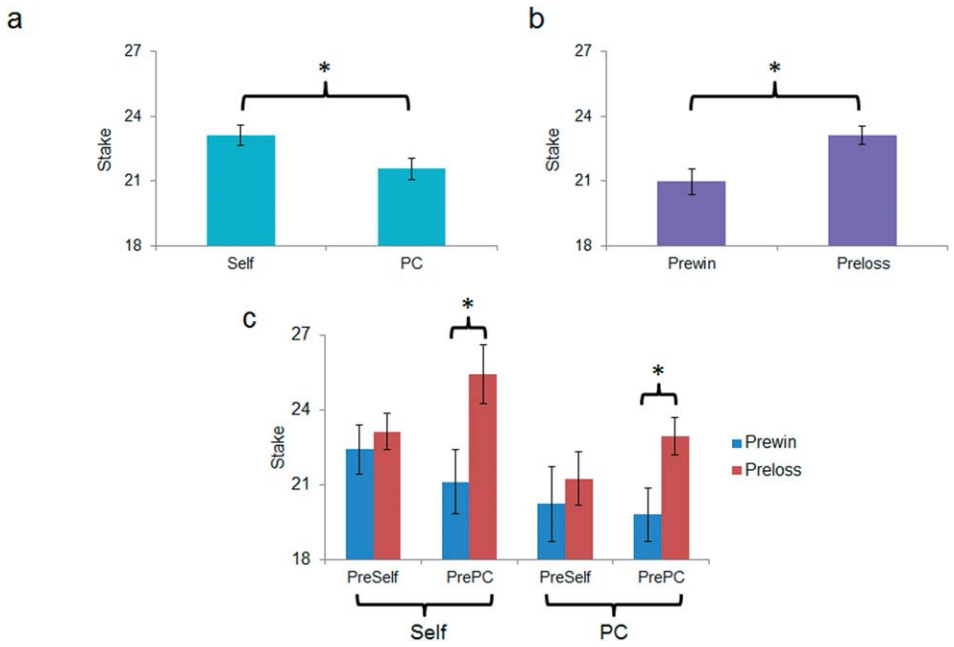


**Figure 2.**

Participants' averaged stakes placed (**a**) under self-selected versus computer-selected conditions; (**b**) immediately following previous winning versus losing outcomes; and (**c**) immediately following previous self-selected winning versus losing outcomes and previous computer-selected winning versus losing outcomes, separately displayed for current self-selected and computer-selected trials. Prewin/Preloss: immediately following a previous winning/losing outcome. PreSelf/PrePC: immediately following a previous self-selected/computer-selected trial. *Indicates statistically significant difference at $P < 0.05$. Error bars indicate $\pm 1$ standard error of the mean.

the cards ($\beta = 0.072$, $Z = 3.01$, $P < 0.05$) (Fig. 2a), and they tended to bet higher if they also betted higher on the immediately previous trial ($\beta = 0.134$, $Z = 5.58$, $P < 0.05$). However, participants placed smaller stakes immediately following previous winning compared with previous losing outcomes ($\beta = -0.089$, $Z = -3.73$, $P < 0.05$) (Fig. 2b). Participants also betted lower if they had received higher numbers of accumulated winning outcomes up to that trial ($\beta = -0.063$, $Z = -2.66$, $P < 0.05$). Thus, we observed patterns of betting behaviors characteristic of both IoC and GF after controlling for the influence of previous accumulated winning histories.

We obtained no evidence of an interactive effect of control and previous outcome ($\beta = 0.000$, $Z = 0.02$, $P > 0.1$). However, the interactive effect of previous control and previous outcome was positive and significant ($\beta = 0.054$, $Z = 2.14$, $P < 0.05$) (Fig. 2c). Further analysis showed that participants betted lower immediately following a winning outcome compared with following a losing outcome only when that outcome resulted from computer-controlled choices ($\beta = -0.137$, $Z = -4.10$, $P < 0.05$), but not if it resulted from self-controlled choices ($\beta = -0.036$, $Z = -1.09$, $P > 0.1$) (Fig. 2c). The 3-way interaction of control, previous control, and previous outcome was non-significant ($\beta = -0.017$, $Z = -0.67$, $P > 0.1$) (Fig. 2c). For completeness, the main effect of previous control and the interactive effect of previous and current control are included in Supporting Information—Additional behavioral analyses.

Individual participants also showed considerable variations in the extent to which their stakes were positively influenced by control ($\beta$ ranged from $-0.34$ to 0.49). Correlation analyses suggested that participants whose betting behaviors were more positively influenced by self-selection (i.e., more positive $\beta$) also reported that they felt a better chance of winning when the cards were chosen by themselves rather than by the computer ($r$ (28) = 0.441, $P < 0.05$) (Supporting Information Fig. S1a), as well as more of an internal rather than external locus of control ($r$ (29) = 0.419, $P < 0.05$) (Supporting Information Fig. S1b), as indicated by their responses to the post-game questionnaire.

