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The amygdalostriatal and corticostriatal effective connectivity in anticipation and evaluation of facial attractiveness

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ABSTRACT

Decision-making consists of several stages of information processing, including an anticipation stage and an outcome evaluation stage. Previous studies showed that the ventral striatum (VS) is pivotal to both stages, bridging motivation and action, and it works in concert with the ventral medial prefrontal cortex (vmPFC) and the amygdala. However, evidence concerning how the VS works together with the vmPFC and the amygdala came mainly from neuropathology and animal studies; little is known about the dynamics of this network in the functioning human brain. Here we used fMRI combined with dynamic causal modeling (DCM) to investigate the information flow along amygdalostriatal and corticostriatal pathways in a facial attractiveness guessing task. Specifically, we asked participants to guess whether a blurred photo of female face was attractive and to wait for a few seconds ("anticipation stage") until an unblurred photo of feedback face, which was either attractive or unattractive, was presented ("outcome evaluation stage"). At the anticipation stage, the bilateral amygdala and VS showed higher activation for the "attractive" than for the "unattractive" guess. At the outcome evaluation stage, the vmPFC and the bilateral VS were more activated by feedback faces whose attractiveness was congruent with the initial guess than by incongruent faces; however, this effect was only significant for attractive faces, not for unattractive ones. DCM showed that at the anticipation stage, the choice-related information entered the amygdalostriatal pathway through the amygdala and was projected to the VS. At the evaluation stage, the outcome-related information entered the corticostriatal pathway through the vmPFC. Bidirectional connectivities existed between the vmPFC and VS, with the VS-to-vmPFC connectivity weakened by unattractive faces. These findings advanced our understanding of the reward circuitry by demonstrating the pattern of information flow along the amygdalostriatal and corticostriatal pathways at different stages of decision-making.

1. Introduction

Organisms seek to maximize its reward and minimize its punishment, a tendency called behavioral optimization (Diekhof, Kapsb, Falkaib, & Gruberb, 2012). Behavioral optimization depends on the neural capacity to represent reward-related information and to use this information to guide decision-making. Psychological and neurobiological investigation of decision-making conceptualizes it as consisting of action selection, anticipation and evaluation of outcome, and updating of value representation (Knutson & Greer, 2008; Platt, 2003). Neuroimaging research in the past decade has identified three functionally related brain structures that probably form the core network for reward processing and decision-making, i.e., the ventral striatum (VS), the ventral medial prefrontal cortex (vmPFC), and the amygdala (Balleine & Killcross, 2006; Rangel, Camerer, & Montague, 2008; Schoenbaum, Roesch, Stalnaker, & Takahashi, 2009).

The VS is pivotal to reward processing, reinforcement learning, and goal-directed behavior (Delgado, Li, Schiller, & Phelps, 2008; Diekhof et al., 2012; Haber & Knutson, 2010; O'Doherty et al., 2003; Schultz, 1998; Sesack & Grace, 2010) and it functions at different stages of decision-making (Platt, 2003). For instance, anticipation of both primary (e.g., pleasant taste or unpleasant electrical stimulation) and secondary (e.g., money) reinforcer elicits VS activation (Knutson & Greer, 2008). At the outcome evaluation stage, the VS is found to encode the prediction error signal, i.e., the discrepancy between the prediction and the actual outcome (Bayer & Glimcher, 2005; Hare, O'Doherty, Camerer, Schultz, & Rangel, 2008; Li et al.,

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2011; Schultz, 1998). The vmPFC and the adjacent parts of the medial orbitofrontal cortex (mOFC) are consistently implicated in representing abstract value of choices and outcomes (FitzGerald, Seymour, & Dolan, 2009; Kim, Shimojo, & O'Doherty, 2010; Knutson, Fong, Adams, Varner, & Hommer, 2001; Knutson, Fong, Bennett, Adams, & Homme, 2003; O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001; for reviews, see Kringelbach, 2005; O'Doherty, 2004; Schoenbaum, Roesch, Stalnaker, & Takahashi, 2009).

The vmPFC and VS are structurally and functionally connected. Anatomical studies on non-human primates showed that tracers injected in the vmPFC labeled the fibers that terminate in the nucleus accumbens (NAcc), a limited area within the VS (Haber, Kunishio, Mizobuchi, & Lynd-Balta, 1995). Instead of directly innervating the prefrontal cortex, the efferent projections from VS primarily target the pallidum and midbrain. The latter structures in turn project back to the prefrontal cortex, including the vmPFC (Hedreen & DeLong, 1991). Neuroimaging techniques, such as the diffusion tensor imaging (DTI) and resting state MRI, have also demonstrated the frontostriatal structural connectivity in humans (Cauda et al., 2011; Di Martino et al., 2008). Functionally, studies on drug addiction provide evidence for the interplay between the vmPFC and the VS (Goldstein & Volkow, 2002; Kalivas & Volkow, 2005), suggesting that the prefrontal-to-NAcc glutamate projection may substantiate the transmission from the value of the reinforcer (e.g., cues of drug) represented in the prefrontal cortex to the craving sensation generated in the striatum. However, little is known about the role of this functional interplay in decision-making in healthy population.

