Title: Neural representations of the committed romantic partner in the nucleus accumbens

Running title: Neural representations of the romantic partner

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Abstract

Having an intimate romantic relationship is an important aspect of life. Dopamine-rich reward regions, including the nucleus accumbens (NAcc), have been identified as neural correlates for both emotional bonding with the partner and interest in unfamiliar attractive nonpartners. Here, we aimed to disentangle the overlapping functions of the NAcc using multivoxel pattern analysis (MVPA), which can decode the cognitive processes encoded in particular neural activity. Forty-six romantically involved males performed the social incentive delay task during fMRI scanning, in which a successful response resulted in the presentation of a dynamic and positive facial expression from their partner and unfamiliar females. MVPA revealed that the spatial patterns of NAcc activity could successfully discriminate between partner and unfamiliar females while anticipating the target presentation. We speculate that neural activity patterns within the NAcc represent the committed partner, which might be a key neural mechanism for single-minded romantic relationships.

Keywords: fMRI, reward, romantic love, social cognition, value

Statement of Relevance

Having an intimate romantic relationship with a significant other is an important aspect of life for most people. Brain imaging studies have indicated that dopamine-rich regions of our brain underlie the euphoria of love. However, we know little about whether and how a romantically involved individual's brain encodes a significant other differently from other opposite-sex, attractive individuals. Here, we provide evidence for distinct spatial patterns of activity in the brain's center of pleasure and addiction, the nucleus accumbens, for committed partners and unfamiliar nonpartners. The unique neural representations of a committed partner might be associated with single-minded romantic relationships.

Introduction

Romantic love is observed in nearly all societies (Jankowiak and Fischer 1992). Emotional bonding with a partner usually involves intrusive thinking about the partner (Fisher 2004) and positively affects physical and mental health (Holmes and Rahe 1967; House et al. 1988; Uchino et al. 1996; Diener et al. 1999; Kiecolt-Glaser and Newton 2001; Furman 2002). Romantically involved individuals tend to exhibit a more positive evaluation of their partner's attractiveness than others do (Murray et al. 1996; Murray and Holmes 1997; Barelds-Dijkstra and Barelds 2008; Barelds et al. 2011). These individuals also exhibit a more significant devaluation and less attentive adhesion toward alternative partners, which could contribute to relationship maintenance (Johnson and Rusbult 1989; Simpson et al. 1990; Miller 1997; Maner et al. 2008, 2009).

Early studies using functional magnetic resonance imaging (fMRI) aimed to reveal how emotional bonding with a committed partner is established and maintained. Those studies reported greater neural responses to their romantic partner in dopamine-rich reward regions, including the ventral tegmental area, caudate nucleus, and nucleus accumbens (NAcc) (e.g., Bartels and Zeki 2000; Aron et al. 2005; Fisher et al. 2010; Acevedo et al. 2012). These mechanisms are believed to be shared with other animals, including prairie voles, which exhibit a selective preference for the partner in long-term paired relationships (for reviews, Young and Wang 2004; Walum and Young 2018). Recent fMRI studies have found the reward circuitry to be involved in love, regardless of relationship length (e.g., >10 years in Acevedo et al. 2012), culture (Xu et al. 2011), or sexual orientation (Zeki and Romaya 2010).

However, it is still unknown whether this circuitry encodes unique neural representations related to the partner. Greater responses in the reward circuitry to the opposite-sex partner may simply indicate a preference for attractive opposite-sex individuals (e.g., Aharon et al. 2001; Kim et al. 2007; Bzdok et al. 2011; Mende-Siedlecki et al. 2013) regardless of the relationship. Disentangling the reward circuitry's overlapping functions could clarify the cognitive mechanisms that underlie exclusive and long-term relationship commitment.

We used multivoxel pattern analysis (MVPA), which uses a machine learning technique to decode the mental states, or the cognitive processes elicited by different stimuli from the spatial patterns of activity in a given brain region (Haxby et al. 2014; Cohen et al. 2017). MVPA exhibits higher sensitivity than the traditional univariate fMRI approach and allows better interpretation of overlapping functional activations in a targeted region (Norman et al. 2006; Peelen and Downing 2007). Among the reward-related regions, we focused on the NAcc as potentially containing a unique representation of the committed partner for the following two reasons. First, as described above, the NAcc has been believed to play a crucial role in establishing emotional bonding with a long-term partner (Young and Wang 2004; Fisher et al. 2010; Acevedo et al. 2012; Walum and Young 2018). Second, several studies have demonstrated that oxytocin treatment promotes avoidance behaviors for alternative partners and selectively enhances the perceived attractiveness of the committed partner, paralleled by an increased NAcc response (Scheele et al. 2012, 2013, 2016; Kreuder et al. 2017). Based on these observations, the NAcc likely differentially encodes representations of the committed partner relative to other opposite-sex individuals.

To effectively measure NAcc activity, we employed a variant of the social reward incentive delay (SID) task (Spreckelmeyer et al. 2009), an adaptation of the monetary incentive delay task (Knutson et al. 2000), which requires participants to quickly and accurately respond to the presentation of a target following a cue. The SID task includes a brief delay before striving to gain social approval from different persons to maximize the motivational aspects of reward processing, allowing measurement of neural activity that represents reward anticipation in the absence of deliberate evaluation. Here, we expected to observe distinct neural representations in the NAcc between the committed partner and other opposite-sex individuals.

Materials and Methods

Participants

The participants in this study were 46 right-handed males with no history of neurological or psychiatric disease. The optimal sample size was determined based on a G-Power analysis (Version 3.1.9.4; Faul et al. 2007, 2009). A sample size of 36 participants was required to reach a power of 0.9, with a medium effect size of d = 0.5 for the one-sample t-test (one-tailed) to test decoding accuracy against chance level (*Means: Difference from constant, one sample case*) and an α level of 0.05. Assuming an exclusion rate of approximately 20%, a final sample size of 46 was determined to be required. Because males generally express a stronger desire for romantic relationships with more individuals (Buss and Schmitt 1993; Wiederman 1997), we chose only heterosexual males for the present investigation to reduce confounding factors and render the studied phenomena clearer. All volunteers were between 20 and 29 years old and were in a committed romantic relationship at the time of the experiment. The female partners of the participants also participated in this study through a video recording, in which we collected their pictures and movie clips to be presented in the fMRI task (see Section 1 in *Supplemental Material*). We excluded eight volunteers from the analysis for the following reasons: four exhibited excessive head motion during fMRI scanning (repetitive movements larger than 2 mm within a session), one had neurological abnormalities that were identified during scanning, and three self-identified as gay. Thus, the present results were based on the remaining 38 participants (mean age = 21.9 years; range = 20–27 years). No participants were in a marital relationship. The mean length of relationship with the current partner was 18.3 months (SD = 13.3 months; median = 15.5 months; range = 2–66 months). We did not assess whether the participant was living with his partner. The mean number of partners, including past partners, was 2.7 (SD = 1.3, median = 3, range = 1–7). After receiving a detailed description of the study, all participants provided written informed consent that conformed with the guidelines approved by the Ethics Committee of Kyoto University.

Tasks

SID task. The participants were engaged in the SID task during fMRI scanning, which assesses the neural responses that underlie the anticipation of positive feedback from a cued person (Spreckelmeyer et al. 2009; Rademacher et al. 2010; Kohls et al. 2013). Figure 1 presents a schematic diagram for the SID task. In the present study, the SID task had four conditions: partner female, attractive female, unattractive female, and control. Similar to a previous study (Kohls et al. 2013), we prepared facial pictures and short movie clips for each person presented in the SID task as stimuli (see Section 1 in *Supplemental Material*). The stimuli presented in the partner condition were unique to each participant (i.e., the participant's current partner's facial picture and movie clips). The stimuli for the attractive and unattractive conditions were fixed for all participants. For the stimuli presented in the control condition, we created mosaicked pictures and movie clips generated from stimuli presented in the other three experimental conditions.