## Image Analysis

### *Event contrasts of interest*

Activations elicited by event contrasts of *a priori* interest in the betting and outcome phases are displayed in Table I. During betting, the main effect of control revealed a region of the dorsal ACC (dACC) as well as the left middle frontal gyrus (lMFG), both of which were more

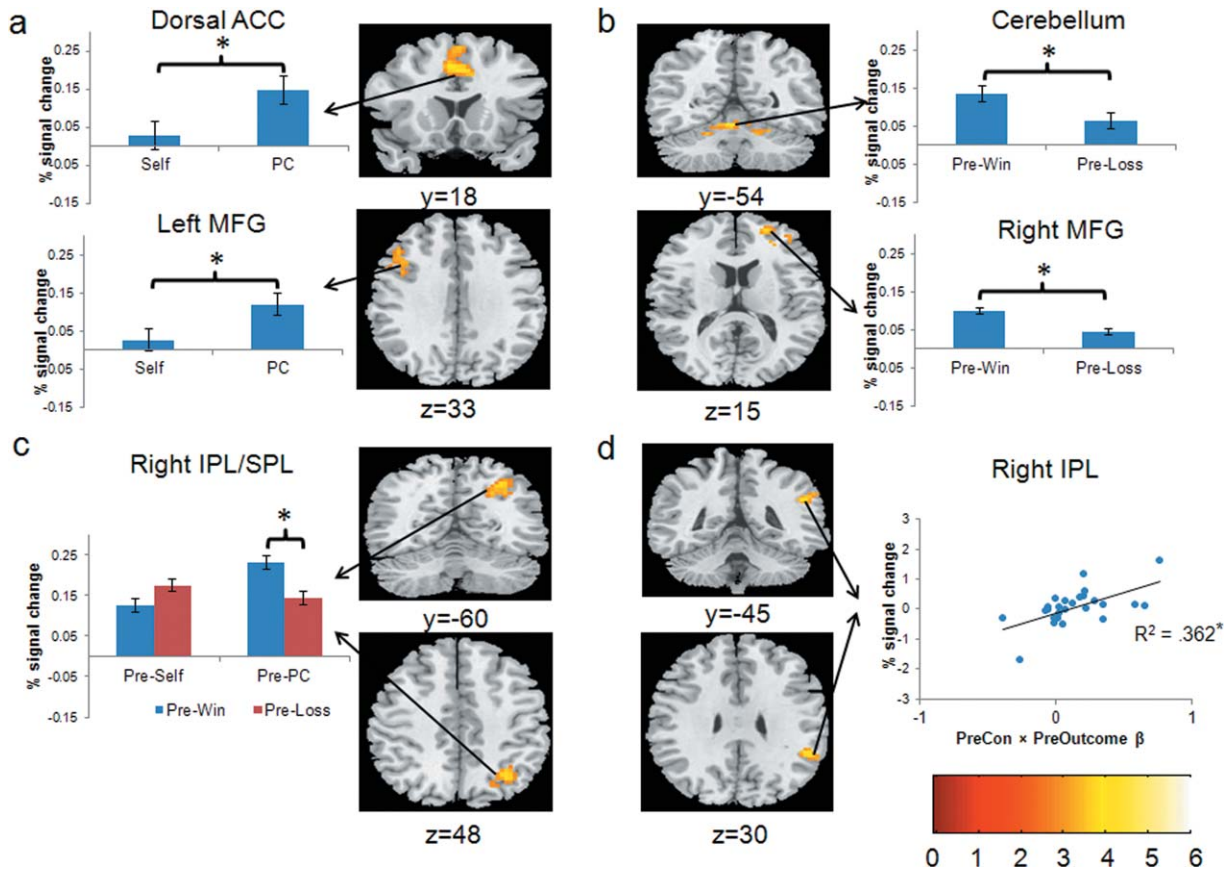


**Figure 3.**

Brain regions exhibiting betting-related BOLD signals that were modulated by the factors of control, previous outcome and previous control × previous outcome, overlaid on standard anatomical template (ch2bet). (**a**) Dorsal ACC (upper) and left middle frontal gyrus (lower) showed greater signals in computer-selected versus self-selected trials. (**b**) Bilateral cerebellum (upper) and right middle frontal gyrus (lower) exhibited signals that were greater following previous winning versus losing outcomes. (**c**) Right IPL extending into SPL exhibited positive signals to the interactive effect of previous control and previous outcome. Signals were more positive following previous computer-selected winning versus losing outcomes, but showed a reverse pattern if the previous trial was self-selected. (**d**) The right IPL showed signals to the contrast of winning versus losing outcomes in previous computer-selected versus self-selected trials, which were predicted by the standardized beta coefficients associated with the previous control × previous outcome effect on participants' betting behaviors. MNI coordinates are provided below each of the coronal and axial slices. ACC: anterior cingulate cortex; MFG: middle frontal gyrus; IPL/SPL: inferior/superior parietal lobule; PreSelf/PrePC: immediately following a previous self-selected/computer-selected trial; Prewin/Preloss: immediately following a previous winning/losing outcome.*Indicates statistically significant difference/effect at $P < 0.05$. Bar graphs and scatter plots are for display purposes only and should not be considered as independent from the contrasts-of-interest or covariate analyses. Error bars represent mean within-subject error. Color bar denotes *t*-statistics.

