RESEARCH ARTICLE

WILEY

Role of anterior midcingulate cortex in self-reward representation and reward allocation judgments within social context

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Abstract

Evaluating rewards for the self and others is essential for social interactions. Previous research has probed the neural substrates signaling rewards in social decision-making tasks as well as the differentiation between self- and other-reward representations. However, studies with different designs have yielded mixed results. After analyzing and comparing previous designs, we differentiated three components in this study: task (reward representation vs. social judgment of reward allocation), agency (self vs. other), and social context (without vs. within). Participants were asked to imagine various share sizes as a proposer in a dictator game during fMRI, and then rated their willingness and preference for these offers in a post-scan behavioral task. To differentiate the regions involved in processing rewards without and within context, we presented the reward to each agent in two sequential frames. Parametric analyses showed that, in the second frame (i.e., within social context), the anterior midcingulate cortex (aMCC) signaled self-reward and preferences for the offer, whereas the right insula tracked the likelihood of proposing the offer. Belief in a just world is positively associated with aMCC responses to self-reward. These results shed light on the role of the aMCC in coding self-reward within the social context to guide social behaviors.

KEYWORDS
anterior cingulate cortex (ACC), anterior midcingulate cortex (aMCC), belief in a just world, dictator game, right insula (rINS), self-reward, social context

1 | INTRODUCTION

Estimating the cost and benefit for self and others is crucial during social decision-making; however, the underlying neural substrates have not been thoroughly explored. Several recent studies have investigated brain activation in reward-based social decision-making (Chen et al., 2017; Moll et al., 2006; Waytz, Zaki, & Mitchell, 2012; Zaki & Mitchell, 2011). Furthermore, dissociable self- and other-reward representations have been investigated in various studies. (Apps, Green, & Ramnani, 2013; Apps & Ramnani, 2014; Apps, Rushworth, & Chang, 2016; Behrens, Hunt, & Rushworth, 2009; Chang, Gariépy, & Platt, 2013; Enzi, De Greck, Proesch, Tempelmann, & Northoff, 2009; Kennerley, Behrens, & Wallis, 2011; Kennerley & Wallis, 2009; Lockwood et al., 2018; Lockwood, Apps, Roiser, & Viding, 2015;

Moran, Macrae, Heatherton, Wyland, & Kelley, 2006). However, empirical findings of the neural signals involved in reward-based social decision-making, and processing of self-reward or other-reward, specifically, from the anterior midcingulate cortex (aMCC) and medial prefrontal cortex (mPFC), have been inconclusive. The present study aimed to examine how the brain represents reward for self and others and its association with reward allocation decisions by dissecting the decision-making process using functional magnetic resonance imaging (fMRI).

It is noteworthy that there are various nomenclatures for the sub-regions of the cingulate cortex. An increasing number of cytoarchitectural studies have proposed a four-region model of the cingulate cortex including the anterior cingulate cortex (ACC), MCC, posterior cingulate cortex (PCC), and retrosplenial cortex (RSC) (Vogt, 2005, 2016). Specifically, the ACC includes two subdivisions: the subgenual ACC (sACC) and the pregenual ACC (pACC). Moreover, the ventral aMCC (vaMCC) includes the cingulate gyrus area a24a′, a24b′, and callosal sulcus area a33′, whereas the dorsal aMCC (daMCC) is located between the paracingulate sulcus and the cingulate gyrus, and is comprised of area 32′ and a24c′. For coherence, we used the terminology proposed by Vogt throughout this article.

Several reward-related brain regions have been implicated in studies on social decision-making, with varying results, and the roles played by these regions in social interaction remain ambiguous. Abundant evidence has shown that the dorsal medial prefrontal cortex (dmPFC) (Waytz et al., 2012), ventral medial prefrontal cortex (vmPFC) (Zaki & Mitchell, 2011), and striatum (Moll et al., 2006) are involved in making altruistic decisions. In contrast, the vmPFC, dmPFC, vaMCC, daMCC, and nucleus accumbens (NAcc) have been reported to be more active while making selfish offers than making fair offers (Chen et al., 2017). It is intriguing that overlapping brain regions were elicited by making drastically different decisions (altruistic vs. selfish). This has been interpreted such that the higher activation in the vaMCC and daMCC, the greater the contemplation of rewards for the other and oneself, respectively, when choosing a slightly selfish offer over a fair offer (Apps et al., 2016; Lockwood et al., 2015).

However, the underlying processes may not only involve reward representation for each player but also other factors during social interaction, such as prosocial intention or strategic motives (Chen et al., 2017; Zaki & Mitchell, 2011). Therefore, to achieve a clearer understanding of the roles of these brain activations, it is important to investigate the neural activities in the aMCC, mPFC, and NAcc during reward-based social decision-making.

The aforementioned regions respond to reward-based social decisions and have been found to be differentially involved with self- and other-reward representations in a complicated manner. A majority of the previous studies have revealed that the vaMCC is associated with processing information about rewards for others, but some contradictory reports exist (Apps et al., 2013; Apps et al., 2016; Apps & Ramnani, 2014; Behrens et al., 2009; Chang et al., 2013; Enzi et al., 2009; Lockwood et al., 2015, 2018). Recent neuroimaging studies on humans have indicated the involvement of vaMCC in

monitoring the outcomes of others' choices or outcomes of choices that will be experienced by others (Apps et al., 2013; Apps et al., 2016; Apps & Ramnani, 2014; Behrens et al., 2009; Lockwood et al., 2015, 2018). In contrast, Chang et al. (2013), using a passively viewing reward allocation task with a single-neuron record method, found that a subgroup of neurons in vaMCC was engaged in tracking self-reward in rhesus macaques. Similarly, Enzi et al. (2009) reported the role of vaMCC in processing self-reward. In addition, there is still another evidence which showed that the vaMCC contained another subgroup of neurons that engaged in tracking both self- and other-reward (Chang et al., 2013). Taken together, whether or how vaMCC is involved in tracking self-, other-, or both rewards remains unclear.

Previous studies have found inconsistent findings regarding the role of vaMCC in reward processing possibly because it activates differentially according to different experimental designs. By examining said experimental designs, we suggest that the context of reward representation may be the reason for the seemingly contradictory findings. Studies revealing that the vaMCC is involved with self-reward representation seem to provide information that gives participants the relative value of a self-reward. For example, in Chang et al.'s (2013) study, the reward was designed to give juice to self, other, or neither, in a mutually exclusive manner. In Enzi et al.'s (2009) study, participants were shown the accumulated total reward after they received a reward. The accumulated total amount serves as a context, providing a sense of the relative value of the current reward.

In contrast, information providing a sense of the relative value of the reward seemed not to be included in studies which revealed that the vaMCC is involved with rewarding others, but not self-reward. For example, in the Apps and Ramnani (2014) study, participants had to remember how many presses are needed to acquire a reward when a certain cue is presented; further, they are required to press the correct number of times in a first-person trial (self-reward) and judge whether the confederate can receive rewards in a third person trial (other-reward). It is noteworthy that in this design, participants were required to press the correct number of times, rather than as much as possible. Therefore, the reward earned is based on a rule, but not to the amount of effort. Hence, we suggest that this design does not involve a relative meaning of the reward. Similarly, in the study by Lockwood et al. (2015), participants were required to judge the expectation of receiving a reward under a given probability, and the self and other trials were independently separated. In this design, the context of reward was the probability for a single person and did not involve any social meaning.