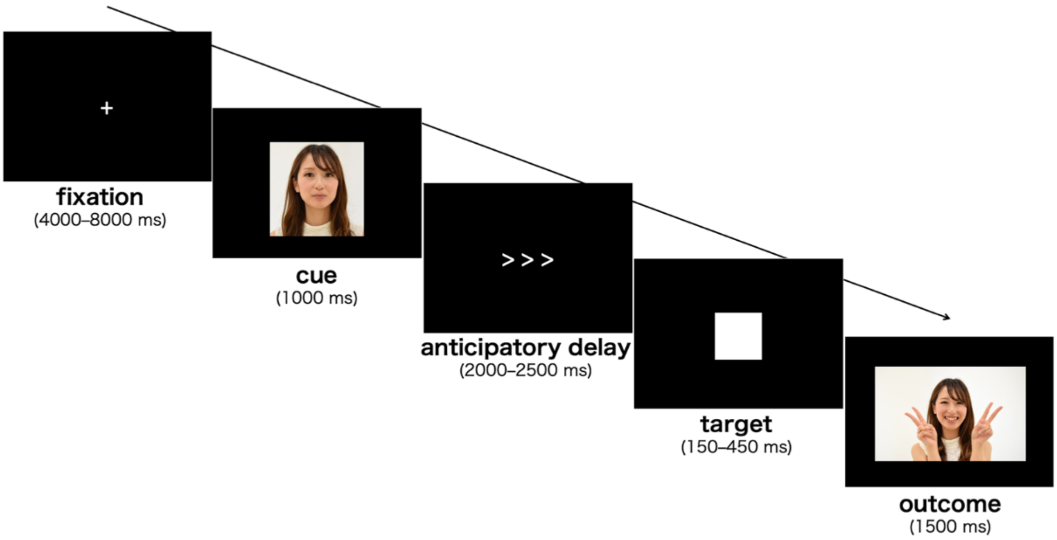
The SID task is a simple speeded response task, where pressing a button during the brief presentation of the target stimulus was considered a successful response and resulted in observing a movie clip depicting positive feedback from the cued person. Notably, the participants were informed of the type of trial at the beginning of the trial; in this way, the extent to which the participants were motivated to obtain positive feedback from the viewed person could be assessed based on both reaction time and neural response during the anticipation of the target presentation. Because anticipatory delay involves no explicit evaluation, observing this allows us to minimize possible confounding effects, such as concerns about the social desirability of demonstrating a preference for a potential alternative partner (Scott 2000).

The task consisted of five sessions, where each session lasted approximately 7 min and 40 s. Each session consisted of four conditions (partner, attractive, unattractive, and control) with ten trials for each condition. A total of 40 trials were presented in a pseudorandom order. At the beginning of each trial, the participants viewed a neutral-expression facial picture for 1000 ms, which indicated the trial type. For example, in the partner condition, a picture of the partner with a neutral expression appeared on the screen as a cue. Following the cue presentation, the participants were presented with an object that indicated the target's presentation within a variable interval (anticipatory delay phase, 2000–2500 ms). Upon the appearance of a white target square that appeared for a variable length of time (150–450 ms), the participants responded with a button press. They were instructed to press the button with their right forefinger as rapidly as possible in response to the appearance of the target square in all conditions. In the subsequent outcome phase, the target hits (i.e., responses that occur during the presentation of the target stimulus) resulted in the presentation of a short movie clip of the cued person for 1500 ms, who showed happy facial expressions and a positive gesture (*Hit*). There were ten positive movie clips for each person (see Section 1 in *Supplemental Material*), and they appeared on the screen in a pseudorandom order in each session to encourage participants to maintain engagement with the task. Error responses (i.e., responses that occur in the absence of the target stimulus) resulted in the presentation of a short movie clip of the cued person with a neutral facial expression without any gestures for 1500 ms (*Miss*).

Unlike the hit trials, a single movie clip was presented in the miss trials for each condition. A fixation was presented for a variable intertrial interval (4000–8000 ms) following each trial. In trials for the control condition, a mosaicked picture was presented as a cue, and in the outcome phase, a mosaicked movie clip appeared on the screen, regardless of the performance.

To approximately equate the performance in the SID task across participants, we applied an adaptive algorithm that dynamically adjusted the duration of each target presentation as a function of target performance to allow participants to achieve a standardized hit rate of ~66% (Buckholtz et al. 2010; Kohls et al. 2013; Abe and Greene 2014). To achieve this, the duration of time in which the square appeared in the subsequent trial was shortened in 25-ms increments if the current hit rate exceeded 66% or lengthened in 25-ms increments if the current hit rate fell below 66%. The duration of the target was set to never fall below 150 ms or exceed 450 ms. In the first trial for each condition in the session, the target presentation was fixed at 300 ms. The mean hit rate for all participants was 61.9% (SD = 4.0%). We also confirmed that no participants had mean hit rates lower than 3 SD below the mean of all participants (<50.0%), which ensured that all participants were seriously engaged in the task.

Rating task and questionnaires. Following the completion of the SID task, the participants performed a rating task outside of the scanner, in which they rated a total of 30 movie clips that showed expressions of positive feedback by the partner, the attractive female, and the unattractive female presented in the hit trials. Each movie clip appeared on the screen for 1500 ms in a pseudorandom order. The participants were asked to rate the degree of likeability for each clip on a 7-point scale (1: not at all, 7: extremely). A fixation was presented for 1000 ms following each trial. After completing the rating task, the participants completed two questionnaires on relationship quality, including relationship commitment and attitudes toward extrapair relationships (see Section 2 in *Supplemental Material*).



<u>Figure 1</u>

Schematic of the SID task. This task required the participants to give a simple, rapid response to the target presentation. The presentation of positive feedback from the cued person depended on the participant's performance. In each trial, the participants were shown one of four pictures (cue phase), which indicated the upcoming condition. Each session had four conditions (partner, attractive, unattractive, and control), with ten trials each. The participants were presented with an object indicating the target presentation over a variable interval (anticipatory delay phase), and then they responded to a white target square with a button press. Target hits (i.e., responses that occur during the target stimulus presentation) resulted in a short movie clip presentation of the cued person showing a happy facial expression with a positive gesture (outcome phase). Error responses (i.e., responses that occur in the absence of the target stimulus) resulted in a short movie clip presentation of the cued person showing a neural facial expression with no gesture. In control condition trials, a mosaicked movie clip appeared on the screen, regardless of the performance.

Image acquisition and analysis

Acquisition parameters and image preprocessing. The participants were scanned using a 3.0-Tesla Siemens Magnetom Verio MRI scanner (Siemens, Erlangen, Germany) with a 32-channel head coil. A $T2^*$-weighted echo-planar imaging (EPI) sequence that was sensitive to blood oxygen level-dependent (BOLD) contrast was used for functional imaging with accelerated multiband acquisitions (Feinberg et al. 2010; Moeller et al. 2010; Xu et al. 2013) that had the following parameters: repetition time = 2000 ms; echo time = 43 ms; flip angle = 80°; acquisition matrix = 96 × 96; field of view = 192 mm; in-plane resolution = 2 × 2 mm; number of axial slices = 76; slice thickness = 2.0 mm without interslice gap (interleaved order); and multiband acceleration factor = 4. A high-resolution (spatial resolution = 1 × 1 × 1 mm) structural image was also acquired with a T1-weighted magnetization-prepared rapid-acquisition gradient echo (MP-RAGE) pulse sequence. Head motion was restricted with firm padding placed around the head. Visual stimuli were projected onto a screen and viewed through a mirror attached to the head coil, and behavioral responses were recorded with a fiber-optic response box. The first five volumes of the 230 volumes collected in each session were discarded to allow for equilibration effects.

Data preprocessing and statistical analyses were performed using SPM12 (Wellcome Department of Imaging Neuroscience, London, UK). For preprocessing, the EPI images were first corrected for slice acquisition time. Then, all images were realigned to correct for small movements between scans. This generated an aligned set of images and a mean image per subject. Each participant's T1-weighted structural MRI was then coregistered to the mean of the realigned EPI images. The coregistered T1 image was normalized to a template image that was based on the Montreal Neurological Institute

(MNI) template using unified segmentation (Ashburner and Friston 2005). The parameters of this normalization process were applied to the EPI images. EPI images were reformatted to isometric voxels (2 × 2 × 2 mm). These normalized but unsmoothed EPI images were used for classification analyses for each participant.

General linear model. We designed a general linear model (GLM) for each participant and each run. The GLM contained four regressors indicating the anticipatory delay phase for the four conditions (partner, attractive, unattractive, and control; duration = 2000–2500 ms), as well as regressors separately indicating the outcome phase of the four conditions for each hit and miss trial (duration = 1500 ms). The GLM also contained an error trials regressor that indicated the delay and outcome phases in the trials in which participants made no response or in those in which they made responses before the target presentation. All regressors were convolved with a canonical hemodynamic response function. In addition, six motion-correction parameters were included as regressors of no interest. A high-pass filter (1/128 Hz) was used to remove low-frequency noise, and a first-order autoregressive (AR(1)) model was employed to correct for temporal autocorrelation. The parameter estimates (betas) for each event were calculated for all brain voxels. The fMRI responses were entered into the classification analysis as classification samples.