The amygdala, although typically envisaged as the center of fear conditioning and negative emotions (LeDoux, 2000; Morris et al., 1996; Phelps & LeDoux, 2005), has been demonstrated to play specific roles in reward processing and appetitive learning (Li, Schiller, Schoenbaum, Phelps, & Daw 2011; Paton, Belova, Morrison, & Salzman, 2006; for reviews, see Baxter & Murray, 2002; Seymour & Dolan, 2008), in both human (Gottfried, O'Doherty, & Dolan, 2002; O'Doherty et al., 2002) and non-human animals (Shabel & Janak, 2009). It was proposed that the amygdala signals the biological salience of potential actions or outcomes, rather than encodes fear-related information alone (Balleine & Killcross, 2006). A recent model-based fMRI study confirmed this hypothesis by demonstrating the computational role of amygdala in reinforcement learning (Li et al., 2011). The authors found that the amygdala represents the importance of the prediction error signal, generated in the VS, to the organism's goal and thus determines the extent to which the organism learns from it. Indeed, the amygdala has strong unidirectional anatomical projection to the VS. While both the dorsal striatum and VS receive input from the cortex, thalamus, and brainstem, the VS alone receives a dense projection from the amygdala and hippocampus (Friedman, Aggleton, & Saunders, 2002; Fudge & Haber, 2000; Russchen & Price, 1984). Russchen and Price (1984), for example, found that the striatum was labeled from injections of anterograde tracer into the amygdaloid complex. It has also been demonstrated that the amygdalostriatal interaction is critical for goal-directed behaviors in rodent (Di Ciano & Everitt, 2004; Setlow, Holland, & Gallagher, 2002). In Setlow et al. (2002), rats with contralaterally placed unilateral lesions of basolateral amygdala complex and nucleus accumbens (part of the VS) failed to acquire second-order conditioned responses in an appetitive Pavlovian learning task. Since contralaterally placed unilateral lesions effectively disconnected the amygdala and the VS functionally, this finding demonstrated that these two structures form a functionally connected system critical for processing information concerning learned motivational value. However, given that evidence for the functional interplay between the amygdala and the VS came mainly from non-human animal studies, it is important to demonstrate directly the functional connectivity between the two structures in human decision-making.

In this study, we used fMRI and dynamic causal modeling (DCM) to investigate the patterns of effective connectivities of the amygdalostriatal and the corticostriatal pathways at different stages of decision-making in human. We asked participants to guess whether a blurred photo of female face was attractive and to wait for a few seconds ("anticipation stage") until an unblurred photo of feedback face, which was either attractive or unattractive, was presented ("outcome evaluation stage"; Fig. 1). Attractive faces are rewarding and can drive the neural activation of the brain areas related to reward processing (e.g., the VS and the vmPFC) in the observers (Aharon et al., 2001; Chatterjee, Thomas, Smith, & Aguirre, 2009; Cloutier, Heatherton, Whalen, & Kelley, 2008; Ishai, 2007; Senior, 2003; Winston, O'Doherty, Kilner, Perrett, & Dolan, 2007). Thus, our experimental setup allowed us to disassociate: (1) the neural activations related to anticipation from the those related to the evaluation of feedback faces and (2) the "cognitive" reward (Elliott, Frith, & Dolan, 1997; Poldrack, Prabhakaran, Seger, & Gabrieli, 1999) of feedback (correct vs. wrong in the guessing task) from the intrinsic rewarding value (or biological salience) of the feedback (attractive vs. unattractive faces). Based on existing evidence concerning the functions of the amygdalostriatal and corticostriatal pathways in decision-making, we tested two specific hypotheses: (1) at the anticipation stage, the choice-related anticipatory information would be projected from the amygdala to the VS and (2) at the outcome evaluation stage, the outcome-related information would be projected from the vmPFC to the VS and the strength of this projection would be modulated by the attractiveness of feedback faces.

2. Materials and methods

2.1. Participants

Eighteen undergraduate students (nine female; mean age 21 years, ranging from 18 to 22 years) participated in the experiment. Participants reported no abnormal neurological history, had normal or corrected-to-normal vision, and participants were strongly right-handed. The study was carried out in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Department of Psychology, Peking University.