In summary, we suggest that vaMCC may be involved with both self-reward and its context, providing a sense of the relative value of the reward (such as reward for another person or accumulated amount), and solely self/other contrast would not be enough to examine the process. A design that examines self- and other-reward and context for both separately would be helpful.

The findings regarding daMCC in terms of processing self- and other-rewards are also unclear. The daMCC was found to be involved in processing self-referential information and signaling the net value of rewards to be received by oneself (Kennerley et al., 2011;

Kennerley & Wallis, 2009). In contrast, Chang et al. (2013) revealed that the neurons in the daMCC responded more strongly to other-reward and foregone reward, in which neither the participants themselves nor others received the reward, than it did to self-reward. Similar to our analysis of vaMCC studies, Kennerley and Wallis (2009) and Kennerley et al. (2011) found that the amount of self-reward is associated with the probability and correct number of lever press, and thus were not involved with a context providing relative value of self-reward. In contrast, in Chang et al. (2013), the self- and other-rewards were mutually exclusive; hence, the relative meaning of both rewards was provided.

The dmPFC and vmPFC have also been found to be involved in processing reward for self or other. While the findings regarding the role of the dmPFC are similar across publications, the functions of the vmPFC are inconsistent. The dmPFC has been indicated to represent other-regarding values (Sul et al., 2015) and making other-related judgments (Denny, Kober, Wager, & Ochsner, 2012). On the other hand, some evidence suggests that the vmPFC is linked to the processing of self-related information (Campbell-Meiklejohn, Simonsen, Frith, & Daw, 2017; Chang et al., 2013; Kim & Johnson, 2014), making self-related judgments (Denny et al., 2012), and value representation of rewards for self (Knutson, Taylor, Kaufman, Peterson, & Glover, 2005; Rushworth, Behrens, Rudebeck, & Walton, 2007; Sul et al., 2015). Nevertheless, Suzuki et al. (2012) reported that the vmPFC was associated with simulated reward for both the self and others (Suzuki et al., 2012). It is noteworthy that in previous studies contexts providing a relative meaning of how much self-reward/choice value is given, such as previous value, accumulated reward, or real objects that have a certain range of prices in the real world (e.g., Kennerley et al., 2011; Kim & Johnson, 2014; Knutson et al., 2005). Hence, the literature on self-rewards *without* such context is sparse.

Finally, there is a consensus that the NAcc is involved in reward anticipation for the self (Kable & Glimcher, 2009; Knutson et al., 2005; Rutledge, Dean, Caplin, & Glimcher, 2010). However, previous studies have not examined the NAcc responses to self-reward when another individual is taken into consideration.

The main purpose of the present study is to re-examine the relevant neural activities by dissecting the experimental design into separate stages. We developed our experimental paradigm by modifying the tasks of Chen et al. (2017) and Lockwood et al. (2015). First, we adopted the dictator game (DG) as the framework in our study. In the DG, a proposer decides how to divide a stake between themselves and a recipient, who can only accept the proposal (Thaler, 1988).

We chose DG instead of the ultimatum game (UG), used by Chen et al. (2017), because proposing behaviors in DG may be less complicated as the potential confound caused by fear of rejection was eliminated. We manipulated the amount of money available to each agent systematically in the DG in both fMRI and post-scan behavioral tasks, which enabled us to examine the brain regions that were associated with the magnitude of reward for the participants themselves and others, the likelihood of proposing the offer, and preference for the proposal separately. In the fMRI task, we asked participants, as a

proposer in DG, to imagine different situations on the screen in order to examine the neural substrates of self- and other-reward representations.

Without making a decision in this stage, we were able to examine purely reward representation that is needed to make a social decision. Notably, we modified the reward task in Lockwood et al. (2015) and presented each reward (to oneself/other) at different time frames. This modification allowed us to examine the neural correlates of the self/other reward without any context (in the first frame) and the self/other value with knowing how much the other person received (in the second frame). Thus, in the second frame, reward processing is in a social context that provides the meaning of the current reward, that is, more or less or equal to the reward of the counterpart presented in the first frame. Therefore, all of the information needed for making reward allocation judgments has already been presented. Hence, participants *could* make these social judgments if they were asked. This manipulation allowed us to further link brain activation and later social judgments. In the post-scan behavioral task, we presented the same stimuli again and asked the participants to rate their likelihood of making proposals and their preferences for the proposals. Thus, the task is not to make a decision; instead, it is to make judgments about a social decision.

In summary, we performed three important modifications to disentangle multiple processes. First, by separating the task of reward processing from that of social judgment (indicating likelihood and preferences toward the proposals), we were able to examine the neural underpinnings of rewards for oneself and others without the potential confounds caused by complex decision processes.

Second, by presenting share sizes in two separate frames, we were able to dissociate self- and other-reward processing into processing without and within a social context (i.e., how much the other person received).

Third, we asked participants to rate their willingness and preference for the proposal using a continual scale rather than to make a binary decision. A continual rating can prompt a deliberate evaluation process and avoid the process being overridden by dominant factors or strategies specific to a final binary decision. These ratings were input as parametric modulators in the fMRI analyses to inspect whether reward-related regions could track the likelihood of making proposals and preferences for proposals while viewing rewards for oneself or others (before they were asked to make a judgment or decision) because they already received full information in the DG in the scanner. Specifically, we investigated how neural signals respond to (1) reward cues of self and others at different time frames, and (2) likelihood and preference toward the proposal in the DG.

Based on the literature reviewed, we hypothesized that the NAcc would be engaged in processing self-reward, whereas the dmPFC would be involved in processing other-reward. Moreover, we explore new possibilities of neural activities in the vaMCC, daMCC, and vmPFC in response to self-reward or other-reward without or within context, which provide a relative meaning of how much the reward is. We also predicted that the aMCC, mPFC, and NAcc would play important roles in social judgment tasks. Hence, we were interested in

how neural signals in these regions vary with the likelihood and preference of proposals in the modified DG.

Some subjective attitudes about rewards and social relations might also be involved in the process of tracking rewards and social judgment upon reward allocation. Thus, this study incorporated questionnaires to assess individual dispositions from three aspects: self-benefit, altruism (other-benefit), and social context (reward distribution context). First, the behavioral approach system or the behavioral activation system (BAS) regulates appetitive motives, driving individuals to pursue their desires (Carver & White, 1994). Previous studies indicated that individuals with higher BAS sensitivity are more aroused, have greater activation in the striatum facing reward cues, and focus more on rewarded behaviors (Avila, 2001; Costumero et al., 2013; Patterson, Kosson, & Newman, 1987).

Second, benevolence is defined by actively taking actions to help others, in contrast to the passive state of empathy (Sonne & Gash, 2018). The trait benevolence is positively associated with individuals' prosocial disposition, charitable behaviors, and the representation of rewards and values, which are associated with brain activation in the NAcc, aMCC, and mPFC (Clithero & Rangel, 2014; Hubbard, Harbaugh, Srivastava, Degras, & Mayr, 2016; Kable & Glimcher, 2007; Levy & Glimcher, 2012). Third, the just-world hypothesis suggests that individuals need to represent the world as a just and orderly place where people generally get what they deserve and they deserve what they get (Lerner & Miller, 1978). Belief in a just world (BJW) is applicable to both self (personal-BJW) and others (general-BJW). Although several studies have investigated how these two BJWs influence helping propensity (Li, Lu, Wang, Zhu, & Zhang, 2018) and social goals (Sutton, Stoeber, & Kamble, 2017), the neural underpinnings remain obscure.