MVPA. To test whether the anticipation of positive feedback from partners and unfamiliar females can be decoded from patterns of fMRI responses, we performed a classification analysis. We focused on neural responses in the NAcc during the anticipatory delay phase, a critical region for social reward anticipation (Cromwell et al. 2020). Previous studies using the SID task have indicated increased NAcc activation while anticipating more attractive social rewards (Spreckelmeyer et al. 2009; Rademacher et al. 2010; Kohls et al. 2013). We anatomically defined regions of interest (ROIs) for the left and right NAcc. In addition, we investigated neural responses in the medial orbitofrontal cortex (mOFC), a key region for subjective evaluation of facial attractiveness or preference (O'Doherty et al. 2003; Kranz and Ishai 2006; Ishai 2007; Kim et al. 2007), and white matter as a control region (see Section 3 in *Supplemental Material*). In the classification analysis, we extracted voxelwise fMRI responses during the anticipatory delay phase and the outcome phase in each condition as classification samples. Then, we employed a linear support vector machine with a cost parameter of C = 1 as a classifier using The Decoding Toolbox (Version 3.994; Hebart et al. 2015). For each ROI, classification accuracies were estimated using leave-one-run-out cross-validation. Specifically, a classifier was trained to discriminate experimental conditions (e.g., partner vs. attractive conditions) from the spatial patterns of brain activity in four runs. Then, the discrimination performance was tested on the remaining run whose data were not used in the training. If the ROI encodes significantly distinguishable neural representations for each condition, the classifier is expected to successfully learn the patterns of the activity during the training and accurately predict the conditions in the new dataset during the testing. This procedure was repeated for all five runs, and we obtained mean accuracy scores across runs for each participant, which allowed us to avoid the problem of overfitting by performing a single test. For each ROI, we examined whether the mean accuracy across participants was greater than chance using a one-sample t-test (one-tailed) to test a directional hypothesis. More specifically, we tested the three-way comparison between partner, attractive, and unattractive conditions (chance = 33.3%). Planned one-tailed t-tests on mean classification accuracy in the comparison with the chance have been widely employed in previous studies of MVPA (e.g., Skerry and Saxe

2014; Seymour et al. 2015; Dungan et al. 2016; Loose et al. 2017; Suzuki et al. 2017). If neural activities within the ROI do not demonstrate dissociable patterns between these three conditions, classification performances should be at chance level. If above-chance performance was observed in the three-way comparison, we continued to test all possible pairs (partner vs. attractive, partner vs. unattractive, and attractive vs. unattractive; chance = 50%). In this post hoc pairwise test, we report adjusted p-values with Bonferroni correction (i.e., adjusted p-value = p-value multiplied by 3) to control the familywise error rate of multiple comparisons, unless otherwise specified.

Results

Behavioral data

All of the statistical analyses were performed with R version 3.5.3 (R Core Team 2019). Statistical tests were two-tailed, except one-tailed tests to determine whether mean classification accuracy across participants was greater than chance (see *Materials and Methods*). For t-tests, we calculated the effect size, Cohen's d with Hedges's correction using the "effsize" package version 0.8.1 implemented with R (Torchiano 2020).

We performed one-way ANOVA on response times to the target presentation in the SID task, taking condition (partner, attractive, unattractive, and control) as a within-subject factor, and found a significant main effect of condition ($F(3, 111) = 22.80$, $p < 0.001$, $\eta_p^2 = 0.38$; Figure 2A). Post hoc t-tests with adjusted p-values with Bonferroni correction (i.e., adjusted p-value = p-value multiplied by 6) indicated that the participants tended to respond significantly more quickly in the partner condition than in the other three conditions (partner vs. attractive: $p < 0.001$, $d = 0.29$; partner vs. unattractive: $p < 0.001$, $d = 0.47$; partner vs. control: $p < 0.001$, $d = 0.42$). The participants also responded significantly more quickly in the attractive condition than in the unattractive condition ($p = 0.002$, $d = 0.21$). These results were consistent with those of previous studies showing that the anticipation of more attractive feedback elicited a more rapid response (Spreckelmeyer et al. 2009; Rademacher et al. 2010; Kohls et al. 2013).

We then performed one-way ANOVA on the likeability ratings for the movie clips with happy expressions in the rating task outside the scanner with condition (partner, attractive, and unattractive) as a within-subject factor and found a significant main effect for condition ($F(2, 74) = 109.20$, $p < 0.001$, $\eta_p^2 = 0.75$; Figure 2B). Post hoc t-tests with adjusted p-values with Bonferroni correction (i.e., adjusted p-value = p-value multiplied by 3) indicated that the participants had greater preference for their partner's clips over attractive and unattractive unfamiliar females' clips (partner vs. attractive: $p = 0.007$, $d = 0.71$; partner vs. unattractive: $p < 0.001$, $d = 3.07$). The participants also exhibited a greater preference for the clips with the attractive female than those with the unattractive female ($p < 0.001$, $d = 2.22$), which indicated a successful manipulation of stimuli. We further confirmed that greater preference for the partner's movie clips over the attractive nonpartner was observed only in the fMRI participants, not in an independent participant group (see Section 4 in *Supplemental Material*).

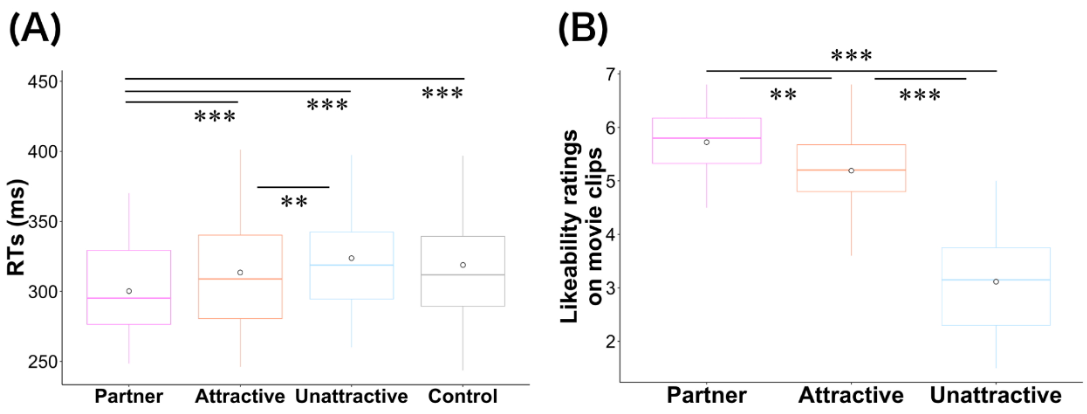


Figure 2

(A) Response times (RTs) to the target presentation in the SID task and (B) likeability ratings for the happy-expression movie clips presented in the SID task. In each box and whisker plot, the central line denotes the median, and the bottom and top hinges of the box indicate the 25th and 75th percentiles, respectively. The upper whisker extends to the largest value no further than 1.5 times the interquartile range (IQR) from the hinge, and the lower whisker extends to the smallest value no further than 1.5 times the IQR from the hinge. White dots indicate mean values across participants. $^{***}p < 0.001$, $^{**}p < 0.01$

fMRI data

MVPA for the anticipatory delay phase

We assessed whether the NAcc encoded unique representations of anticipated positive feedback from the partner. The classification analyses of the three-way comparison across the conditions for partner, attractive, and unattractive during the anticipatory delay phase (chance = 33.3%) showed above-chance classification performances both in the left and right NAcc (left: mean accuracy across participants = 38.6%, SD = 13.7%, $t(37) = 2.38$, adjusted $p = 0.022$, $d = 0.38$, lower 95% confidence interval (CI) = 34.8%; right: mean = 40.7%, SD = 16.6%, $t(37) = 2.75$, adjusted $p = 0.009$, $d = 0.44$, lower 95% CI = 36.2%, one-tailed; p-values were multiplied by 2). As the paired t-test indicated no significant differences in these mean accuracies between the left and right NAcc ($t(37) = -0.62$, $p = 0.54$, $d = 0.14$, 95% CI = [−8.94, 4.73]), we report averaged accuracies (i.e., mean of the left and right NAcc) hereafter unless otherwise specified. We confirmed that this averaged accuracy for the three-way comparison was also above chance (mean = 39.6%, SD = 11.1%, $t(37) = 3.52$, $p < 0.001$, $d = 0.56$, lower 95% CI = 36.6%, one-tailed). Similar results were observed when the control condition was included (four-way comparison across the conditions for partner, attractive, unattractive, and control: chance = 25%; mean = 30.5%, SD = 10.8%, $t(37) = 3.17$, $p = 0.002$, $d = 0.50$, lower 95% CI = 27.6%, one-tailed; see also Section 5 in *Supplemental Material*).