activated in the computer-selected than in the self-selected condition (Fig. 3a). ROI analyses indicated that participants whose betting behavior was less positively influenced by self-selection also exhibited more positive signals in this dACC cluster during betting ($F$ (1, 24) = 5.851, $P < 0.05$). Similar trend was observed for signals in the lMFG cluster ($F$ (1, 24) = 3.654, $P = 0.068$). The main effects of immediately previous outcomes elicited activations in the bilateral cerebellum and the right middle frontal gyrus (rMFG), both of which showed higher activations following previous winning rather than losing outcomes (Table I, Fig. 3b). However, the associations between participants' behavioral sensitivity to the effect of previous outcome and the cerebellum and rMFG signals failed to reach statistical significance ($F$ (1, 24) = 1.194, $P = 0.285$ and $F$ (1, 24) = 0.741, $P = 0.398$, respectively). The interactive effect of previous control and previous outcome revealed activations in the right IPL extending into the superior parietal

**TABLE I. The Montreal Neurological Institute (MNI) coordinates and the associated t-statistics of neural activations to task-event contrasts of interest**

| | Region | BA | *X* | *Y* | *Z* | *T* | $K_e$ |
|---|---|---|---|---|---|---|---|
| Betting | Control | | | | | | |
| | *Self > PC* | | | | | | |
| | N.S | | | | | | |
| | *PC > Self* | | | | | | |
| | Dorsal ACC/DMPFC | 32 | −3 | 24 | 36 | 5.88 | 225 |
| | Left middle frontal gyrus | 46 | −45 | 27 | 27 | 4.61 | 107 |
| | Previous Outcome | | | | | | |
| | *Prewin > Preloss* | | | | | | |
| | Bilateral cerebellum | | −3 | −54 | −15 | 4.26 | 207 |
| | Right middle frontal gyrus | 10 | 30 | 39 | 0 | 3.82 | 159 |
| | *Preloss > Prewin* | | | | | | |
| | N.S. | | | | | | |
| | Previous Control × Previous Outcome | | | | | | |
| | *PreSelf (Prewin > Preloss) > PrePC (Prewin > Preloss)* | | | | | | |
| | N.S. | | | | | | |
| | *PrePC (Prewin > Preloss) > PreSelf (Prewin > Preloss)* | | | | | | |
| | Right IPL/SPL | 7/40 | 33 | −57 | 48 | 3.97 | 113 |
| Outcome | Control | | | | | | |
| | *Win: Self>PC* | | | | | | |
| | N.S. | | | | | | |
| | *Win: PC>Self* | | | | | | |
| | N.S. | | | | | | |
| | *Loss: Self>PC* | | | | | | |
| | PCC | 23/29 | 6 | −45 | 21 | 4.85 | 182 |
| | Left lingual gyrus | 18 | −6 | −69 | 3 | 4.79 | 397 |
| | Right precuneus | 7 | 6 | −60 | 57 | 3.92 | 126 |
| | *Loss: PC>Self* | | | | | | |
| | N.S. | | | | | | |
| | Control × Outcome | | | | | | |
| | *Self (Win>Loss) > PC (Win>Loss)* | | | | | | |
| | N.S. | | | | | | |
| | *PC (Win>Loss) > Self (Win>Loss)* | | | | | | |
| | Right IPL/STG/TPJ | 40 | 66 | −33 | 15 | 4.22 | 160 |

Activation clusters were identified by group-level analysis on the BOLD signals elicited during betting, which were modulated by the within-subjects effects of control, previous outcome, and previous control × previous outcome, and those elicited during feedback, which were modulated by the within-subjects effects of control and control × outcome. Please note that task effects of lesser *a priori* interest but were also generated by the GLM for each of the two task phases are included in Supporting Information Table S1. Activation threshold was set at $P < 0.005$ at peak-level and $P < 0.05$ at cluster level (minimal cluster size = 90). BA: Brodmann area; $K_e$: cluster size; PC: computer; ACC: anterior cingulate cortex; DMPFC: dorsomedial prefrontal cortex; IPL: inferior parietal lobule; PreSelf/PrePC: immediately following a previous self-controlled/computer-controlled trial; Prewin/Preloss: immediately following a previous winning/losing outcome; PCC: posterior cingulate cortex; SPL: superior parietal lobule; STG: superior temporal gyrus; TPJ: temporo-parietal junction.