As BAS, benevolence, and BJW are all closely related to information processing of rewards for self or others, we incorporated scales accordingly to measure individual differences in these personal dispositions. Thereafter, we examined the extent to which they vary with the neural responses to reward processing and social judgments on reward allocation. We expected that neural signals of self-reward and other-reward would have positive correlations with BAS scores and the level of benevolence, respectively. Moreover, we inspected the association between neural activities of brain regions involved in self-reward, other-reward, and BJW.

2 | MATERIALS AND METHODS

2.1 | Participants

Forty-three native Mandarin speakers (21 females and 22 males, mean age = 21.72 ± 1.44) were recruited from National Chengchi University. All participants were right-handed. They had normal or corrected-to-normal vision and no history of neurological or psychiatric disorders or contraindications to MRI. They had no background in economics or related subjects (non-major and non-minor) and had not participated in experiments on game theory. All participants provided written informed consent for the study, which was approved by the Research Ethics Committee of the National Chengchi University before its initiation. The participants received NT$ 700 (around US$ 23.33) for their participation and bonuses from a randomly selected trial.

2.2 | Experimental design and stimuli

Participants were asked to imagine proposing different offers to the next participant in the DG while inside the scanner (Figure 1). The mean stake size was NT$ 300 (around US$ 10), ranging from NT$ 228 to NT$ 372 (around US$ 7.6–US$ 12.4). For the fMRI task, we manipulated two independent variables: agency (self vs. other) and share size. There were five types of share sizes: 10, 30, 50, 70, or 90% of the stake. Each share size condition comprised 24 stimuli, resulting in a total of 120 stimuli. The stimuli were repeated twice during the scanning (session 1). Half of the trials showed the amount of money for oneself in the first frame and the amount of money for others in the second frame, while the other half presented the amounts in the reverse order. At the end of each trial, the participants were tested on whether or not they paid attention to the stimuli. The contents of the questions were composed of four possible combinations: agency (self/other) × amount of money (mine/others) of that trial. Accurate responses were answering "yes" to trials with matching agency and amount of money and "no" to trials with mismatching agency and amount of money. Consequently, 240 trials were divided into four blocks for the fMRI experiment. The order of trials within each block was randomized.

After scanning, all 120 stimuli were presented again in a four-block behavioral task (session 2). There was only one independent variable, that is, share size, in the behavioral task. The stimuli included the stake (on the top), the amount of money for oneself, and the other participant (at the bottom left and right) in a single frame. The positions (left/right) of the amount of money for oneself and the other participant were counterbalanced between participants. The two questions posed were "Would you make this proposal?" and "Do you like the way the money was divided in this proposal?"

2.3 | Procedure

Before scanning, the DG was explained to the participants. Participants were informed that they were assigned to be a proposer, and the next participant in this study would be their recipient. To motivate participants to pay attention to the stimuli, we also informed them that they would receive a bonus from one randomly selected trial from the fMRI task if their answer to that trial was accurate. The participants underwent five trial rounds and sought clarification before the experiment.

During scanning, participants performed trials that began in a jittered fixation for 1,000–2000 ms, followed by the stimuli presenting the amount of money for the other participant or the
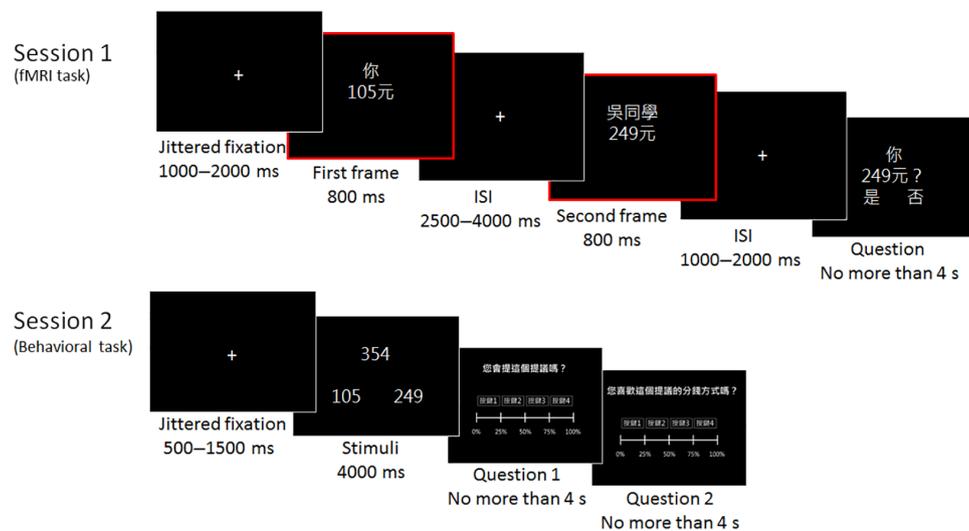
FIGURE 1 Experimental procedure of the functional magnetic resonance imaging (fMRI) task and the behavioral task. In session 1, participants in a scanner adopted the role of proposer in the dictator game and imagined different offers presented on the screen. Each trial began in a jittered fixation followed by two frames indicating the agent and the corresponding amount of money (self = "you" with NT$ 105, that is, US$ 3.5, and other = "schoolmate Wu" with NT$ 249, that is, US$8.3, in this example). Half of the trials showed first the amount of money for self, while the other half showed first the amount of money for the other participant. At the end of each trial, a question appeared checking whether the participants had paid attention to the stimuli. Participants had 4 s to answer whether the amount of money corresponded to the agent or not. Participants were informed that they would receive a bonus from a randomly selected trial if their answer was accurate. In session 2, participants performed a behavioral task. After a jittered fixation, the screen showed the stake and the amount of money for the two players for 4 s (e.g., NT$ 105 for self and NT$ 249 for other). The position of the amount of money was counterbalanced between participants. Next, the participants had to answer two questions, each within 4 s: "Would you make this proposal?" and "Do you like the way the money was divided in this proposal?" Participants were instructed to press any of the four buttons (marked as 1–4) to indicate the extent of their willingness and preference as a percentage: 0–25%, 25–50%, 50–75%, and 75–100%. Abbreviation: ISI, interstimulus interval

participant himself/herself for 800 ms (Figure 1). Then, a jittered interstimulus interval (ISI) appeared for 2,500–4,000 ms before the second frame, which displayed the amount of money for the participant himself/herself or the other participant for 800 ms. Then, there was another jittered ISI for 1,000–2000 ms. At the end of each trial, the participants had no more than 4 s to answer the questions by pressing either of the buttons numbered 1 or 2 corresponding to "yes" or "no," respectively.

After scanning, the participants performed a behavioral task. In each trial, participants were presented with a fixation cross for 500–1,500 ms, and then a stake with a proposal for 4,000 ms. Participants had to answer the following two questions each within 4 s: "Would you make this proposal?" and "Do you like the way the money was divided in this proposal?" Participants indicated the extent of their willingness and preference in percentage, that is, 0–25%, 25–50%, 50–75%, and 75–100%, by pressing one of four corresponding buttons (numbered 1, 2, 3, and 4, respectively). The responses and reaction times (RT) of each participant were recorded.