Additional pairwise analyses revealed dissociable neural representations between the partner and nonpartner conditions (chance = 50%, adjusted p-value = p-value multiplied by 3; Figure 3); that is, we observed significantly higher classification accuracies over the chance level in both partner vs. attractive conditions (mean = 58.7%, SD = 13.6%, $t(37) = 3.94$, adjusted $p < 0.001$, $d = 0.63$, lower 95% CI = 55.0%, one-tailed) and partner vs. unattractive conditions (mean = 59.7%, SD = 17.9%, $t(37) = 3.35$, adjusted $p = 0.003$, $d = 0.53$, lower 95% CI = 54.8%, one-tailed). We further explored whether individual differences in the NAcc activity patterns during anticipating feedback from the partner were associated with relationship commitment and attitudes toward extrapair relationships (see Sections 6 and 7 in the *Supplemental Material*). However, as the sample size of the present study is not enough to provide adequate power for the across-participant correlation tests, we refrain from discussing those results.

In the white matter control region, we did not observe classification performance better than chance in the three-way comparison (chance = 33.3%; mean = 29.8%, SD = 14.3%, $t(37) = -1.50$, $p = 0.93$, $d = 0.24$, lower 95% CI = 25.9%, one-tailed).

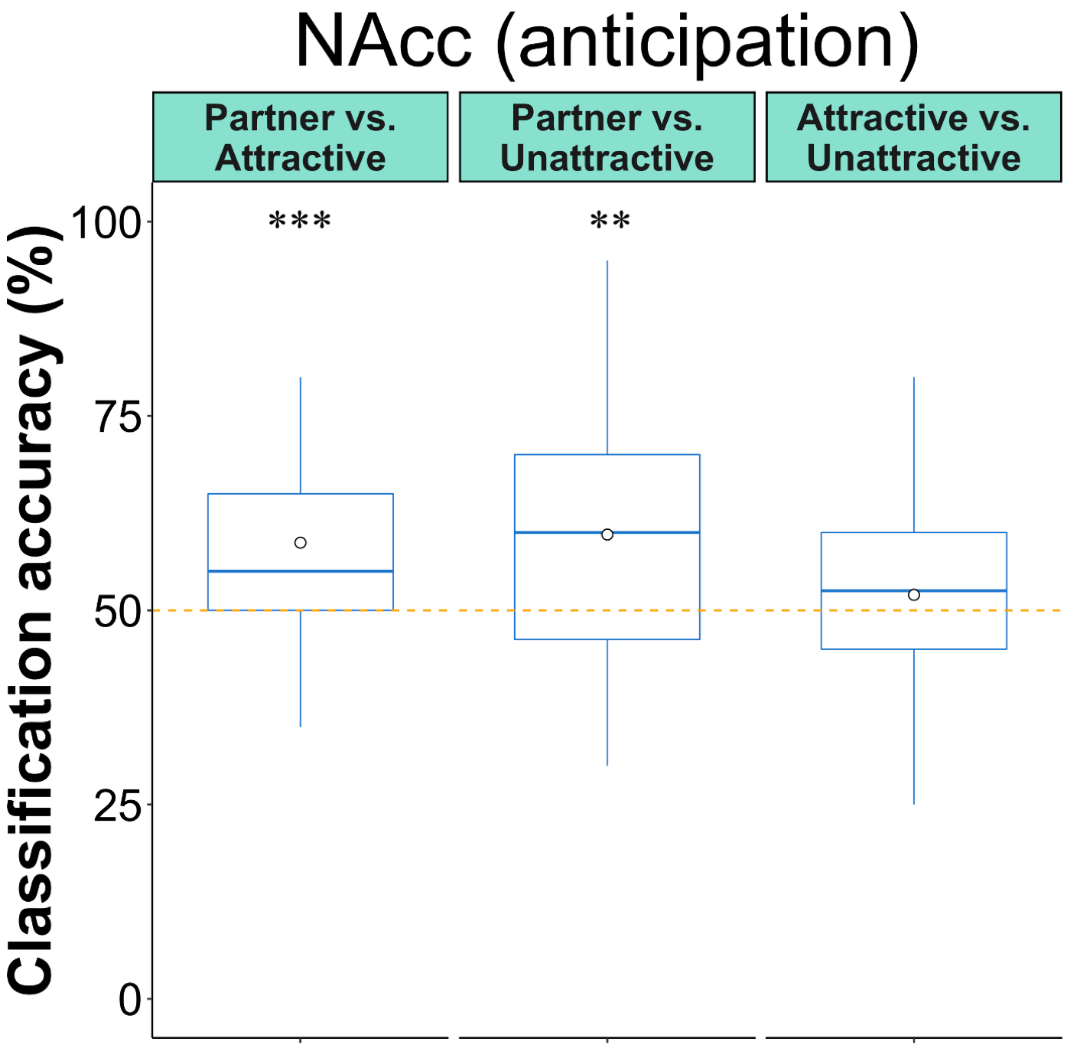


Figure 3

Results of the classification analysis for the nucleus accumbens (NAcc) during the anticipatory delay phase, illustrating mean accuracies of the left and right NAcc. Box and whisker plots with white dots are as defined in Figure 2. A classification accuracy better than chance was determined using a one-sample t-test vs. 50% (one-tailed). $^{***}p < 0.001$, $^{**}p < 0.01$

MVPA for the outcome phase

In the comparison between the attractive and unattractive conditions, above-chance differences in classification performance were not observed in the NAcc during the anticipatory delay phase (mean = 52.0%, SD = 12.8%, $t(37) = 0.95$, adjusted $p = 0.52$, $d = 0.15$, lower 95% CI = 48.5%, one-tailed; Figure 3). It might be thought that this was because the participants were not attracted to the attractive model. However, this explanation is inconsistent with behavioral data showing a greater preference for attractive females than unattractive females. One alternative explanation for the null finding is that this information could be decodable during the outcome phase rather than the anticipatory delay phase. Numerous studies have reported the involvement of the NAcc and mOFC in the positive social evaluation of faces (Aharon et al. 2001; O'Doherty et al. 2003; Kranz and Ishai 2006; Ishai 2007; Kim et al. 2007; Bzdok et al. 2011; Mende-Siedlecki et al. 2013; Ueda et al. 2017). Kim et al. (2007) suggested functional dissociations between these regions in reward processing, such that the NAcc conveys information on the reward to the orbitofrontal cortex, which underlies subjective evaluation processes. A meta-analysis study of the monetary incentive delay task also suggested that the mOFC represents the value of the reward received rather than anticipation of the reward (Oldham et al. 2018). These findings lead us to predict that neural activity patterns in the mOFC could be more sensitive to differences in attractive and unattractive females than in the NAcc, especially during the outcome phase, which could involve an evaluation of the presented stimulus.

Consistent with this prediction, we observed above-chance classification performance in the mOFC (mean of the left and right) during the outcome phase in a three-way comparison across partner-hit, attractive-hit, and unattractive-hit conditions (chance = 33.3%; mean = 38.4%, SD = 10.3%, t(37) = 3.06, p = 0.002, d = 0.49, lower 95% CI = 35.6%). As in the NAcc during the anticipatory delay phase, we found no significant differences in the mean accuracies for this three-way comparison between the left (mean = 39.1%, SD = 15.5%) and right (mean = 37.7%, SD = 14.6%) mOFCs (t(37) = 0.39, p = 0.70, d = 0.09, 95% CI = [−5.84, 8.65]). We also observed above-chance classification performance in a four-way comparison including the control-hit condition (chance = 25%; mean = 34.3%, SD = 7.7%, t(37) = 7.44, p < 0.001, d = 1.18, lower 95% CI = 32.2%, one-tailed; see also Section 8 in *Supplemental Material*). Pairwise analysis (adjusted p-value = p-value multiplied by 3; Figure 4) revealed an above-chance difference in classification performance in the attractive-hit vs. unattractive-hit conditions (chance = 50%; mean = 55.0%, SD = 11.9%, t(37) = 2.59, adjusted p = 0.021, d = 0.41, lower 95% CI = 51.7%, one-tailed). We also observed higher mean classification accuracy over the chance level for the comparisons between the partner-hit and unattractive-hit conditions (mean = 62.1%, SD = 12.9%, t(37) = 5.77, adjusted p < 0.001, d = 0.92, lower 95% CI = 58.6%, one-tailed); however, above-chance performance was not observed for the classification between the partner-hit and attractive-hit conditions (mean = 53.0%, SD = 15.7%, t(37) = 1.19, adjusted p = 0.36, d = 0.19, lower 95% CI = 48.7%, one-tailed), which likely reflected smaller differences in likeability ratings between the partner and attractive conditions relative to those between the partner and unattractive conditions (Figure 2B).