2.2. Stimuli

One hundred and ninety-two grayscale photos of Asian female faces were selected from the photo pools of Peking University and the Institute of Psychology, Chinese Academy of Sciences, and were rated by twenty participants who did not participate in the scanning. A 7-point scale was used for each rating, with "1" indicating unattractive, "4" indicating not sure and "7" indicating attractive. The 96 attractive faces selected were consistently rated as attractive (with scores more than five) while the 96 unattractive faces selected were consistently rated as unattractive (with scores less than three). Faces met the following criteria: eye gaze forward, head position forward, neutral or mildly positive facial expression, and unfamiliar to the participants. We did not include male faces because participants in the pretest showed large variation in their attractiveness rating for male faces. Stimuli were adjusted to be of approximately equal size and luminance and centered in a 200×200 pixel frame with a dark background.

Another ten faces were Gaussian-blurred with Photoshop™ and were used as uninformative blurred faces for the anticipation stage. The attractiveness rating of these faces was between 3 and 5 on the 7-point scale. Unknown to the participants, the blurred face in each trial was not the same one as the feedback face. The purpose of this manipulation was to exclude the potential

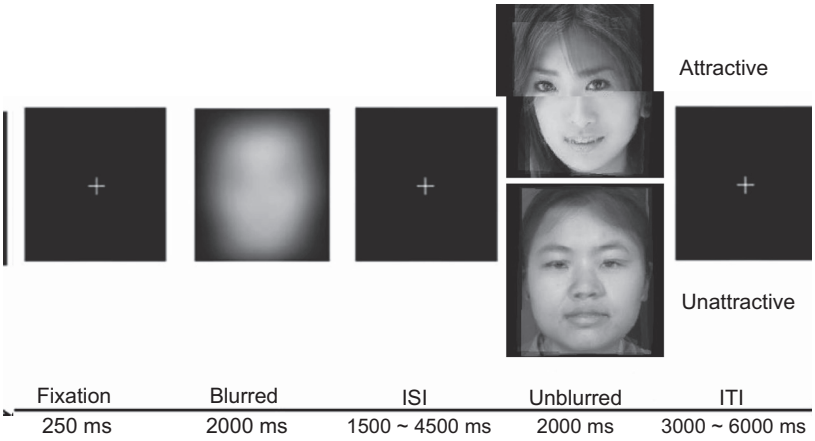

Fig. 1. Sequence of events in a single trial. For purposes of illustration, the attractive and the unattractive faces in the figure were morphed from several faces used in the experiment.

influence of the blurred faces on the perceptual processing of the subsequent feedback faces as well as to make sure that about half of the trials would constitute "correct" trials.

2.3. Procedures

Stimuli were presented at a viewing distance of about 60 cm through an LCD projector onto a rear projection screen located behind the participant's head. Participants viewed the screen through an angled mirror on the head-coil. The task was administered using Presentation software (http://nbs.neuro-bs.com/) to control the presentation and timing of stimuli.

A similar experiment procedure was adopted here as in our previous study (Zhang, Li, Qian, & Zhou, 2012). At the start of each trial, a white fixation cross was presented for 250 ms against a black screen. Next, one of the ten blurred photos was presented for 2000 ms at the center of the screen, during which the participant made a guess as to whether the blurred face was attractive or unattractive by pressing a button with the right index or ring finger. The mapping between responses and fingers was counterbalanced across participants. The participant was told to press the button as soon as possible, and if the response was made after the blurred photo disappeared from the screen this trial was removed from the analysis. After the response, a fixation sign was presented again with a varying duration, ranging from 1500 to 4500 ms. Then an unblurred face was presented for 2000 ms. The participant was asked to watch it but do nothing. The unblurred face served as an (implicit) feedback from which the participant was able to infer whether he had made a right guess. The inter-trial interval (ITI) was jittered between 3000 ms and 6000 ms, during which a fixation cross was presented (Fig. 1).

The experiment was divided into two functional scanning sessions, each containing 96 trials and lasted about 17.2 min. The 96 attractive faces and 96 unattractive faces were randomly and equally presented in each session. The order of feedback was pseudo-randomized so that no more than four attractive or unattractive faces were presented consecutively. Before scanning, participants were familiarized with the task by practicing in a training session for about 20 trials.

2.4. MRI data acquisition

A Siemens 3T Trio scanner with a standard head coil at the Beijing MRI Center for Brain Research was used to obtain T2*-weighted echo-planar images (EPI) with blood oxygenation level-dependent (BOLD) contrast (matrix, 64×64, in-plane resolution, 3×3). Thirty-two transversal slices of 4 mm thickness that covered the whole brain were acquired according to an interleaved order with a 1 mm gap (repetition time = 2000 ms, echo time = 30 ms, field of view = 200×200, and flip angle = 90°).