The mean accuracy was 95.85 ± 4.01% in the fMRI task, suggesting that participants paid attention to most of the stimuli and were apprehensive of the amount of money for themselves/others in each trial. One of the 43 participants did not respond accurately to the selected trial and did not receive a bonus. The mean amount of bonus was NT$ 141.54 ± 91.71 (around US$ 4.72 ± 3.06).

2.4 | Questionnaires for measures

After performing the behavioral task, participants completed the following questionnaires: Behavioral Inhibition System (BIS)/BAS (Carver & White, 1994), benevolence measure from the extended 16-personality-adjective (16PA) scales (Brandstatter, 1988), and belief in a just world questionnaire (Dalbert, 1999).

The BIS is activated by conditioned stimuli, signaling punishment, and non-reward, and is associated with avoidance behavior. On the other hand, the BAS is activated by conditioned stimuli signaling reward and non-punishment and is associated with approach behavior (Gray, 1981, 1987; Pickering & Gray, 1999). The three subscales comprising the BAS are as follows: reward responsiveness, for example, "When I get something I want, I feel excited and energized."; drive, for example, "I go out of my way to get things I want."; and fun-seeking, for example, "I'm always willing to try something new if I think it will be fun." Items were rated on a four-point scale from "very true for me" to "very false for me" The BIS/BAS scale has good reliability and construct validity (Che et al., 2020).

Following the same approach used by Brandstatter and Güth (2002), level benevolence was measured using the following items of the extended 16 PA questionnaire: not sociable–sociable, tough-minded–tender-minded, insensitive–sensitive, cold–warm, inconsiderate–considerate, unemotional–emotional, and not benevolent–benevolent. Items were rated on a nine-point scale. The

benevolence scale has good internal consistency (Brandstatter & Güth, 2002).

The belief in a just world questionnaire measures the extent to which participants believed that people generally get what they deserve in a just world (Dalbert, 1999; Lerner, 1965). This belief enables people to confront the world in a stable and orderly manner (Lerner & Miller, 1978). The questionnaire comprises two subscales: belief in a just world for self, for example, "I believe that, by and large, I deserve what happens to me."; and belief in a just world for others, for example, "I believe that the world is a just place." Belief in a just world scale has good reliability and validity (Begue & Bastounis, 2003).

2.5 | Statistical analysis of behavioral data

Nine participants were excluded from both the behavioral and imaging analyses; eight participants were excluded due to excessive head motion (i.e., overall motion <5 mm across the runs and motion between adjacent functional volumes <2.5 mm) and one due to incomplete responses to the questionnaires.

IBM SPSS (version 21.0; IBM Corp., Armonk, NY, USA) was used for behavioral analysis, with the α value set at 0.05. The responses and RT of the behavioral task were analyzed using a one-way (5 share size) repeated-measures analysis of variance. The Greenhouse–Geisser correction was employed in situations where sphericity was violated. To correct for multiple comparisons, Bonferroni correction was adopted.

2.6 | Functional neuroimaging data collection and analysis

2.6.1 | Data acquisition

MRI images were collected using a 64-channel head coil in a 3 T scanner (Skyra, Siemens Medical Solutions, Erlangen, Germany). A T2*-weighted gradient-echo planar imaging sequence was used in an interleaved manner, with a voxel size of $3 \times 3 \times 3$ mm^3, 81° flip angle, 42 slices, 2,500 ms repetition time (TR), and 32 ms echo time (TE). Anatomical, T1-weighted high-resolution images ($1 \times 1 \times 1$ mm^3) were acquired using a standard magnetization-prepared rapid gradient-echo sequence, with a 7° flip angle, 2,530 ms TR, 3.3 ms TE, and 1,100 ms inversion time.

2.6.2 | Image processing

Preprocessing and statistical analysis of brain images were performed using the Statistical Parametric Mapping 12 (SPM12; Wellcome Trust Center for Neuroimaging, London, UK) software package. The functional image of each participant was corrected for slice timing and head motion, and then co-registered to the participant's segmented gray matter image. Thereafter, the images were normalized to the standard Montreal Neurological Institute (MNI) standard space and spatially smoothed by convolution using an 8 mm full-width at half-maximum Gaussian kernel.

2.6.3 | Data analysis

Three general linear models were created at the first level, and a parametric approach was used. Four event types (first-self, first-other, second-self, and second-other) were used to construct regressors in which event onsets were convolved with the SPM's canonical hemodynamic response function in each block. These events were modeled with 0.8 s duration for trials where participants answered accurately. Each of these regressors was associated with parametric modulators indicating the amount of money for the agent (Model 1), the likelihood of making the proposal (Model 2), or preference for the proposal (Model 3). The onsets of the questions and responses were also modeled in two regressors across all event types. An additional eleventh regressor may be added to model missing/mistake trials in which the participants did not respond in 4 s or did not answer accurately in some blocks according to participants' performance. Six head motion parameters modeled the residual effects of head motion as covariates of no interest.

Contrast images included the parametric modulator for self and the parametric modulator for the other at the time of the first frame, as well as the second frame. These contrast images were input into a second-level one-sample t-test to examine the regions that parametrically tracked the parametric modulators. The threshold of the statistical maps was at a whole-brain voxel-wise intensity of $p < .001$, with false discovery rate (FDR) correction. The resulting regions of activation were reported in terms of peak voxels in the MNI coordinate space.

2.6.4 | Region of interest analysis

We selected the aMCC, mPFC, and NAcc as *a priori* regions of interest (ROIs) based on previous studies that linked responses in these regions to self-reward and other-reward (Apps & Ramnani, 2014; Enzi et al., 2009; Knutson et al., 2005; Lockwood et al., 2018; Moran et al., 2006). We built spheres with a radius of 5 mm centered at the coordinates of the vaMCC ([4, 24, 24] Enzi et al., 2009), daMCC ([−3, 19, 38] Moran et al., 2006), mPFC ([−3, 47, 0] Moran et al., 2006), and NAcc ([−11, 11, −4] and [12, 14, −4] Knutson et al., 2005) based on literature evidence using the MarsBaR 0.44 (Brett, Anton, Valabregue, & Poline, 2002). Greater neural activity in these regions was correlated with behavioral indices using bivariate correlations. The α value was set at 0.007 using Bonferroni correction (i.e., $0.05/7 \approx 0.007$) to correct for multiple comparisons (seven subscales).

3 | RESULTS

3.1 | Behavioral results

The responses and RTs in the behavioral task are represented as the mean ± standard error of the mean and are shown in Figure 2.

3.1.1 | Likelihood of making the proposal

Regarding the first question ("Would you make this proposal?") share size had a significant effect on the responses ($F_{[1.269,41.873]} = 63.782$, $p < .001$, $\eta^2 = .659$) (Figure 2a). The highest percentage of positive responses to the question was given to fair offers (88.9%), followed by slightly selfish offers (67.3%), extremely selfish offers (62.2%), slightly altruistic offers (38.2%), and extremely altruistic offers (27.7%). Pair-wise comparisons showed that these percentages differed significantly between all pairs, except for the slightly selfish vs. extremely selfish pair.