Contrary to successful decoding in the mOFC, we did not observe above-chance differences in classification performance in the outcome phase for the NAcc in the three-way comparison (chance = 33.3%; mean = 35.8%, SD = 10.0%, t(37) = 1.53, p = 0.067, d = 0.24, lower 95% CI = 33.1%, one-tailed). Here, the critical test for this asymmetry was to determine whether a region x phase interaction was significant. Two-way ANOVA on classification performances with region (NAcc and mOFC) and phase (anticipatory delay and outcome) as the within-subject factors revealed a significant interaction ($F(1, 37) = 7.73$, $p = 0.009$, $\eta_p^2 = 0.17$).

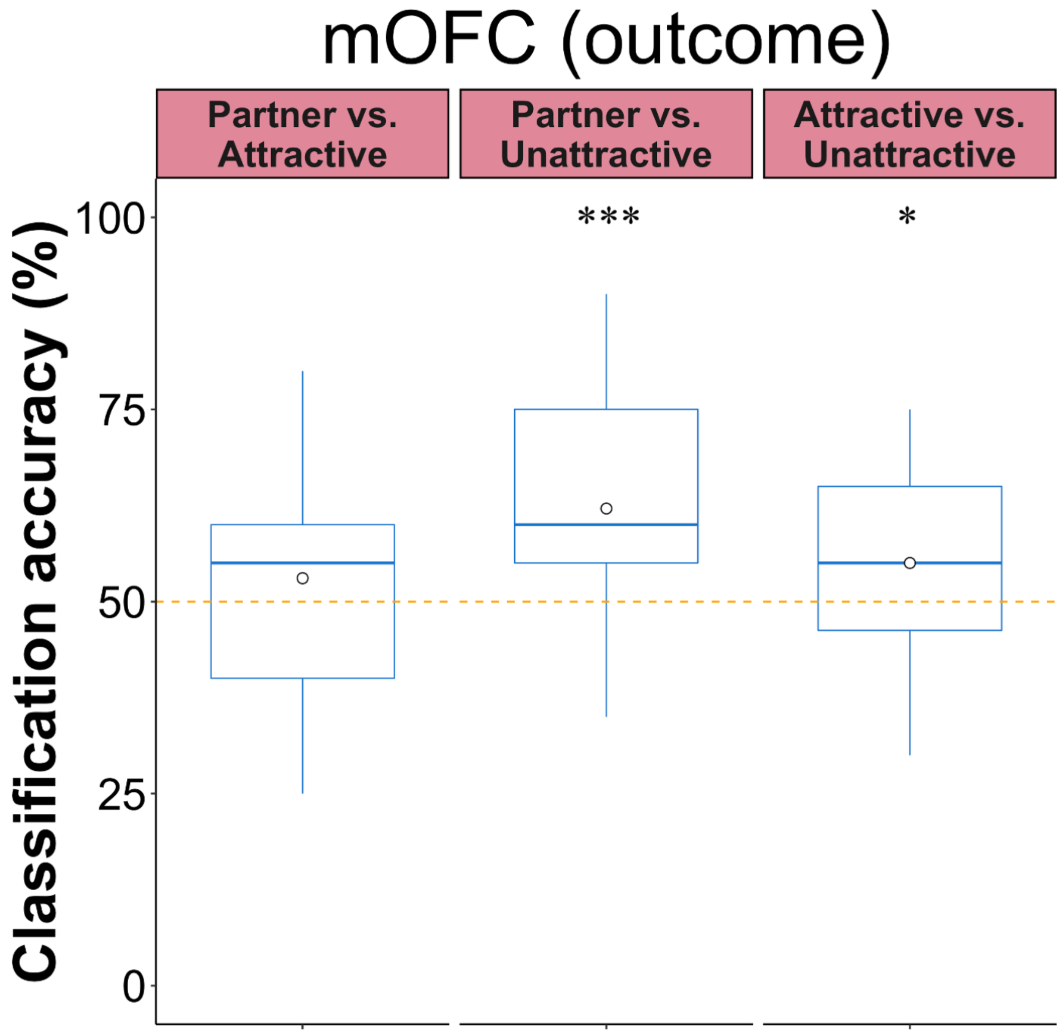


Figure 4

Results of the classification analysis for the medial orbitofrontal cortex (mOFC) during the outcome phase, illustrating mean accuracies of the left and right mOFC. Box and whisker plots with white dots are as defined in Figure 2. A classification accuracy better than chance was determined using a one-sample t-test vs. 50% (one-tailed). $^{***}p < 0.001$, $^{*}p < 0.05$

Discussion

While there has been a consensus that reward circuitry underlies romantic attachment toward a committed partner, it is unclear whether this is encoded in a dissociable way from a general preference for attractive opposite-sex individuals. Numerous studies have reported biased behaviors that could contribute to relationship maintenance shown by romantically involved individuals; therefore, we expected to observe distinct neural representations in the NAcc between the committed partner and other opposite-sex individuals. Using MVPA and the SID task, we found unique neural activity patterns in the NAcc when positive feedback from the committed partner was anticipated.

The classification approach used in the present study allowed us to clarify unique neural representations in the NAcc related to the romantic partner, which could extend previous findings on the neural basis for emotional bonding with the partner, identified using conventional univariate fMRI (Fisher et al. 2010; Acevedo et al. 2012). Our results are consistent with previous studies showing the NAcc as a crucial region for establishing both selective preferences toward the committed partner and avoidance behavior toward alternative partners both in human and nonhuman monogamous animals (Young and Wang 2004; Scheele et al. 2012, 2013, 2016; Kreuder et al. 2017; Walum and Young 2018). The present findings for the NAcc also fit well with a theoretical framework of the automatic regulation of amorous temptation via emotional bonding with a partner (Finkel and Eastwick 2015; Fletcher et al. 2015; Lydon and Karremans 2015).

Another notable finding was that the mOFC differentially encoded positive feedback from attractive females and unattractive females, while the NAcc did not during anticipation of the feedback. These results imply that neural activity patterns in the mOFC could be more sensitive to differences in attractive and unattractive females than in the

NAcc, especially during the outcome phase, which could involve an evaluation of the presented stimulus. These findings provide tentative support for the idea of functional dissociation in the NAcc and mOFC in the domain of reward anticipation and receipt (e.g., Kim et al., 2007; Oldham et al. 2018), which contributes to explaining the lack of differences in the NAcc classification accuracy between attractive and unattractive females during the anticipatory phase.

In this study, we aimed to reveal whether the NAcc encodes emotional bonding with the committed partner differently from an interest in new relationships. To this end, we used movie clips and pictures of unfamiliar opposite-sex individuals instead of those of familiar individuals. Therefore, our findings cannot rule out the possibility that the effects observed in the present study reflect differences in other variables, such as saliency or familiarity of each person. Future studies should extend our findings by testing whether neural representations of emotional bonding with committed partners could be dissociable from the romantic interest in familiar nonpartners (e.g., opposite-sex friends to whom the romantically involved individual is attracted). In such an investigation, implicit measures would be more desirable to avoid potential confounding effects, including concern for social desirability, by explicitly demonstrating romantic interest in nonpartners. Applying MVPA to neural data obtained from sophisticated experimental procedures, such as a visual attention task (Miller 1997; Maner et al. 2007), might allow us to reveal how the NAcc encodes such implicit romantic interest in familiar nonpartners. We discuss the other possible future directions in Section 9 in *Supplemental Material*.