2.5. fMRI data preprocessing

The obtained fMRI data were preprocessed and analyzed using Statistical Parametric Mapping software SPM8 (Wellcome Trust Department of Cognitive Neurology, London, UK). The first five volumes of each session were discarded to allow stabilization of magnetization. Images were realigned to the sixth volume of the first session for head motion correction. Then the mean EPI image of each participant was computed and spatially normalized to the MNI single subject template using the 'unified segmentation' function in SPM8. This algorithm is based on a probabilistic framework that enables image registration, tissue classification, and bias correction to be combined within the same generative model. The resulting parameters of a discrete cosine transform, which define the deformation field necessary to move individual data into the space of the MNI tissue probability maps, were then combined with the deformation field transforming between the latter and the MNI single subject template. The ensuing deformation was subsequently applied to individual EPI volumes. All images were thus transformed into standard MNI space and re-sampled to $2\text{ mm} \times 2\text{ mm} \times 2\text{ mm}$ voxel size. The data were then smoothed with a Gaussian kernel of 8 mm full-width half-maximum to accommodate inter-subject anatomical variability. Different ways of re-sampling and spatial smoothing do not change the pattern of brain activations. A temporal high-pass filter with a cutoff frequency of 1/128 Hz was used to remove low-frequency drifts in an fMRI time series.

2.6. Basic fMRI data analyses

Statistical analyses based on the general linear model (GLM) were performed first at the participant level and then at the group level. At the participant-level, events for response and outcome delivery were modeled with a delta function convolved with a canonical hemodynamic response function (HRF) (Friston et al., 1998). The first-order temporal derivatives were included (Henson, Price, Rugg, Turner, & Friston, 2002). Six critical regressors were defined: two corresponded to the anticipation phase (guess attractive vs. guess unattractive) and the others corresponded to the four possible combinations of outcome evaluation (attractiveness × congruency). The six rigid body parameters were also included to correct for the head motion artifact. For the group level analysis, we first calculated the simple main effects for each of

the six critical regressors for each participant. The six first-level individual contrast images were then fed into a flexible factorial test across participants in the second-level design matrix.

Contrasts corresponding to anticipation and the outcome evaluation were defined: ''Guess_Attractive > Guess_Unattractive'', ''Attractive_Outcome > Unattractive_Outcome'', ''Congruent_Outcome > Incongruent_Outcome'', and the reversed contrasts of the above ones. Statistical analyses were conducted both at the whole-brain and predefined region of interest (ROI). For the whole-brain analysis, clusters that survived $p < 0.001$ (uncorrected) at peak voxel level and p (FWE) < 0.05 at cluster level were reported (Table 1). A priori ROI activations were tested for significance by using small-volume correction (SVC) within a 10 mm-radius sphere with a peak threshold of p (FWE) < 0.05 and an extent threshold of 100 mm

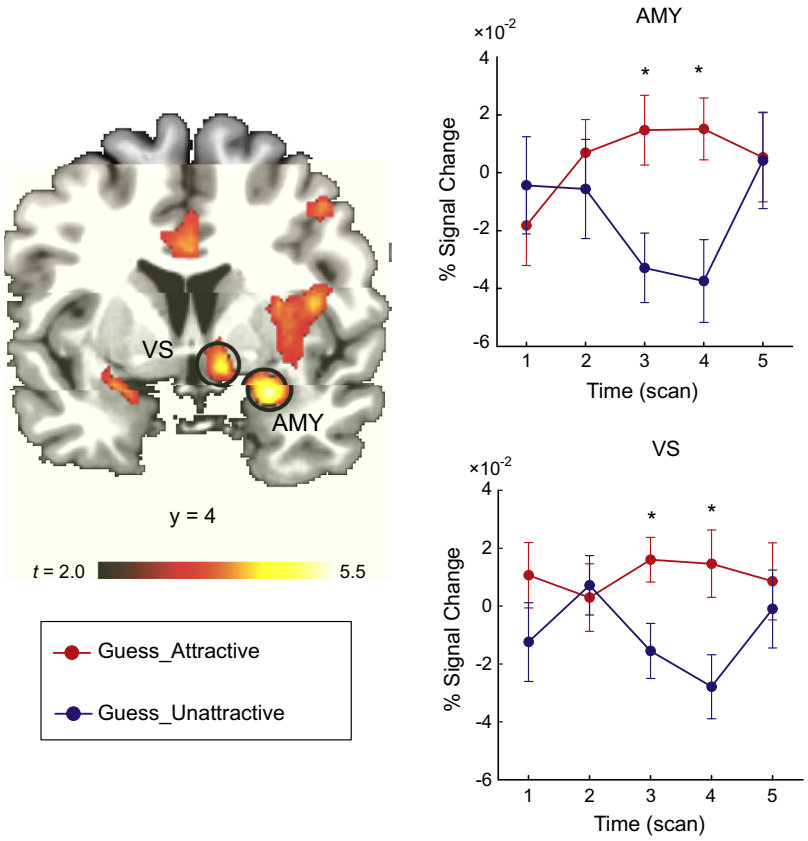

Fig. 2. Brain activation map corresponding to the anticipation stage. The right amygdala and the right ventral striatum (VS) were more activated by anticipation of attractive faces compared with anticipation of unattractive faces (left panel). Percent signal changes in these areas are depicted on the right panel. $^{*}p < 0.05$.