In addition, share size had a significant effect on RT ($F_{[2.606,86.010]} = 17.613$, $p < .001$, $\eta^2 = 0.348$) (Figure 2b). The RTs in cases of fair offers (524.34 ms) were significantly shorter than those in cases of slightly altruistic (792.45 ms, $p < .001$), slightly selfish (765.67 ms, $p < .001$), and extremely selfish offers (642.99 ms, $p = .002$). The RTs for altruistic offers and selfish offers followed the same pattern: the RTs for slightly altruistic offers were significantly longer than those for extremely altruistic offers (590.10 ms, $p = .001$), and the RTs for slightly selfish offers were significantly longer than those for extremely selfish offers ($p = .015$).

3.1.2 | Preference for the proposal

Regarding the second question ("Do you like the way the money was divided in this proposal?") The effect of share size on response was significant ($F_{[1.583,52.244]} = 107.982$, $p < .001$, $\eta^2 = 0.766$) (Figure 2C). The percentages of positive answers to fair (82.6%), slightly selfish (79.0%), and extremely selfish offers (84.6%) did not differ significantly. However, they were significantly higher than the percentages of positive answers to slightly altruistic (38.2%, $p < .001$) and extremely altruistic offers (28.1%, $p < .001$).

The effect of share size on RT was also significant ($F_{[3.196,105.476]} = 5.363$, $p = .001$, $\eta^2 = 0.140$) (Figure 2D). The pattern of RT regarding preference for the proposal was similar to that concerning the likelihood of making the proposal. Therefore, the RTs for fair offers were the shortest (406.82 ms) and were significantly shorter than those for slightly altruistic (514.34 ms, $p = .019$) and slightly selfish offers (517.30 ms, $p = .004$). In addition, the RTs for slightly altruistic offers were significantly longer than those for extremely altruistic offers (424.98 ms, $p = .011$).

3.2 | Imaging results

To investigate the brain regions that tracked the amount of money for self/other, the likelihood of making the proposal, and the preference for the proposal, we implemented parametric modulation analyses for the three models. For Model 1, we examined the contrasts in both the first and second frames. For Models 2 and 3, we inspected the
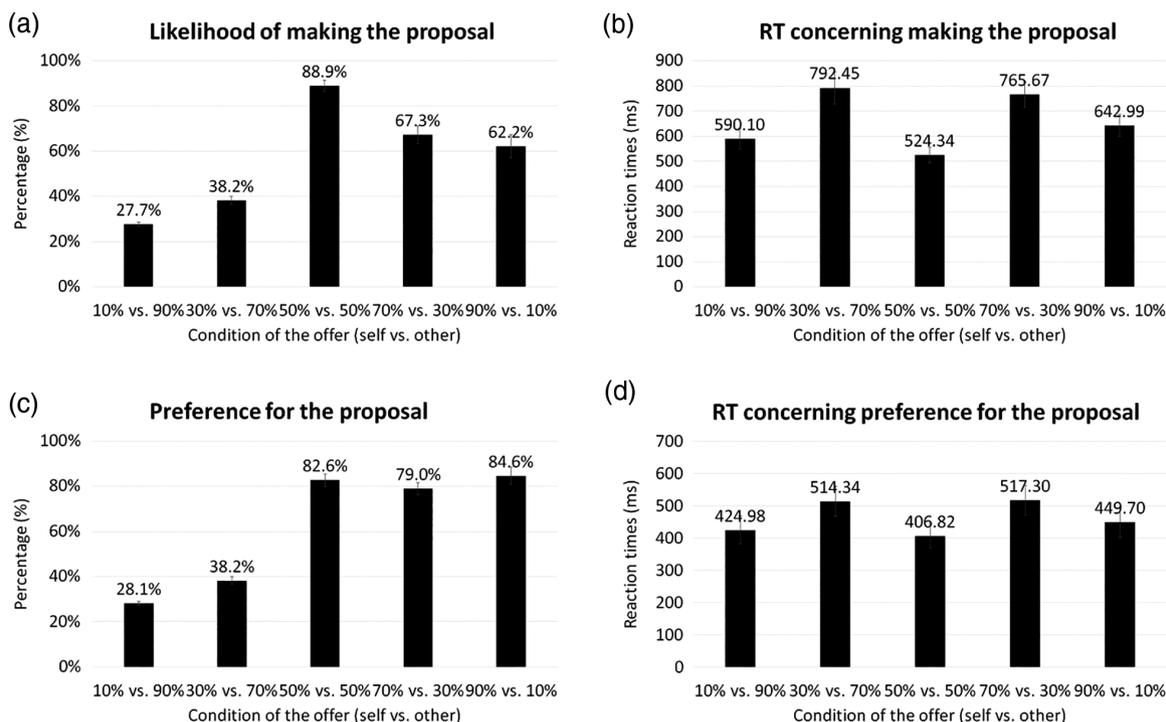

FIGURE 2 Behavioral results. (a) Likelihood of making the proposal. (b) Reaction times (RT) for making the proposal. (c) Preference for the proposal. (d) RT concerning the preference for the proposal. The data is represented as mean ± standard error of the mean (SEM)

contrasts only in the second frame because the participants did not have full information of the offers until they saw cues of self-reward and other-reward. The results are shown in Table 1.

3.2.1 | Model 1: ACC and MCC tracked amount of money for self

Parametric modulation analysis of Model 1 showed brain activation scaling with the amount of money for self when it was shown in the second frame in the following two clusters: the pMCC (MNI coordinates: 6, −12, 40; $Z = 4.16$, $k = 519$, $p < .001$ FDR corrected), and subgenual anterior cingulate cortex (sACC) (MNI coordinates: −4, 36, −6; $Z = 4.05$, $k = 1,000$, $p < .001$ FDR corrected). The first cluster extended from the pMCC to posterior cingulate cortex (PCC). The second cluster was composed of 1,000 voxels, extending from the sACC to the pregenual ACC (pACC) and aMCC (Figure 3a). The other contrast images did not show significant activation with FDR correction at the cluster level using the criteria at $p < .001$.

However, it is noteworthy that the parametric modulation analysis of Model 1 also showed brain activation scaling with the amount of money for self when it was shown in the first frame in the vaMCC (MNI coordinates: 4, 22, 14; $Z = 2.84$, $k = 8$) when using a more lenient criterion ($p < .005$ whole brain analysis, uncorrected).

When the criteria were set at $p < .005$ (whole brain analysis, uncorrected), modulation of activity for other-reward in the second frame was observed in the left superior temporal sulcus (MNI coordinates: −56, −20, 0; $Z = 3.33$, $k = 81$; MNI coordinates: 46, −20, −2, $Z = 3.08$, $k = 10$), the right precuneus (MNI coordinates: 12, −52, 24; $Z = 3.23$, $k = 92$), the left inferior gyrus (MNI coordinates: −50, 38, 8, $Z = 2.85$, $k = 14$), and the bilateral orbital gyri (MNI coordinates: −28, 40, −12; $Z = 3.15$, $k = 15$; MNI coordinates: 34, 30, −14, $Z = 3.06$, $k = 13$). In other words, no significant activation in the ROIs was detected for the contrast images modeling parametric modulators that track other-reward either at the first or the second frame using lenient criteria ($p < .005$ whole brain analysis, uncorrected).