lobule (SPL) and the precuneus (Fig. 3c). This region showed greater activity in response to a previous winning versus losing outcome if the previous trial was computer-selected compared with self-selected (Table I). Further analysis revealed that following a computer-selected trial, activity in this region was significantly greater after a winning compared with losing outcome ($F$ (1, 25) = 12.478, $P < 0.05$). In contrast, when preceded by a self-selected trial, this parietal region exhibited marginally greater activity in response to previous losing compared with winning outcomes ($F$ (1, 25) = 3.37, $P = 0.078$) (Fig. 3c). ROI analyses revealed that within this IPL/SPL region, the association between participants' behavioral sensitivity and neural signals to the previous control × previous outcome effect did not reach statistical significance ($F$ (1, 24) = 1.88, $P = 0.183$). However, following a median split of the previous control × previous outcome $\beta$ values, among those participants whose betting was less positively influenced by the interactive effect, the previous control × previous outcome contrast only had marginal effect on the

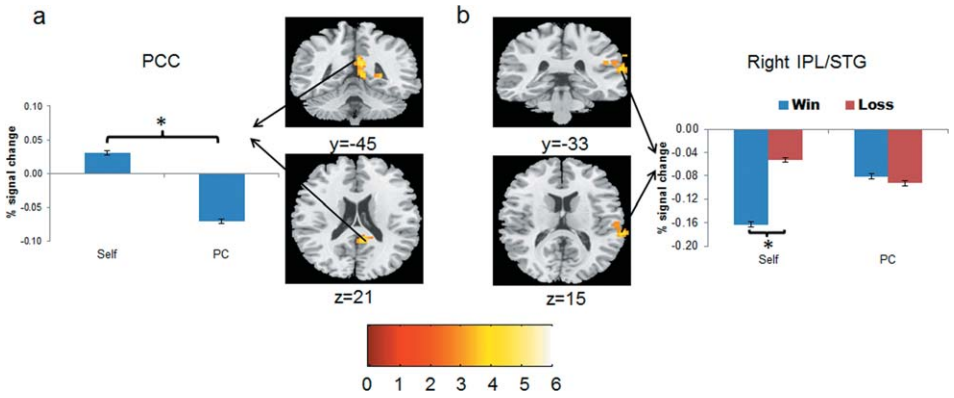


**Figure 4.**

Brain regions exhibiting BOLD signals that were modulated by the factors of control and control × outcome during the feedback stage, overlaid on a standard anatomical template (ch2bet). (**a**) The PCC showed signals to losing outcomes that were greater in self-selected versus computer-selected trials. (**b**) The right IPL extending into the STG showed positive signals to the interactive effect of control and outcome. Signals were more positive for self-selected losing versus winning outcomes, but were similar for computer-selected outcomes. MNI coordinates are provided below each of the coronal and axial slices. IPL: inferior parietal lobule; PC: computer; PCC: posterior cingulate cortex; STG: superior temporal gyrus. *Indicates statistically significant difference at $P < .05$. Bar graphs and scatter plots are for display purposes only and should not be considered as independent from the contrasts-of-interest or covariate analyses. Error bars represent mean within-subject error. Color bar denotes *t*-statistics.

PSC of this IPL region ($F$ (1, 12) = 4.067, $P = 0.067$), while for those exhibiting greater behavioral sensitivity to the interactive effect, the same contrast had clearly significant effect on the IPL signals ($F$ (1, 12) = 13.085, $P = 0.004$).

During the feedback stage, winning compared to losing outcomes elicited widespread activations in the bilateral prefrontal, cingulate, occipito-parietal, limbic, and striatal networks, whereas the reverse contrast generated activations in the right temporo-parietal junction (TPJ) (Supporting Information Table S1). The magnitude of winning had no positive or negative modulatory effect on brain activities to winning outcomes. The magnitude of losing also

**TABLE II. The Montreal Neurological Institute (MNI) coordinates and the associated *t*-statistics of neural activations identified by group-level covariate analyses**