Two further limitations of the present study warrant attention. First, we note that the classification approach does not tell us what kinds of information are included in the neural representations. Unique neural representations related to the partner might involve distinctively perceived attractiveness to that person, or it might involve more general likeability to that person. To address this issue, representational similarity analysis (RSA, Kriegeskorte et al. 2008; Kriegeskorte and Kievit 2013; Popal et al. 2019) would be suitable, which can assess higher-order representational space across multiple dimensions. Second, as we focused only on individuals in nonmarital dating relationships, it remains unclear whether our findings are generalizable to relationships involving marriage. We leave these questions as topics for future research.

In conclusion, we found that the NAcc encodes distinctive neural representations of the committed partner and unfamiliar attractive nonpartners using a classification approach. To the best of our knowledge, the present study is the first to directly demonstrate unique neural representations related to the committed partner, which might be a key neural mechanism for single-minded romantic relationships.

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Supplemental Material

1. Stimuli used in the social reward incentive delay task

The participants were engaged in the social reward incentive delay (SID) task, which assesses the neural responses that underlie the anticipation of positive feedback from a cued person. The SID task had four conditions: partner female, attractive female, unattractive female, and control. Similar to a previous study (Kohls et al. 2013), we prepared facial pictures and short movie clips for each person as stimuli. The stimuli presented in the partner condition were unique to each participant (i.e., the participant's current partner's facial picture and movie clips). The stimuli for the attractive and unattractive conditions were fixed for all participants. For the stimuli presented in the control condition, we created mosaicked pictures and movie clips generated from stimuli presented in the other three experimental conditions.

Since our interest was in comparing neural responses across conditions, especially comparing the committed partner and the attractive opposite-sex individual, we sought to maximize the participants' reaction to the attractive female. To prepare the attractive female's facial picture and movie clips, we recruited seven candidate females (aged 22–28 years) and took pictures of them with a neutral facial expression. For the stimuli signaling positive feedback as social approval, we recorded ten short movie clips for each in which a person expressed happiness with the face and performed positive gestures (e.g., smiling with the V-sign, OK-sign, or waving the right hand to the camera). For the nonapproval stimuli presented in error trials, we recorded a short clip where a person adopted a neutral facial expression without making any gestures. The models were asked to imitate the sample pictures and movie clips, during which they were photographed and recorded. The resulting pictures and movie clips were modified using Adobe Photoshop and Premiere Pro. Before the fMRI experiment, 20 male participants who did not participate in the fMRI study rated the movie clips of the models' neutral and happy expressions on a 7-point scale of facial attractiveness (1: very unattractive, 7: very attractive). Using the means of these ratings, we selected the most attractive female and the least attractive female. Two-way ANOVA with factors for the model (attractive or unattractive) and expression (a movie clip with a neutral expression and mean ratings for ten movie clips with happy expressions) confirmed significant main effects for model (attractive > unattractive: $F(1, 19) = 96.06$, $p < 0.001$, $\eta_p^2 = 0.83$) and expression (happy > neutral: $F(1, 19) = 7.87$, $p = 0.011$, $\eta_p^2 = 0.29$) in the absence of an interaction effect ($F(1, 19) = 0.13$, $p = 0.72$, $\eta_p^2 = 0.007$). Thus, the stimuli for highly attractive and unattractive females were prepared, for whom the clips with happy expressions were considered preferable to those with a neutral expression. These stimuli were presented as attractive and unattractive conditions in the SID task.

We also obtained pictures and movie clips of the female partners of the fMRI participants using the same procedure described above. The females participated in the recording without the presence of the fMRI participants. They were asked not to disclose any details of the recording to their partners until the experiment was completed.

2. Questionnaire measuring relationship commitment and attitudes toward extrapair relationships

Following task completion, the participants completed two questionnaires on relationship quality, including relationship commitment and attitudes toward extrapair relationships. Since these features have been demonstrated to influence relationship duration (Simpson 1987; Betzig 1989; Felmlee et al. 1990; Miller 1997; Whisman et al. 1997; Amato and Previti 2003; Le et al. 2010; Ueda et al. 2017), we expected that they could be associated with neural representations related to the partner. The results of this exploratory analysis are summarized in Sections 6 and 7 in the Supplemental Material.

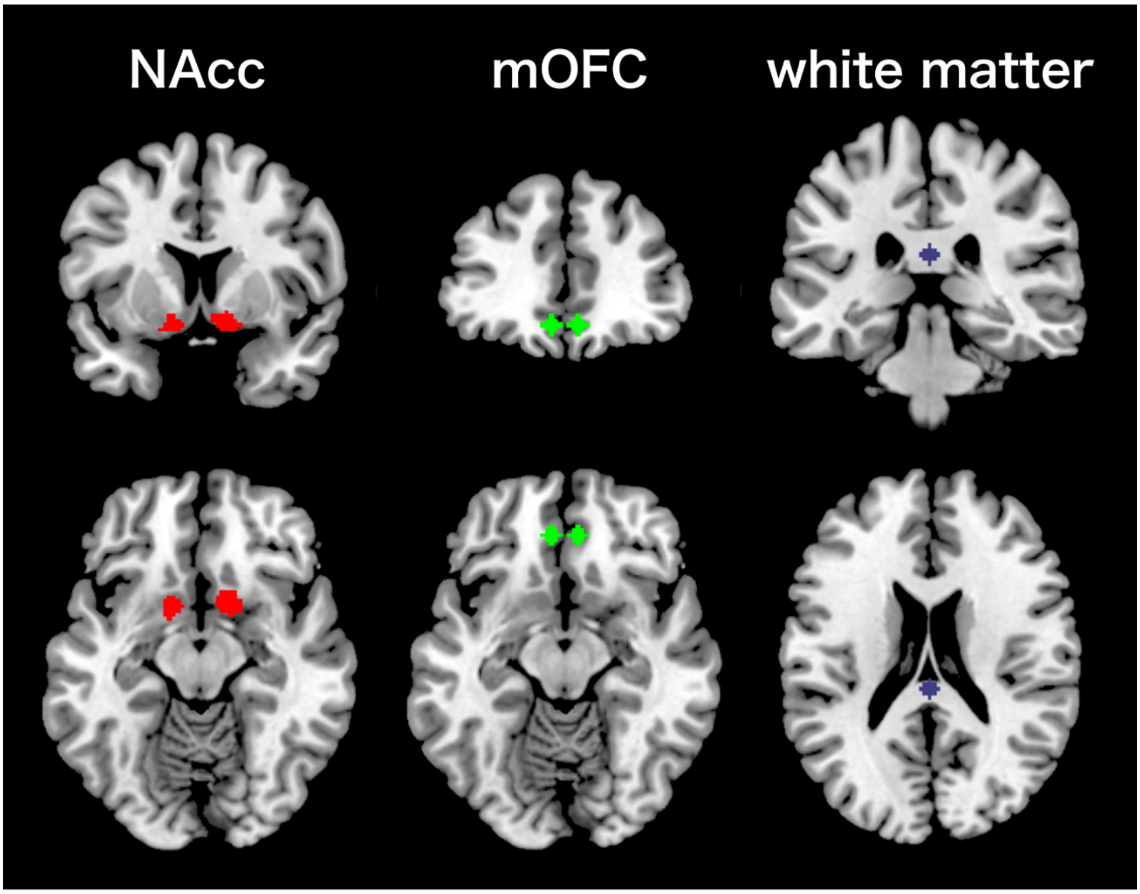
To assess the degree of relationship commitment, we used a standardized questionnaire (Gagne and Lydon 2003). This questionnaire has nine items, of which four inquire into the extent to which the respondent feels committed to, obligated to, attached to, and a sense of duty toward the relationship (moral commitment factor). The next four items inquire into the extent to which the respondent enjoys the current relationship, feels enthusiastic about it, is not burdened by it, and would not feel relieved if it were to end (enthusiastic commitment factor). The participants responded to these items on a 9-point scale (1: not at all, 9: extremely). The last item asks respondents to estimate how long they expect their relationships to last on a scale of 1 (a week or so) to 9 (decades). Following the procedure given by Gagne and Lydon (2003), we excluded the duty and obligation scores when calculating the aggregated score, as they were not significantly correlated with the remaining items in the original study. Then, we created an aggregated relationship commitment score by averaging the scores of the remaining 7 items. Higher scores represent greater relationship commitment. The mean score across participants was 7.09 (SD = 1.27, range = 2.29–9.00). Interitem reliability was very high (Cronbach's α =

0.84) and comparable to that of the original study (α = 0.87). Before conducting statistical tests, we performed winsorization on one participant's relationship scores whose scores (aggregated, moral, and enthusiastic commitment scores) were 3 SDs below the means across all participants; that is, his scores were replaced with the next lowest scores. The correlation coefficients of the aggregated relationship commitment score with the subscales were 0.73 (with moral commitment score) and 0.94 (with enthusiastic commitment score).