"unattractive" guesses ($M = 82$, $SD = 18$; $t(17) = 3.13$, $p < 0.01$, two tailed). A post-experiment test showed that participants all agreed with the facial attractiveness categorization of the unblurred faces derived from the pretest. At the feedback stage, the distribution of trials for the four conditions was as follows: attractive-congruent, 26.7%, attractive-incongruent, 21.8%, unattractive-congruent, 21.0%, and unattractive-incongruent, 27.7%.

3.2. Neuroimaging results

3.2.1. Neural activations related to anticipation and outcome evaluation

The "Guess_Attractive > Guess_Unattractive" revealed activation in the right amygdala and right VS (Table 1 and Fig. 2). The left amygdala and the left VS activation clusters were also observed at a relatively liberal threshold ($p < 0.001$ uncorrected at peak voxel level and contained more than 100 voxels). The reversed contrast did not reveal any significant clusters.

At the outcome evaluation stage, congruent feedbacks activated the left VS and the left inferior parietal lobule compared with incongruent feedbacks (Table 1 and Fig. 3A and B). The reversed contrast did not reveal anything significant. On the other hand, compared with the unattractive feedback faces, the attractive feedback faces activated bilateral FG and IOG (Fig. 3C). Again, the reversed contrast did not reveal anything significant.

It has been shown that vmPFC is activated for attractive faces, relative to unattractive faces (Cloutier et al., 2008; Winston et al., 2007) and is activated for correct responses, relative to incorrect ones (Elliott et al., 1997). However, this area did not show up in the present, corresponding contrasts, although it did show up for the feedback congruency at a relatively liberal threshold ($p < 0.001$ uncorrected at peak voxel level and contained more than 100 voxels). To examine in detail how this area was activated in response to attractiveness and feedback consistency manipulations, we carried out ROI analysis on a vmPFC region (MNI coordinate: [2,42,−14]), which was determined according to a meta-analysis of the neural processing of facial attractiveness and trustworthiness (Bzdok et al., 2011; see Methods). A significant cluster that survived the ROI threshold was found in the left vmPFC (MNI coordinate: [−6,40,−12], p (FWE) < 0.01 at the peak level with 86 voxels). Repeated measures ANOVA on the beta estimates of this ROI showed a significant interaction between congruency and attractiveness ($F(1,17) = 6.13$, $p < 0.05$), such that congruent attractive faces elicited significantly higher activation than incongruent attractive faces ($t(17) = 3.49$, $p < 0.005$) whereas this differential effect was absent for unattractive faces ($t(17) < 1$, $p > 0.5$; Fig. 3B, right panel).

To confirm the result of this ROI analysis that the main effect of congruency in the vmPFC activation was driven by attractive faces, we defined the contrast "Congruent_Attractive > Incongruent_Attractive" at the whole-brain level. This contrast revealed a cluster within the vmPFC (MNI coordinate: [−4,42,−10]) that passed the whole-brain level statistical threshold.

3.2.2. Functional interplay between amygdala and VS during anticipation

For the anticipation stage, the model family in which the amygdala served as information input (Family A) had an exceedance probability (0.85) far greater than the exceedance probability of the alternative model family (0.15). The estimated DCM parameters of the average model of the winning family A (Fig. 4 and Table 4) highlighted three main findings. First, the input to the amygdala of anticipation of unattractive faces was significantly less than 0 ($t(17) = -2.82$, $p < 0.05$) and also less than the input of anticipation