| | Standardized β/LoC-Internal | Region | BA | X | Y | Z | T | $K_e$ |
|---|---|---|---|---|---|---|---|---|
| Betting | | *PrePC (Prewin > Preloss) > PreSelf (Prewin > Preloss)* | | | | | | |
| | Previous control× Previous outcome | Right middle frontal gyrus | 8/9 | 30 | 21 | 57 | 6.08 | 203 |
| | | Left inferior parietal lobule | 40 | −42 | −48 | 18 | 4.44 | 100 |
| | | Left cerebellum | | −18 | −90 | −21 | 4.35 | 91 |
| | | Right inferior parietal lobule | 40 | 48 | −45 | 30 | 4.22 | 106 |
| Outcome | | *Self (win > loss) > PC (win > loss)* | | | | | | |
| | LoC-Internal | PCC | 23 | 3 | −48 | 21 | 4.27 | 95 |
| | Control | PCC/Precuneus | 31 | 42 | −27 | −9 | 5.28 | 412 |
| | | Left striatum | | −21 | 3 | 18 | 4.95 | 254 |
| | | Left postcentral gyrus | 2/3 | −39 | −15 | 27 | 4.70 | 135 |
| | | Right striatum | | 15 | 3 | −3 | 4.38 | 263 |
| | | *PC (Win > loss) > Self (win > loss)* | | | | | | |
| | Previous control× Previous outcome | Left VMPFC | 32 | −6 | 39 | −12 | 3.95 | 94 |

The covariate analyses involved assessing the influences of the standardized beta coefficients associated with the behavioral effects of control and previous control × previous outcome, on individual participants' betting and outcome signals to the corresponding task effects, as well as those of the self-reported locus-of-control scores on participants' neural signals to the agency effect. Higher locus-of-control scores indicate more of an internal locus of control. Activation threshold was set at $P < 0.005$ at peak-level and $P < 0.05$ at cluster level (minimal cluster size = 90). LoC: locus of control; BA: Brodmann area; $K_e$: cluster size; PreSelf/PrePC: immediately following a previous self/PC-controlled trial; Prewin/Preloss: immediately following a previous winning/losing outcome; PCC: posterior cingulate cortex; VMPFC: ventromedial prefrontal cortex.

had no positive modulatory effect on brain activities to losing outcomes, but had negative modulatory effect on activities in the bilateral IPL, bilateral dorsal and ventral prefrontal regions, and bilateral precuneus/PCC. Direct comparisons of self-selected versus computer-selected trials revealed no difference of the modulatory effect of winning or losing amount on win- or loss-elicited activities. More details about the win and loss magnitude analyses and relevant discussions are included in Supporting Information—Additional imaging analyses and discussion.

Planned comparison of self-selected versus computer-selected outcomes revealed significant activations in the posterior cingulate cortex (PCC) (Fig. 4a), right precuneus and left lingual gyrus in response to losing outcomes specifically (Table I). Moreover, ROI analyses indicated that this activity in the PCC cluster was negatively associated with the potentiating effect of self-selection on individual participants' betting behaviors ($F$ (1, 24) = 9.513, $P < 0.05$). The interactive effect of control and outcome generated activations in the right IPL extending into the superior temporal gyrus (STG) and the TPJ (Table I, Fig. 4b). This region showed greater responses to losing compared with winning outcomes in self-selected trials ($F$ (1, 25) = 17.824, $P < 0.05$), but similar activities in response to winning and losing outcomes in computer-selected trials ($F$ (1, 25) = 0.418, $P > 0.1$) (Fig. 4b). ROI analyses indicated that the association between the behavioral sensitivity and the neural signals to the control × outcome interaction showed a trend ($F$ (1, 24) = 3.021, $P = 0.095$). Further analyses based on a median split of the behavioral $\beta$ values showed that the right IPL/STG/TPJ signal to the control × outcome interactive effect was more pronounced in those participants whose betting was under more positive influence of the previous control × previous outcome interaction ($F$ (1, 12) = 15.644, $P = 0.002$), compared with those showing less positive influence of the interaction on betting ($F$ (1, 12) = 7.085, $P = 0.021$).

### *Whole-brain covariate analysis*

Participants' behavioral $\beta$ for control, previous outcome, and previous control × previous outcome effects correlated minimally with each other ($|r|s < 0.05$). While participants' LoC scores correlated moderately with their control $\beta$ values ($r = 0.419$), the correlations between LoC scores and the $\beta$ values for both previous outcome and previous control × previous outcome were weak ($r = -0.094$ and $r = -0.096$, respectively). At a whole-brain level, participants whose betting behaviors were under more positive interactive influence of previous control and previous outcome showed greater betting-related neural activities following winning versus losing outcomes in computer-selected compared with self-selected trials, within the regions of right middle frontal gyrus, left and right IPL encompassing the angular gyrus and the TPJ (Table II, Fig. 3d), and left cerebellum. During feedback, participants with more internal LoC exhibited greater activities in the PCC in response to self-selected versus computer-selected winning versus losing outcomes (Table II). Participants who tended to bet higher during self-selected compared with computer-selected trials showed greater activities in the PCC/precuneus, bilateral striatum (Supporting Information Fig. S2a), and left postcentral gyrus in response to winning versus losing outcomes in self-selected versus computer-selected trials (Table II). Participants whose betting behaviors were under more positive interactive effect of previous control and previous outcome also showed greater left ventromedial prefrontal cortex (VMPFC) activities to the reverse contrast pattern of the control × outcome interaction—that is, more positive signals to winning versus losing outcomes in computer-selected relative to self-selected trials (Table II and Supporting Information Fig. S2b).