In order to investigate whether there was neural activity in our ROI tracking reward for oneself vs. other conditions, these contrasts in both the first and second frames were also examined. The results

TABLE 1 Peak MNI coordinates of activations from the SPM contrasts ($p < .001$ with FDR correction at the cluster level)

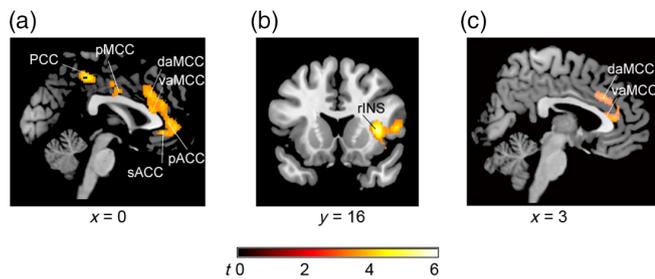| Brain regions	Cluster size	t value	Z value	Peak MNI x y z
Parametric modulator: The amount of money for self at the first frame				
None				
Parametric modulator: The amount of money for other at the first frame				
None				
Parametric modulator: The amount of money for self at the second frame				
Right posterior midcingulate cortex (pMCC)	519	4.82	4.16	6, −12, 40
Left posterior cingulate cortex (PCC)		4.81	4.16	0, −38, 48
Left pMCC		4.11	3.67	−4, −6, 34
Left subgenual anterior cingulate cortex (sACC)	1,000	4.65	4.05	−4, 36, −6
Left dorsal anterior midcingulate cortex (daMCC)		4.57	3.99	−4, 24, 32
Left ventral anterior midcingulate cortex (vaMCC)		4.51	3.95	2, 26, 16
Parametric modulator: The amount of money for other at the second frame				
None				
Parametric modulator: The likelihood of making the proposal at the second frame showing self-reward				
Right insula (rINS)	551	5.58	4.65	36, 16, 6
rINS		4.63	4.03	40, 20, −6
rINS		4.59	4.01	42, 20, 2
Parametric modulator: The likelihood of making the proposal at the second frame showing other-reward				
None				
Parametric modulator: Preference for the proposal at the second frame showing self-reward				
Right vaMCC	196	4.59	4.01	16, 36, 14
Left vaMCC		4.12	3.67	2, 36, 12
Left daMCC	168	4.18	3.72	−6, 28, 32
Right daMCC		4.04	3.62	4, 30, 28
Parametric modulator: Preference for the proposal at the second frame showing other-reward				
None				

showed that the vaMCC tracked self-reward more than it tracked the other-reward both in the first frame (MNI coordinates: −2, 22, 16; Z = 3.07, k = 45, p < .005 uncorrected) and the second frame (MNI coordinates: 6, 26, 18; Z = 3.67, k = 30, p < .001 uncorrected). No significant activation in the ROIs was detected for the other vs. self contrasts in either frame using lenient criteria (p < .005 whole brain analysis, uncorrected).

3.2.2 | Model 2: rINS tracked likelihood of making the proposal

The results showed that the neural response in the rINS varied with the likelihood of making the proposal at the time of the second frame displaying money for self (MNI coordinates: 36, 16, 6; Z = 4.65, k = 551, p < .001 FDR corrected) (Figure 3b). The other contrast images did not show any significant activation.

3.2.3 | Model 3: aMCC tracked preference for the proposal

Parametric modulation analysis of Model 3 revealed that neural activity in the right vaMCC (MNI coordinates: 16, 36, 14; Z = 4.01, k = 196, p < .001 FDR corrected) and left daMCC (MNI coordinates: −6, 28, 32; Z = 3.72, k = 168, p < .001 FDR corrected) varied with

preference for the proposal at the time of the second frame displaying money for self. The vaMCC cluster extended from vaMCC to daMCC (Figure 3c). The other contrast images did not show any significant activation.

3.2.4 | Association with individual differences

To examine the relationship between neural responses and personal traits, we used MarsBaR 0.44 (Brett et al., 2002), to extract individual parameter estimates from the significantly activated clusters that overlapped with our a priori ROIs. Further, we correlated these estimates with participants' responses to the questionnaires (BAS/BIS, benevolence, and belief in a just world questionnaire). To correct for multiple comparisons, the α value was set at 0.007 using Bonferroni correction.

The results showed that, in terms of neural activity tracking amount of money for self (Model 1), the vaMCC [4, 24, 24] parameter estimates were positively correlated with the scores of general belief in a just world ($r_{[34]}$ = .527, p = .001, Figure 4a). Moreover, there was a significant positive correlation between the daMCC [−3, 19, 38] responses to the amount of money for self and the scores of general belief ($r_{[34]}$ = .524, p = .001) and personal belief in a just world ($r_{[34]}$ = .487, p = .003) (Figure 4b).

4 | DISCUSSION

Our behavioral results showed differential patterns of the likelihood of making the proposal vs. participants' preference for the proposal. While participants indistinguishably favored fair (82.6%), slightly selfish (79.0%), and extremely selfish offers (84.6%), only fair offers revealed over 80% in terms of their willingness to make the proposal. To be more precise, compared with the high fondness of the selfish offers, participants rated significantly lower for selfish offers when it comes to making the proposal (p < .05). This suggests that although participants liked lucrative offers, they may not be willing to propose them. Overall, the results were consistent with the literature that most proposers share about 40% of the stake with the recipients, even though the recipient cannot punish or reject them in DG (Camerer, 1997). Such giving cannot be explained by fear of rejection or social norms, but marks the extent of prosociality and altruism.