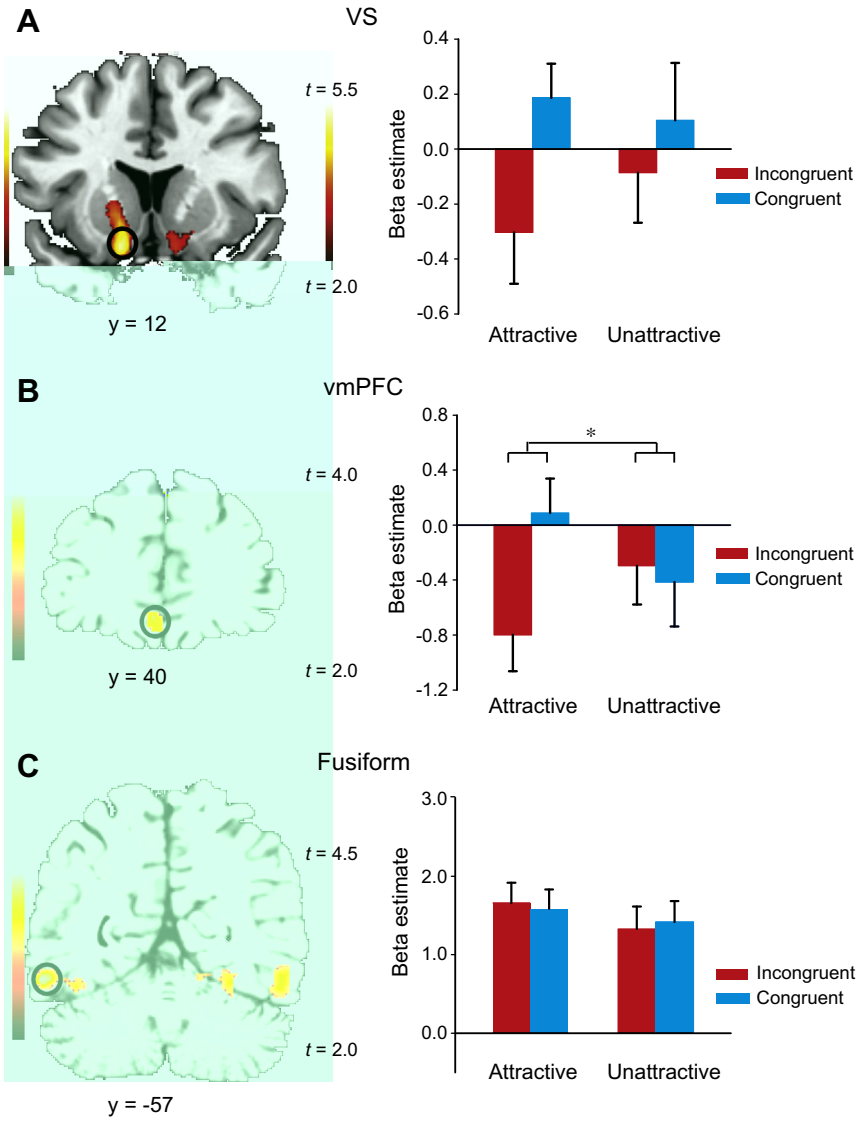

Fig. 3. Brain activation map corresponding to the feedback stage. At the whole-brain level, the attractive feedback faces compared with the unattractive faces activated the bilateral fusiform and occipital areas (A) and the congruent feedback compared with the incongruent feedback activated the bilateral ventral striatum (VS) and the ventral medial prefrontal cortex (vmPFC) (B and C). The parameter estimates extracted from the activation foci (4-mm sphere) were plotted on the right. *: Significant congruency-by-attractiveness interaction at $p < 0.05$. Error bars indicate SEM.

of attractive faces ($t(17) = -2.27$, $p < 0.05$). Second, the intrinsic connectivity from the amygdala to the VS was significantly larger than 0 ($t(17) = 3.01$, $p < 0.01$) and also larger than the intrinsic connectivity from the VS to the amygdala ($t(17) = 3.00$, $p < 0.01$). Third, although the modulatory effects of "Guess_Attractive" (0.11 ± 0.24; $t(17) = 1.91$, $p = 0.07$ uncorrected) and "Guess_Unattractive" (0.03 ± 0.07; $t(17) = 2.07$, $p = 0.05$ uncorrected) on the amygdala-to-VS intrinsic connectivity were marginally significant when tested separately, the combined modulatory effect of these two conditions was significantly larger than zero (0.07 ± 0.14; $t(17) = 2.24$, $p < 0.05$). These results indicated that the choice-related information is first represented in the amygdala and is projected to the vmPFC and that this functional connectivity could be enhanced by the act of choice.

3.3. Functional interplay between VS and vmPFC during outcome evaluation

For the outcome evaluation stage, the model family in which the vmOFC served as information input (Family B) had an exceedance probability (0.98) far greater than the exceedance probability of the alternative model family (0.02). The estimated DCM parameters of the average model of the winning Family B (Fig. 5 and Table 5) highlighted two main findings. (1) There existed bidirectional intrinsic connectivities between the VS and the vmPFC. (2) Unattractive faces reduced the effective connectivity from the VS to the vmPFC (see Table 5).

4. Discussion

In this study, we used fMRI and DCM to investigate the pattern of effective connectivities of the amygdalostriatal and corticostriatal pathways in different stages of decision-making, i.e., anticipation and outcome evaluation. We asked participants to guess whether a blurred photo of female face was attractive (anticipation stage) and then presented them with an unblurred photo of either an attractive or an unattractive face (outcome evaluation stage). We found that at the anticipation stage, anticipating unattractive faces reduced the neural activation in the bilateral amygdala and the VS. Moreover, there existed intrinsic connectivity from the amygdala to the VS and this connectivity could be en-

hanced by the act of choice. At the outcome evaluation stage, the VS and the vmPFC were more activated by outcomes that were congruent with the initial guess as compared with those that were incongruent. This congruency effect was further modulated

Table 2
Model structures for the anticipation stage.