The questionnaire to assess tolerant attitudes toward extrapair relationships asked participants to respond to the following three prompts on a 7-point scale: a) where is infidelity, from very negative or very positive; b) where is it, from very horrible to very attractive; and c) where is it, from very impure to very pure? We confirmed that inter-item reliability was sufficiently high (α = 0.70), and the correlations of item scores with total scores (not corrected for item overlap) were high for all items (item 1, r = 0.78; item 2, r = 0.82; and item 3, r = 0.78). An aggregated attitude score was created by averaging the scores for the three items, where higher scores represented a greater tolerance for extrapair relationships. The mean score across participants was 2.25 (SD = 1.10, range = 1.00–4.67). This relatively low mean score confirms that the committed individuals who participated in the current study generally demonstrated less tolerant attitudes toward extrapair relationships.

3. Region of interest definition

We anatomically defined regions of interest (ROIs) for the left and right nucleus accumbens (NAcc) based on the Individual Brain Atlas using Statistical Parametric Mapping software (IBASPM; Aleman-Gomez et al. 2006), implemented with the WFU PickAtlas (Wake Forest University, Winston-Salem, NC; Maldjian et al. 2003). The sizes of the left and right NAcc mask images were 50 and 77 voxels, respectively. We also investigated the medial orbitofrontal cortex (mOFC), a key region for subjective evaluation of facial attractiveness or preference (O'Doherty et al. 2003; Kranz and Ishai 2006; Ishai 2007; Kim et al. 2007). A meta-analysis of the monetary incentive delay task indicated a functional dissociation between the NAcc and mOFC, suggesting greater mOFC responses during reward receipt relative to anticipation (Oldham et al. 2018). We constructed sphere mask images within the mOFC with center coordinates drawn from the automated meta-analysis of the NeuroSynth database (http://www.neurosynth.org; downloaded on 12 December 2019). First, we obtained statistical maps based on a meta-analysis of 470 studies associated with "value" (taken from a keyword search), and we set the center coordinates of the anatomically defined mOFC ROIs: the left mOFC centered on MNI coordinates −6, 40, −12, Z = 7.52; the right mOFC centered on MNI coordinates 6, 40, −12, Z = 4.62. Then, bilateral mOFC ROIs were defined as spheres with a 4-mm radius (33 voxels) centered on each coordinate using MarsBar software (Brett et al. 2002). The mask sizes were determined to be nearly equivalent to the bilateral NAcc ROI masks. We also created an ROI mask as a sphere with a 4-mm radius within the white matter (splenium of corpus callosum, centered on MNI coordinates 0, −30, 20). Supplemental Figure 1 illustrates these masks.



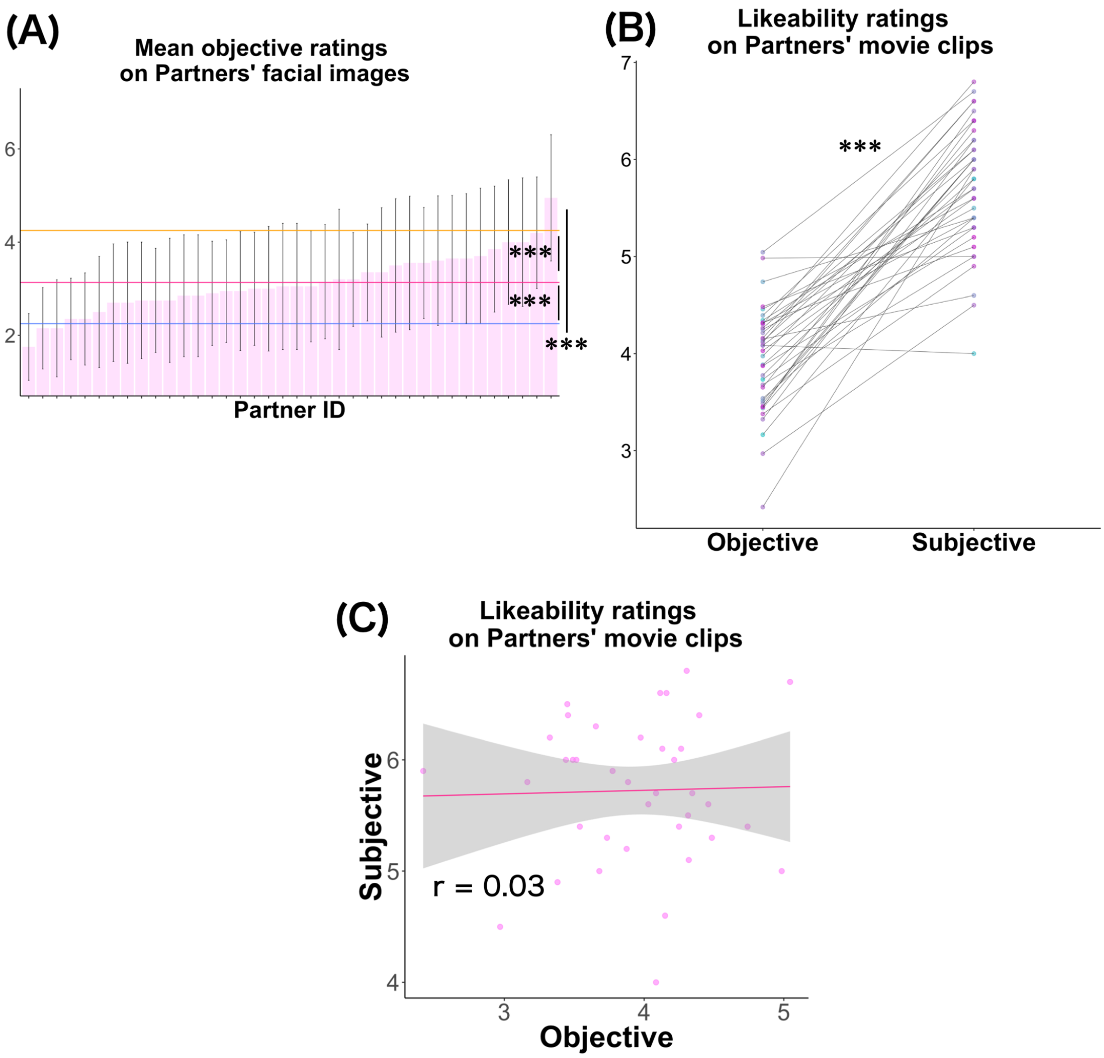
Supplemental Figure 1

The mask images for the regions of interest (ROIs) used in the classification analysis. We anatomically defined the bilateral nucleus accumbens (NAcc) from the Individual Brain Atlas using Statistical Parametric Mapping (IBASPM) software. We also generated sphere mask images of the bilateral medial orbitofrontal cortex (mOFC: left centered on MNI coordinates −6, 40, −12; right centered on MNI coordinates 6, 40, −12) and of white matter (splenium of corpus callosum: centered on MNI coordinates 0, −30, 20).

4. Positive reactions to the committed partner

The greater preference for the happy expression of the partner compared with that of the attractive female, which we observed in the rating task (see Figure 2), might represent a positive illusion experienced by romantically involved individuals (Murray et al. 1996; Murray and Holmes 1997; Barelds-Dijkstra and Barelds 2008; Barelds et al. 2011). We anticipated that this greater preference for the movie clips of the partner females would be observed only in the fMRI participants. To test this prediction, we recruited an independent group of 20 heterosexual male participants who did not participate in the fMRI study. They were asked to rate the facial attractiveness of images of faces with neutral expressions (1: very unattractive, 7: very attractive) and the likeability of movie clips with happy expressions (1: not at all, 7: extremely) for all females presented in the SID task.