On the other hand, RT concerning making the proposal and RT concerning preference for the proposal showed a similar pattern, such that the fair offers took the shortest time, whereas the slightly altruistic/selfish offers took the longest time. Our results are similar to the previous findings of Chen et al. (2017), who reported that proposers spent a longer time choosing between a fair offer and a slightly selfish offer than an extremely selfish offer in the ultimatum game. These results demonstrate that considering slightly altruistic/selfish offers requires greater cognitive resources than fair offers or extremely altruistic/selfish offers.
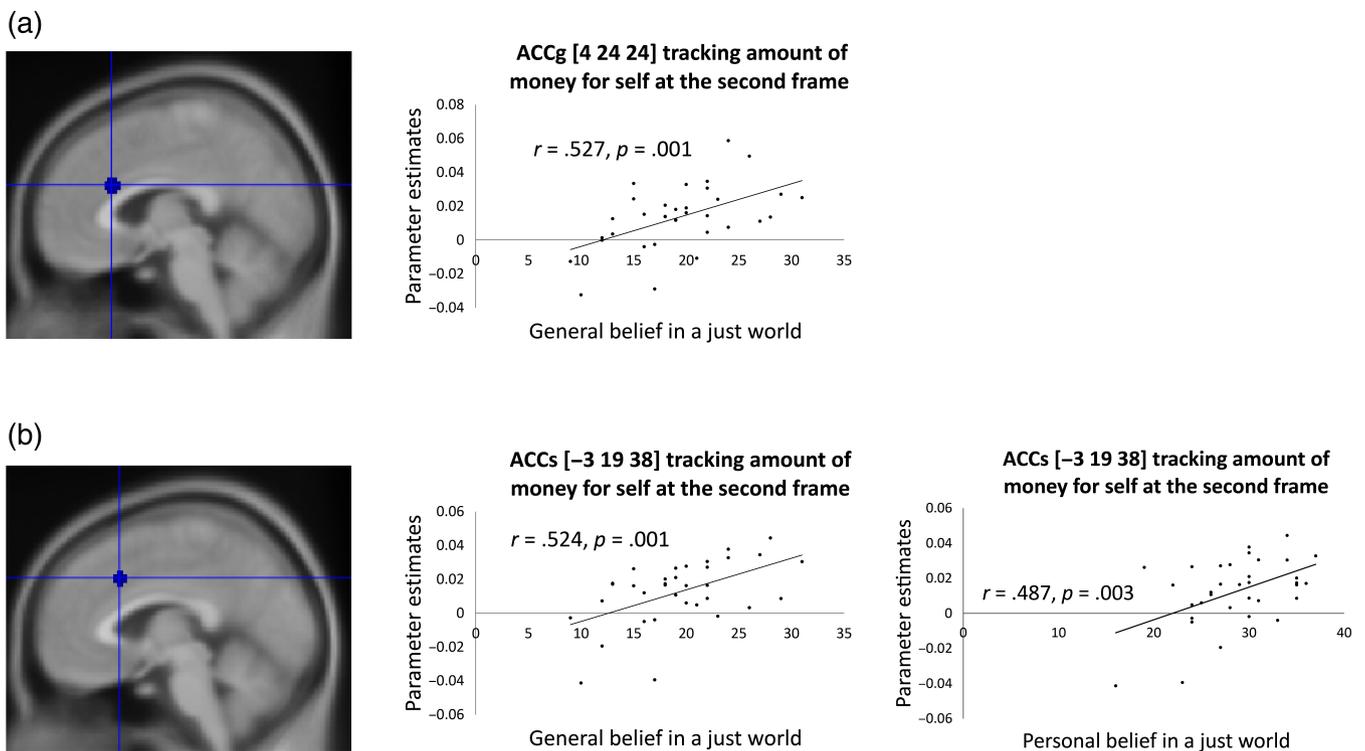
(a)

ACCg [4 24 24] tracking amount of
money for self at the second frame

r = .527, *p* = .001

(b)

ACCs [−3 19 38] tracking amount of
money for self at the second frame

r = .524, *p* = .001

ACCs [−3 19 38] tracking amount of
money for self at the second frame

r = .487, *p* = .003

FIGURE 4 Results of regions of interest (ROI) analyses. (a) Scatterplot showing a significant positive correlation between self-reward signal in the vaMCC cluster (centered at 4, 24, 24, radius = 5 mm) and the score of general-BJW. (b) A significant association between self-reward signal in the daMCC cluster (centered at −3, 19, 38, radius = 5 mm) and the scores of general-BJW and personal-BJW

By dividing the tasks into two parts: reward representation and social judgments on reward allocation, we can extend the findings of Chen et al. (2017) and examine the role of the aMCC in a more detailed manner. Chen et al. (2017) found that vmPFC, dmPFC, vaMCC, and daMCC were involved in different proposal contrasts in an ultimatum game, in which the self and other, as well as reward representation and decision-making, were not dissociable. Our parametric modulation analyses showed that the majority of aMCC tracked self-reward in the second frame in the reward representation task, including vaMCC, daMCC and regions other than our a priori ROIs: sACC, pACC, pMCC, and PCC. Notably, only aMCC tracked the preference for making the proposal. In addition, the neural signals of the rINS parametrically tracked the likelihood of making the proposal. No significant activity was found to vary with the self-reward presented in the first frame or other-reward in either frame (whole brain analysis, *p* < .001 FDR corrected). The brain regions associated with reward representation, preference judgment, and likelihood judgment were discussed.

Consistent with our hypothesis, the results showed that the vaMCC was involved in processing reward for self and context. This emphasizes the role of vaMCC in social behavior. In the second frame, while the amount of other-reward was already known, complete information and the relative value of self-reward were provided. This finding is consistent with previous evidence that the vaMCC is involved in processing self-reward in a context, which helps make sense of the reward.

Enzi et al. (2009) found that the vaMCC is associated with processing self-reward. As reviewed in the introduction section, the accumulated total amount in their task serves as a context, providing a sense of the value of the current reward. Moreover, Chen et al. (2017) and Chang et al. (2013) found that vaMCC may be involved in self-reward processing within a context that presents how much self-reward is relative to other-reward. In addition, Chang et al. (2013) found three subgroups of neurons in the vaMCC, including those that responded to self-reward, other-reward, and both self- and other-reward. It is possible that within a design involving self-reward and its context, the neurons that respond to the value of reward and its context are firing together (Chang et al., 2013; Chen et al., 2017; Enzi et al., 2009). In contrast, within a design that is not involved with the context providing meaning of self-reward, only part of vaMCC neurons responded to self-reward and thus was not enough to be detected in fMRI analysis (Apps & Ramnani, 2014; Lockwood et al., 2015). In sum, our results showed that the vaMCC plays an important role in tracking self-reward when the context of the reward is given to guide social behavior.

In line with the findings of the majority of previous studies, the neural activity in the daMCC was demonstrated to reflect the value of rewards to be delivered to oneself (Kennerley et al., 2011; Kennerley & Wallis, 2009; Sallet et al., 2007). Furthermore, our results corroborated that the pACC is associated with both self-relatedness and reward, that the sACC is associated with personal relevance (Enzi et al., 2009), that the PCC is associated with self-referential

processing (Brewer, Garrison, & Whitfield-Gabrieli, 2013; Northoff & Bermpohl, 2004).

While only the vaMCC was found to track self-reward in the first frame using lenient criteria ($p < .005$, uncorrected), the additional ventral part of the medial wall of the PFC (i.e., sACC and pACC) was observed to scale with self-reward in the second frame ($p < .001$, FDR corrected). Intriguingly, Nicolle et al. (2012) showed that the ventral-dorsal mPFC reflected executed vs. modeled values rather than self vs. other reward (Sul et al., 2015). In our study, it was not until the second frame that the participants had full information to make a decision in DG. In addition to the neural activity in vaMCC tracking self-reward in the first frame, the neural activity in sACC and pACC scaling with self-reward in the second frame suggests that the decision-making process engaged during this stage and reflects participants' decisions to make the offer. Our results support the view that the mPFC shows a functional gradient along an axis of executed (ventral) vs. modeled (dorsal) choices (Nicolle et al., 2012), rather than an axis of self (ventral) vs. other (dorsal) reward (Sul et al., 2015).

The activation in the proposal preference rating suggested that aMCC is associated with the evaluation of social decisions. Our results showed that the neural activities in the aMCC varied with the participants' preference for the offers. Consistent with our findings, the aMCC has been reported to show greater activation under self-relevance and valence interactions (Moran et al., 2006). Taken together, these findings suggest that the neural activities in aMCC not only encode the magnitude of reward for oneself but also define the degree of subjective inclinations toward the offer.

Overall, our results suggest that the aMCC engages in processing the contextual meaning of reward to guide behavior. The results showed that aMCC activation not only tracked the self-reward within context but also the preference toward the offer. The ACC, aMCC, pMCC, PCC tracked self-reward, whereas aMCC tracked both self-reward and preference, suggesting differential functions in the cingulate cortex. The aMCC has been indicated to play an essential role in encoding the value of outcomes to guide behavior (Rushworth, Walton, Kennerley, & Bannerman, 2004). This may explain why, in our study, the self-reward activity tracked in the aMCC was more specifically encoded in the second frame, during which the full information (reward for both players) was given to guide behaviors. Together, these results suggest that the neural coding of self-reward in the aMCC is context-dependent. Thus, it is implied that aMCC may encode important information for adjusting to the social context.