Family	A								B							
Model	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Input																
AMY	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
VS	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Intrinsic																
AMY → VS	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
VS → AMY	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Modulation																
G_A on AMY → VS	1	0	1	0	1	0	0	0	0	0	0	1	1	0	0	0
G_U on AMY → VS	0	1	0	0	0	1	0	1	0	0	0	0	0	0	1	1
G_A on VS → AMY	0	0	0	1	1	0	0	0	1	0	1	0	1	0	0	0
G_U on VS → AMY	0	0	0	0	0	0	1	1	0	1	0	0	0	1	0	1

Notes: G_A = Guess_Attractive, G_U = Guess_Unattractive, AMY = amygdala; 1 = presence, and 0 = absence.

Table 3
Model structures for the outcome evaluation stage.

Family	A																B													
Model	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Input																																
vmPFC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
VS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Intrinsic																																
vmPFC → VS	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
VS → vmPFC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Modulation																																
I_A on VS → vmPFC	1	0	1	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0
I_U on VS → vmPFC	1	0	0	1	1	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	1
C_A on VS → vmPFC	0	1	1	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1	0
C_U on VS → vmPFC	0	1	0	1	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	1	0	1
I_A on vmPFC → VS	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	0	0	0	0	0	1	0	1	0	1	0	1	0
I_U on vmPFC → VS	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	1	1	0	0	1	0	0	0	0	1	0	0	1	1	0	0	1
C_A on vmPFC → VS	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	1	1	0	0	1	1	0
C_A on vmPFC → VS	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	0	0	0	0	0	1	0	1	0	1	0	1

Notes: C_A = Congruent_Attractive, C_U = Congruent_Unattractive, I_A = Incongruent_Attractive, I_U = Incongruent_Unattractive; 1 = presence, and 0 = absence.

amygdala decreases the activity in the VS through the unidirectional projection. Given the amygdala's role in signaling biological salience (Liberzon, Phan, Decker, & Taylor, 2003; Shabel & Janak, 2009), it is conceivable that the amygdala activation during anticipation encodes the salience of the potential outcomes. This suggestion is in line with evidence from animal studies, which suggests the importance of the integrity of the amygdala-VS network in processing information of motivational value (Di Ciano & Everitt, 2004; Setlow et al., 2002). It is also consistent with human fMRI studies implicating amygdala in gating the prediction error signal in the VS during associative learning (e.g., Li et al., 2011). Thus, our finding provides the first direct evidence for the effective connectivity between the human amygdala and the VS in anticipation of reward.

Table 4
Model parameters estimated based on model Family A (amygdalostriatal).

Parameter	Mean ± SD (Hz)
Intrinsic connectivity	
AMY → VS	0.11 ± 0.15**
VS → AMY	0.02 ± 0.06
Modulation (on AMY → VS)	
Guess_Attractive	0.11 ± 0.24
Guess _Unattractive	0.03 ± 0.07
Driving input	
Guess_Attractive	0.02 ± 0.17
Guess_Unattractive	−0.11 ± 0.16**

Notes: AMY = amygdala. Corrected for multiple comparison following Bonferroni's procedure.
** $p < 0.05$.

4.2. The outcome evaluation-related signal in the VS and the vmPFC

In the outcome evaluation stage, the outcomes that were congruent with participants' initial guesses (i.e., indicating correct decisions) elicited higher activation in the vmPFC and the VS as compared with the incongruent ones. This finding seems to contradict previous evidence that the VS responds more strongly to prediction errors (e.g., Abler, Walter, Erk, Kammerer, & Spitzer, 2006; Hare et al., 2008). However, this discrepancy is likely due to the differences in task requirement and the material used. In those previous studies (e.g., Abler et al., 2006; Hare et al., 2008), the participants were asked to perform monetary gambling or investment tasks, where feedback explicitly indicated monetary gain or loss to the participants. In contrast, in our study, the feedback only implicitly informed the participants of the correctness of their initial guess. Importantly, the participants were explicitly told that the correctness of their responses had nothing to do with their monetary payoff. Indeed, our finding is in line with several other studies in which no monetary incentive was at stake (Elliott et al., 1997; Poldrack et al., 1999; Schnider, Treyer, & Buck,

Table 5
Model parameters estimated based on model Family B (corticostriatal).