### *GPPI analysis*

Functional connectivity analyses in the betting phase was based on a 6-mm-sphere seed region centered on the local maxima of the right IPL/SPL cluster revealed by the previous control × previous outcome interactive analysis (33, −57, 48) (Table I). Participants whose betting behaviors were under more positive interactive influence of previous control and previous outcome showed less positive functional connectivity with the left lingual gyrus (Maxima = −18, −51, 0, $t = 4.01$, cluster size = 58), PCC/precuneus (Maxima = −12, −39, 33/12, −39, 51, $t = 3.82/3.61$, cluster size = 75/52) and the anterior/middle cingulate gyrus (Maxima = 9, 0, 36, $t = 3.51$, cluster size = 47) following previous computer-selected winning versus losing outcomes, and less positive functional connectivity with the rostral ACC (rACC) (Maxima = 3, 42, 15, $t = 4.15$, cluster size = 39) following previous self-selected winning versus losing outcomes (Supporting Information Fig. S3).

## DISCUSSION

In characterizing the interaction of perceived control and GF in risky decision making, we showed that participants took more risks, as reflected by larger stakes placed, immediately following losses only if the losing outcomes resulted from computer-controlled rather than self-controlled selections. The interaction of previous control and previous outcome modulated betting-related activities, and the interaction of current control and current outcome modulated outcome-related activities, in the right IPL. These modulatory effects on betting- and outcome-related IPL signals are also associated with participants' behavioral sensitivity to the interactive effect to some extent. Moreover, participants' behavioral sensitivity to the interactive influence was associated with their differential functional connectivity networks centering on the right inferior parietal regions during betting. Overall, the current

findings provide novel evidence on the behavioral and neural substrates of the dynamic interaction of perceived control and GF during risky decision making, as well as on the neural basis of individual differences in behavioral responsiveness to this interaction.

Consistent with a large body of literature, we employed a gambling task that independently manipulates perceived control and previous outcome on a trial-by-trial basis to show that people exhibited risk-taking behaviors characteristic of both IoC [Kool et al., 2013; Langer, 1975; Presson and Benassi, 1996] and GF [Croson and Sundali, 2005; Roney and Trick, 2003; Xue et al., 2011]. Participants' behavioral sensitivity to perceived control also correlated with their self-reported LoC, suggesting that individuals with stronger tendencies to attribute positive and negative events to internal causes might endorse a different self-world model than those endorsing more external LoC [Xue et al., 2013], which could impact their outcome probability evaluations during risky decision making [Thompson et al., 1998]. Critically, we obtained the first direct evidence indicating that in a dynamic risky context where both the levels of perceived control and outcomes may vary in a trial-by-trial manner, the potentiating effect of a previous losing outcome on people's subsequent risk-taking tendencies depends critically on that outcome resulting from choices initiated by the other agent, not by the self. This finding is consistent with previous research associating GF with the interpretation of preceding events as determined principally by uncontrollable factors rather than by human performance [Ayton and Fischer, 2004; Croson and Sundali, 2005]. More fundamentally, the finding suggests a more refined "world model" [Xue et al., 2012] to which individuals might resort when making decisions under uncertainty—that is, negatively autocorrelated event sequences are attributed to mechanical, random causes but not to human, controllable causes [Ayton and Fischer, 2004]. Our findings further help toward understanding disparities in previous findings regarding the influence of previous outcomes on subsequent risk taking [Gao et al., 2015; Xue et al., 2011]. On the other hand, the level of control associated with the current choice had little direct influence on GF, neither did it interact with previous control in jointly modulating the effect of immediately previous outcome on current risky decision making. While future replications are needed, our current findings indicate that the interactive effect of previous agency and previous outcome on people's risky decision making operates independently from the effect of the current agency, such that the former effect holds regardless of whether the current agency is the same or different from the previous agency. In other words, the potentiating effect of previous causal agency being inanimate or non-human-based on the GF effect arisen from previous outcome operates additively with the effect of current agency in jointly influencing current risky decision making. Such findings have never been demonstrated before, and reveal important characteristics of human decision making in risky contexts.