Neural activity in the rINS during the second frame showing self-reward parametrically tracked the likelihood of proposing the offers. This finding may be explained by the increasing evidence that the insula cortex is a vital hub that integrates somatic information, emotional responses, empathic processes, and external sensory signals (Craig, 2002; Critchley, Wiens, Rotshtein, Öhman, & Dolan, 2004; Crottaz-Herbette & Menon, 2006; Menon & Uddin, 2010; Singer, 2006). Singer, Critchley, and Preuschoff (2009) proposed an integrative model in which the insular cortex plays a critical role in processing subjective feelings, empathy, and uncertainty.

According to this model, the insular cortex integrates bodily and affective responses and uncertainty signals with computations to produce a dominant feeling state, which modulates social behaviors and guides complex decisions in uncertain environments. A recent neuroimaging study has also identified the right anterior insular (rAI) as a key brain region that engages in the processing of social value conversion when making decisions about allocating rewards to others (Fukuda et al., 2019). They reported the rAI, as a key node of the salience network, represents an intermediate value that encodes the effective influence of the offer of value on the outcome. Therefore, we interpret that the neural activities of rINS, which parametrically tracked the likelihood of proposing the offers, is associated with its integral function of affective and cognitive processing of internal states and external stimuli to guide social judgments within a given context.

There are advantages and limitations of our design in that participants rated their willingness instead of making an actual decision in DG. Since there was no actual decision, the bonus payment for the participants was not game-dependent, but task-dependent, that is, not based on their decision but on their accuracy in remembering the reward distribution. This modified task may make the participants less engaged compared with the traditional DG, but it allowed us to detect the neural correlates underlying reward representation for self and other, rather than to detect brain activation that may have been elicited by potential confounding factors to make a decision. The high accuracy (95.85 ± 4.01%) of fMRI results suggests that the participants represented self- and other-reward accurately during scanning. Moreover, our behavioral results of participants' willingness to make the offers are highly consistent with the literature (Camerer, 1997), suggesting that although the participants were not asked to make an actual decision, it is very likely that they had imagined and considered the offers the way they would have when they were asked to make a real offer. Combining both fMRI and behavioral tasks, the continuous rating data allowed us to examine brain regions that reflected the evaluation processes that synthesized all the factors considered. If we had asked the participants to make a binary decision, the brain activation detected may have reflected only the dominant strategy or factor. The current study is limited to investigating brain activities that reflect the evaluation process concerning the offers with a range of share sizes, but not brain activation, which may engage in making a real offer. Building upon the current findings, future studies may have a clearer view when examining specific variables that influence the decision-making process in DG.

Our results did not show the daMCC tracking other-reward more than self-reward, even with more lenient criteria. This finding did not provide further support for Chang et al. (2013), who indicated that daMCC neurons in rhesus monkeys fired more strongly when rewarding other/no one than when rewarding oneself. In our study, there were no experimental conditions in which neither the proposer nor the responder received the reward. Future studies are needed to examine the role of daMCC more thoroughly by incorporating all possible conditions, including the condition of neither participant receiving a reward.

No significant brain activation was detected to vary with the amount of self-reward at the time of the first frame or the other

reward at the time of both frames in our study. This highlights the importance of future research. When the criteria were lenient ($p < .005$, uncorrected), vaMCC tracking of self-reward without context was shown. It is possible that with only a subgroup of neurons firing in vaMCC (Sallet et al., 2007), the activation is not strong enough for fMRI detection. Future studies are encouraged to adopt other experimental designs or techniques to investigate the underlying processes engaged in the early stage, where the value of reward was displayed without context.

Several recent neuroimaging studies have suggested that the vaMCC plays an important role in processing the value of others' rewards (Apps et al., 2013; Apps et al., 2016; Apps & Ramnani, 2014; Behrens et al., 2009; Lockwood et al., 2015, 2018). It is possible that the vaMCC, while tracking another's reward, also responds to other relevant information such as others' effort (Apps & Ramnani, 2014) or the probability of receiving a reward (Lockwood et al., 2015), which was not included in our design. In addition, unanticipated strategies that participants used may have caused the absence of significant brain activities related to other-reward in our study. When participants were asked how they performed the fMRI task during debriefing, around half of the participants indicated that they focused on the amount of money for themselves. Therefore, neural activities related to other-reward in the current study may not be strong enough to be detected in our task. Future refinement of the task could be performed.

One of the limitations of this study was that the participants were informed that they were paired with the next participants of the experiment, rather than meeting the recipient, or a confederate, in person. A review paper has reported that the presence of another person may induce a tendency to conform to social norms (Guerin, 1986), which may prompt prosocial behaviors. Our behavioral results showed that participants rated fair offers higher when asked about their willingness to make the offers than their preference ($p = .001$), and they rated slightly selfish offers ($p = .012$) and extremely selfish offers ($p < .001$) lower when asked about their willingness than preference. This demonstrated that fairness consideration played an important role when they evaluated making social decisions. However, the effect of inequity aversion may have been even larger if the participants had been confronted with the other. Hence, our results should be limited to non-simultaneous virtual interpersonal interactions, but not social situations involving face-to-face interactions.

Among the attitudes assessed by self-report questionnaires, only the BJW was significantly correlated with neural responses. This is in line with our finding that the aMCC plays a role in processing self-reward within a social context. The general-BJW scores positively correlated with the neural responses in the vaMCC to self-reward within context. As stated by the just-world hypothesis, BJW is a cognitive bias that people have a strong need to believe in justice, and they strive for fairness and justice to defend and sustain their beliefs (Lerner & Miller, 1978). It is possible that when individuals are more sensitive to self-rewards neurologically, they have a stronger belief about how the reward is distributed in society (i.e., the context of receiving reward in the real world), such that individuals get what they deserve and deserve what they get. The activation in the daMCC

varying with self-reward within context had a significant positive correlation with both general-BJW and personal-BJW. This may be because the dorsal part of the aMCC is engaged in self-referential processing (Kennerley et al., 2011; Kennerley & Wallis, 2009; Sallet et al., 2007). Taken together, these results imply that aMCC activity is closely linked to the personal disposition of BJW, a belief system in the context of reward delivery in the real world.

5 | CONCLUSION

The current study highlights the key role of the aMCC in processing self-reward within context and preferences for an offer to other individuals. Moreover, we demonstrate individual variation in the degree to which the aMCC responds to self-reward, with only those who have a strong belief in a just world showing enhanced aMCC activity for self-reward. Additionally, we shed light on the adaptive nature of neural circuits when facing different conditions in the social world by providing evidence of contextual neural coding of self-reward.

CONFLICT OF INTEREST

We declare that there is not any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations within 3 years of beginning the submitted work that could inappropriately influence, or be perceived to influence, our work.

ETHICS STATEMENT

All methods were performed in accordance with the ethical principles of the Declaration of Helsinki and were approved by the Research Ethics Committee of the National Chengchi University before its initiation [NCCU-REC-201705-I014]. All participants provided written informed consent for the study before they performed the experiment.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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