Parameter	Mean ± SD (Hz)
Intrinsic connectivity	
VS → vmOFC	0.10 ± 0.15**
vmOFC → VS	0.30 ± 0.25***
Modulation (on VS → vmOFC)	
Congruent_Attractive	−0.02 ± 0.04
Incongruent_Attractive	−0.01 ± 0.10
Attractive	−0.01 ± 0.07
Congruent_Unattractive	−0.02 ± 0.05
Incongruent_Unattractive	−0.03 ± 0.05
Unattractive	−0.03 ± 0.04**
Driving input	
Incongruent_Attractive	−0.23 ± 0.40*
Incongruent_Unattractive	−0.07 ± 0.33
Congruent_Attractive	0.04 ± 0.29
Congruent_Unattractive	0.03 ± 0.36

Corrected for multiple comparison following Bonferroni's procedure.
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

2005). These studies suggested that the knowledge of "success" in doing something is itself rewarding and can drive the activity in the VS. Taken together, we may argue that whether positive feedbacks, as compared with negative feedbacks, can elicit stronger activity in the VS is highly context-dependent.

The vmPFC is consistently implicated in encoding reward magnitude rather than prediction error (Hare et al., 2008). Our finding that the vmPFC was more activated by congruent as compared with incongruent outcomes is in line with the previous studies using similar tasks (Elliott et al., 1997; Poldrack et al., 1999; Schnider et al., 2005) and confirms our suggestion that the knowledge of having made a correct response, relative to the knowledge of making a mistake, is of higher subjective value to the participants in the present setup. We did not observe a main effect of attractiveness in the vmPFC, inconsistent with some previous studies (Cloutier et al., 2008; Ishai, 2007; Winston et al., 2007). However, these studies also highlighted the flexibility of vmPFC in encoding subjective value: while attractive female faces, as compared with unattractive female faces, activated the vmPFC of male or homosexual female observers, such differential effect was absent for female or homosexual male observers (Cloutier et al., 2008; Ishai, 2007; Winston et al., 2007). In our study, while both male and female participants were recruited, only female faces were presented as stimuli. Therefore, at the group level, the main effect of attractiveness for the male and for the female participants could have been canceled out. On the other hand, the feedback congruency, as a function of the attractiveness of the presented faces, did not differ between male and female participants, and thus the effect of congruency showed up in the vmPFC at the group level.

4.3. The effective connectivity between the vmPFC and the VS at the evaluation stage

Confirming our hypothesis, we found that the outcome information entered the reward processing network through the vmPFC. The vmPFC receives inputs from sensory cortices (Bar, 2009) and calculates the reward values (Kringelbach, 2005; Schoenbaum et al., 2009). The intrinsic connectivity from the vmPFC to the VS, which is supported by anatomical evidence (Haber, Fudge, & McFarland, 2000), may reflect the dynamic process by which visual, and perhaps aesthetic (Winston et al., 2007), properties of the feedback faces were conveyed to the VS. In the VS, the valence of the feedback faces (attractive vs. unattractive) was compared with expectation or initial guess, by which the congruency-related signal was generated (Schultz, 1998). This congruency-related information may be projected back to the vmPFC, perhaps via the mediation of the thalamus (Haber & Knutson, 2010), to update the hedonic responses or experienced value of the outcomes.

We further found that this back projection was reduced by unattractive faces, suggesting a modulatory effect of outcome salience on the transmission of congruency-related information from the VS to the vmPFC. The scheme we sketched above was in accordance with a recently proposed theory concerning the circuits for reward processing (Der-Avakian & Markou, 2012) and it echoes an intracranial EEG study of the functional interaction between the VS and the medial frontal cortex in reward processing (Cohen et al., 2009; also see Cohen, Heller, & Ranganath, 2005). The authors recorded electrophysiological activity directly from the NAcc from 5 patients undergoing deep brain stimulation and asked them to perform a reward-learning task in which they first learned stimulus-outcome associations, and then chose from among the learned stimuli to win as much monetary incentive as possible. They observed a dynamic relationship between the medial frontal cortex and the NAcc: the medial frontal cortex activity initially preceded the NAcc activity in time, but then the NAcc activity became preceding the medial frontal cortex activity (Cohen et al., 2009). This pattern of serial activation is consistent with our suggestion of the bidirectional effective connectivities between the VS and the vmPFC.

To conclude, our analyses of effective connectivity fit into a larger picture of the functions of the VS in decision-making and goal-directed behaviors, which proposes that the VS serves as an interface between value and action, integrating reinforcement signals to bias reward-seeking behavior (Haber & Knutson, 2010; Sesack & Grace, 2010). Specifically, at the anticipation stage, the VS receives choice-related anticipatory, salience-related information (Knutson & Greer, 2008) from the amygdala and adjusts its own activity according to such information. At the outcome evaluation stage, the VS receives feedback-related information from the vmPFC and compares it with expectation. This congruency-related information may be projected back to the vmPFC (Haber & Knutson, 2010) to update the hedonic responses or experienced value of the outcome. Moreover, the strength of this connectivity is modulated by the salience of the outcome. This study extended previous understanding of the functions of the reward circuitry by demonstrating the pattern of information flow along the amygdalostriatal and corticostriatal pathways at different stages of decision-making.

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