Our findings that the ACC and DLPFC showed greater signals during betting on computer-selected compared with self-selected trials are consistent with the general role of these neural structures in producing goal-directed instrumental actions, based on the review of the history of action–outcome contingencies in dynamic, risky environments [Glascher et al., 2010; Hecht et al., 2010; Kennerley et al., 2006; Rushworth et al., 2007]. Thus, integrating previous computer-controlled choices and the associated outcomes to decision making might demand greater processing, as those choices tended to be less predictable and more difficult to track. Our data are also consistent with previous evidence implicating the ACC and DLPFC in strategic decision making based on the response patterns of other agents [Steinbeis et al., 2012; Zhu et al., 2012]. Interestingly, we also obtained evidence that the dorsal ACC and, to a lesser extent, the left DLPFC activities during betting were more positive for individuals exhibiting less IoC behavioral effect, suggesting that reduced processing of past action–outcome contingencies in these frontal networks may have led the participant to rely on schematic knowledge (e.g., my own choices carry greater chances of winning) rather than objective evaluation of event histories in making risky decisions. The cerebellum and right DLPFC exhibited greater betting-related activities immediately following winning relative to losing outcomes [Brand et al., 2005; Xue et al., 2011, 2012]. The cerebellum was previously implicated in risky decision making based on past outcome histories [Ernst et al., 2002] and in sequence learning and processing [Dixon and Passingham, 2000; Doyon et al., 1997], and it might guide probabilistic decision making by constructing internal working models of external event sequences [Blackwood et al., 2004]. Similarly, the lateral PFC was proposed to subserve self-initiated response-switching functions in order to attain more favorable outcomes based on an internal "world model" [Daw et al., 2005; Dove et al., 2000; Xue et al., 2011, 2012]. However, given the lack of statistically significant associations between the cerebellum and DLPFC activities and participants' behavioral manifestation of GF, interpretations of the behavioral significance of those neural signals remain tentative.

The IPL plays important roles in processing information about outcome values and probability during risky decision making [Blackwood et al., 2004; Platt and Glimcher, 1999; Seo et al., 2009; Studer et al., 2012] and in enabling individuals to apply alternative strategies based on stored information about previous action–outcome contingencies [Paulus et al., 2001]. Existing evidence also indicates that activity of the right IPL is modulated by agency in both decision making [Studer et al., 2012] and action execution [Farrer et al., 2003]. Nevertheless, the functional significance of the IPL in relation to the interactive effect of perceived control and GF during decision making remains

unclear. We show that a region of the right IPL extending into the SPL exhibited more positive betting signals in response to previous computer-selected winning versus losing outcomes, but the reverse pattern if the previous trial was self-selected. In addition, the right IPL signals predicted participants' behavioral responsiveness to this interactive effect, as revealed by the whole-brain covariate analyses and, to a lesser extent, by the ROI analyses. These results highlight the significance of the IPL in providing the neural substrate for the convergence of information about previous causal agency and outcomes and for their interactive influence on subsequent risk taking [Thompson et al., 1998], possibly via extensive anatomical connections with the cingulate, PFC, and cerebellum networks [Andersen et al., 1990; Clower et al., 2001]. Our findings are also in accordance with existing evidence indicating a critical role of the inferior parietal networks as a cortical "hub" at the system level, where information from other brain regions converges [Bullmore and Sporns, 2009]. Furthermore, another region of the right IPL extending into the posterior STG exhibited feedback activities related to the interactive effect of control and outcome, showing greater signals in response to self-selected losing versus winning outcomes, but similar activities to computer-selected outcomes. In addition, limited evidence from the ROI analyses indicated that this signal was more pronounced among participants whose betting behavior was more positively influenced by the interactive effect of previous control and previous outcome, providing evidence that sub-networks of the IPL are involved in integrative processing of agency and outcome that are either current or (immediately) historical, which signals are, to an extent, further associated with individual differences in behavioral manifestation of this joint influence. Collectively, our findings highlight the dependent nature of the IPL network signals in both decision making and outcome processing on working models about causal agency and outcome event sequences, contributing to individuals' differential behavioral patterns in dynamic risky contexts.

We also observed that the right PCC and precuneus exhibited greater activities in response to self-selected versus computer-selected losing outcomes specifically. Furthermore, such activities in the PCC were less pronounced for those participants showing more positive self-selection effect on betting. Activities in the right PCC/precuneus following self-selected versus computer-selected winning versus losing outcomes also predicted participants' behavioral sensitivity to perceived control. The PCC/precuneus was previously shown to be specifically responsive to rewarding outcomes generated by self-controlled actions [Kool et al., 2013], and it is generally associated with processing self-referential stimuli and self-identity [Kircher et al., 2000; Kjaer et al., 2002; Northoff and Bermpohl, 2004]. Thus, some individuals might exhibit greater tendency to incorporate their task performance into their self-identities (e.g., "I am good at performing this task"), particularly when successes followed self-initiated actions—an attitude that in turn influences their risk-taking tendencies. On the contrary, when self-controlled selections led to negative consequences, reduced self-referential processing in the PCC may prevent the participant to discard the belief that she can make better selections than the computer, who would then continue to bet higher upon her own card choices despite counter-evidence from feedbacks [Thompson et al., 1998]. We also found that bilateral striatal activities in response to winning versus losing outcomes in self-selected compared with computer-selected trials predicted participants' behavioral sensitivity to control, which lends support to the role of striatal networks in shaping individual participants' risk-taking tendencies by providing greater reward signals for successes resulting from self-controlled actions [Leotti and Delgado, 2011].

We obtained illuminating results on the functional connectivity networks centering on the right IPL regions in participants showing differential behavioral sensitivities to the interactive effect of previous control and previous outcome. During betting, among those whose betting behavior following wins was more positively modulated by previous self-selection, the right IPL showed less positive connectivity with the PCC/precuneus following computer-selected winning versus losing outcomes, and with the rACC following self-selected winning versus losing outcomes. The PCC/precuneus was previously implicated specifically for self-referential processing and evaluating outcomes resulted from self-generated choices [Kjaer et al., 2002; Kool et al., 2013], whereas the rACC may provide affective warning signals for reducing risk-taking behaviors following computer-selected losses [Xue et al., 2013]. Thus, our results, while preliminary, led to the speculation that for individuals behaviorally manifesting stronger interactive effects of previous control and previous outcome, the right IPL "cuts off' connections with areas implicated for self-relevant processing in order to strengthen the signaling of the "other" causal agency for the preceding computer-selected outcomes, as well as cutting off connections with the "warning" center that normally regulates risk-taking following computer-selected outcomes, if the preceding outcomes resulted from self-selected actions instead. As a result, betting-related processing following outcomes associated with different causal agencies became more differentiated, leading to manifestations of GF following computer-selected, but not self-selected, outcomes. Our findings highlight a key role of the IPL in integrating information about (previous) causal agency and instrumental outcome through functional connectivities with other frontal and posterior networks, the strengths of which contribute to individual differences in decision making based on converging information [Song et al., 2008].

Overall, we propose that the right IPL provides the neural substrate for the interaction of previous causal agency

and outcome(s) in determining an individual's assessment of future outcome probabilities, through coordinating activities in the anterior and posterior cingulate cortices, along with other distributed networks including the lateral PFC and other parietal regions. This neural framework incorporates both cognitive (e.g., "world model") and affective (e.g., the "warning" signals of the rACC) components of risky decision making. It also recognizes the potential significance of posterior cingulate and striatal signals in predicting individual differences in behavioral sensitivity to perceived self-control. Moreover, this framework is modulated by trait factors such as LoC, which influences posterior cingulate signals that might serve self-reflective functions during outcome processing. Our framework also has clinical implications for maladaptive, risky decision making. For example, pathological gamblers were more likely to increase risk-taking based on self-controlled choices immediately following losses compared with healthy controls [Hewig et al., 2010], and exhibited reduced inferior parietal activities relative to recreational gamblers [van Holst et al., 2010]—observations that are compatible with our framework.

The current investigation can be improved and extended as follows. First, our participants comprised a relatively homogeneous, young, female sample with little gambling experience. Future research could examine more demographically diverse samples with various levels of gambling experience. Second, we did not explicitly manipulate or assess the influence of streak length of previous outcomes (i.e., a bet following 1 win was treated the same as a bet following 2 wins). Given existing evidence indicating the influence of streak length on GF effects [Xue et al., 2012], future research could systematically manipulate the length of outcome streaks and assess its effects. Also, future studies may examine both the GF effects in choice selection, such as betting on an option that has not come up in the recent history compared to one that has just occurred [Xue et al., 2012], and in risky decision-making (e.g., betting), as well as including paradigms in which participants are instructed to provide estimates of immediately future winning probabilities having just received hypothetical winning or losing outcome. Moreover, in both our self-selected and computer-selected conditions participants were able to decide on how much to bet. It would be valuable to include an additional condition in which the computer also decides on the stakes placed for comparison with the current computer-selected condition. Third, future investigations could additionally employ questionnaire measures of IoC and GF, so as to assess the association between self-reported and task measurements of those biases. Finally, future research may replicate the current findings with task paradigms delivering (pseudo)random trial sequences, ideally with larger number of participants in order to dilute the effects due to large between-participants variances in trial delivery sequence.

## CONCLUSION

During the performance of a risky decision-making task involving dynamic schedules of perceived control and previous outcomes, GF-type behaviors were only observed following other-selected, but not self-selected, outcomes. Such interactive effect of previous control and previous outcome was not dependent on the level of current control. The right IPL was activated to the interactive effect of previous control and previous outcome during betting and to the interactive effect of control and outcome during feedback, with both signals predicting participants' behavioral sensitivity to the interactive effect to some levels. Furthermore, following outcomes associated with the self and other causal agencies, the right IPL exhibited more differentiated functional connectivity with other neural networks implicated in processing agency and previous outcomes, among participants showing greater behavioral sensitivity to the interactive effect. We propose that the right IPL provides the neural substrate for the convergence of the influence of agency and outcome, a framework that could help understand the proneness to IoC and GF biases among pathological gamblers.

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