As expected, the results obtained in this independent group and the fMRI participants yielded a stark contrast. One-way ANOVA for the attractiveness ratings of the facial images revealed a significant effect of condition ($F(2, 38) = 32.21$, $p < 0.001$, $\eta_p^2 = 0.63$), and post hoc t-tests with adjusted p-values with Bonferroni correction (i.e., adjusted p-value = p-value multiplied by 3) indicated significant differences across all conditions (partner vs. attractive: $t(19) = 4.43$, adjusted $p < 0.001$, $d = 0.73$, 95% confidence interval (CI) for the mean difference = [0.59, 1.65]; partner vs. unattractive: $t(19) = 4.79$, adjusted $p < 0.001$, $d = 0.85$, 95% CI for the mean difference = [0.50, 1.27]; attractive vs. unattractive: $t(19) = 6.69$, adjusted $p < 0.001$, $d = 1.37$, 95% CI for the mean difference = [1.37, 2.63]). The participants in the independent group rated the image of the attractive female with a neutral expression as more attractive than images of nearly all partners (Supplemental Figure 2A). We found that only one of the 38 partners was assigned a mean attractiveness rating across participants that was higher than the mean for the attractive model. These results indicated a successful manipulation of stimuli (i.e., the attractive model was considered more attractive than the majority of partner females) and the positive illusion of the fMRI participants. As a further indication of this positive illusion, the participants in the fMRI study exhibited greater preference for their partner's movie clips than the participants in the independent group did ($t(37) = 13.24$, $p < 0.001$, $d = 2.10$, 95% CI for the mean difference = [1.51, 2.06]; Supplemental Figure 2B), and no correlation between the likeability ratings for the two groups was observed for the partner females ($r = 0.03$, $t(36) = 0.16$, $p = 0.87$, 95% CI for the coefficient = [−0.30, 0.34]; Supplemental Figure 2C).



Supplemental Figure 2

Comparison of ratings given by the fMRI participants (termed subjective) and the independent group (termed objective). (A) The mean attractiveness ratings for the neutral-expression facial images of the 38 partner females across participants in the independent group. The orange-colored horizontal line indicates across-participant mean ratings for the attractive model (mean = 4.25, SD = 1.59). The pink line presents the mean ratings for the partner females (mean = 3.13, SD = 0.98). The blue line indicates the mean ratings for the unattractive model (mean = 2.25, SD = 1.02). The error bars indicate the standard deviation across participants. (B) The likeability of partners' happy-expression movie clips rated by each group. Each dot represents the mean rating for the partner female across participants in the group. (C) The scatter plot for likeability ratings on partners' happy-expression movie clips between the two groups. Each dot represents the mean rating for the given partner across participants, and the line with shaded areas represents the results of the regression analysis and the 95% confidence interval. The subjective score is the mean rating for the ten movie clips obtained from the fMRI participants (male partner). The objective score was calculated from the mean rating for ten movie clips obtained from the independent group participants. $^{***}p < 0.001$

5. Classification between anticipation of social and nonsocial stimuli

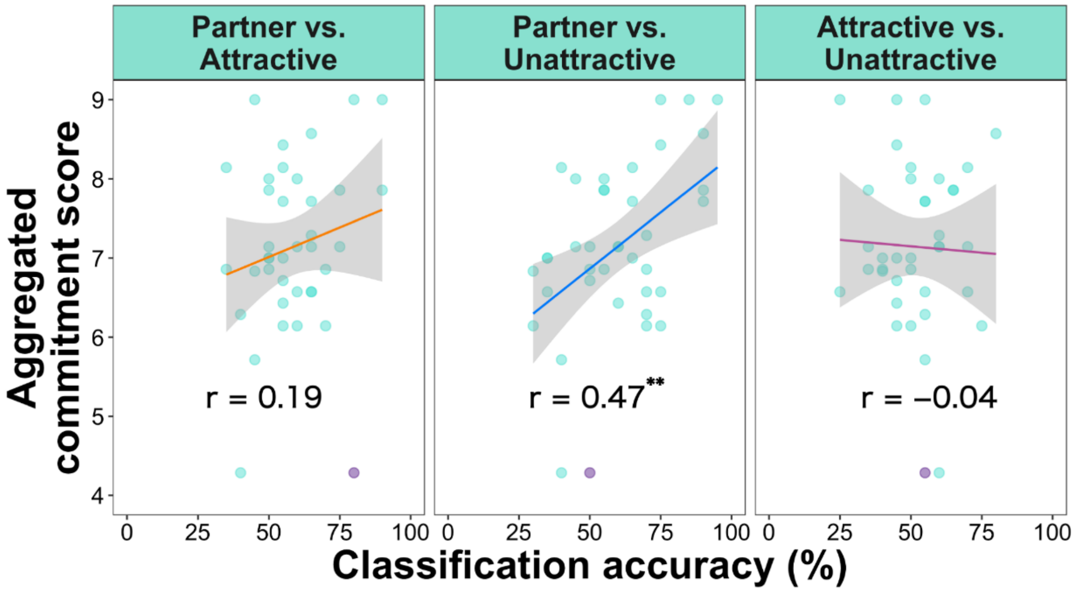
The SID task in the present study included a control condition in which a mosaicked picture was presented as a cue, and in the outcome phase, a mosaicked movie clip appeared on the screen, regardless of the performance. To determine whether NAcc activity could discriminate the control condition from the other experimental conditions, we performed a pairwise classification analysis between the social (partner, attractive, and unattractive) and nonsocial (control) conditions during the anticipatory delay phase. This classification, however, involves an imbalance issue. That is, while the partner, attractive, and unattractive conditions are labeled social conditions, only the control condition is labeled a nonsocial condition; therefore, the numbers of trials for each label are not equalized, which could bias the classification accuracies. To solve this issue, we performed a bootstrap sampling procedure; that is, we randomly removed some samples (without replacement) to ensure that the number of samples in each label was equalized for each run. This process was repeated 1,000 times, which resulted in average classification accuracy for each participant. We observed that mean social vs. nonsocial classification accuracy across participants was above chance (one-sample t-test compared with 50%; mean = 54.0%, SD = 9.1%, $t(37) = 2.69$, $p = 0.005$, $d = 0.43$, 95% CI for the mean = [51.5%, ∞], one-tailed), supporting the notion that the anticipation of positive feedback from the cued person is encoded in the NAcc in a distinguishable way from that of nonsocial stimuli.

6. Exploratory correlation analyses between classification accuracy in the NAcc and relationship commitment

We explored whether individual differences in relationship commitment were associated with classification accuracy in the NAcc. However, the present study's sample size is rather small to provide adequate power for the across-participant correlation tests. To achieve a power of 0.9 to detect the medium-size effect, a sample size of 112 is required (*Correlation: Bivariate normal model* on a G-Power Version 3.1.9.4; Faul et al. 2007, 2009). Thus, we note that our correlation analyses only provide preliminary results.

We performed simple correlation tests using the averaged classification accuracy (i.e., mean of the left and right regions) in the NAcc in the anticipatory delay phase, which is based on the assumption that higher classification accuracy represents better encoding of stimulus information (Etzel et al. 2016). To control the familywise error rate of multiple comparisons (i.e., classifications between partner vs. attractive, partner vs. unattractive, and attractive vs. unattractive), we report adjusted p-values with Bonferroni correction (i.e., adjusted p-value = p-value multiplied by 3). We observed that individuals with greater commitment exhibited significantly higher classification accuracy (i.e., more distinguishable activation patterns) between the partner and unattractive conditions in the NAcc ($r = 0.47$, $t(36) = 3.17$, adjusted $p = 0.009$, 95% CI for the coefficient = [0.17, 0.68]; Supplemental Figure 3). This effect remained significant even after controlling for the participant's age and log-transformed length of the relationship with the current partner (standardized regression coefficient $\beta = 0.41$, $t(34) = 2.30$, $p = 0.028$, 95% CI for the coefficient = [0.05, 0.76]). However, we found no significant correlation with relationship commitment when using the classification accuracy between the partner and attractive condition ($r = 0.19$, $t(36) = 1.13$, adjusted $p = 0.79$, 95% CI for the coefficient = [−0.14, 0.48]) or between the attractive and unattractive condition (r = −0.04, t(36) = −0.23, adjusted p = 1.00, 95% CI for the coefficient = [−0.35, 0.28]), as illustrated in Supplemental Figure 3.

As described in Section 2, the relationship commitment scale that we used (Gagne and Lydon 2003) consisted of two factors, moral commitment and enthusiastic commitment. We observed similar correlations between these subscale scores and classification accuracy between the partner and unattractive conditions (moral commitment score: r = 0.39, t(36) = 2.52, adjusted p = 0.049, 95% CI for the coefficient = [0.08, 0.63]; enthusiastic commitment score: r = 0.53, t(36) = 3.79, adjusted p = 0.002, 95% CI for the coefficient = [0.26, 0.73]). No significant correlations were found between the subscale scores and the classification accuracy between the partner and attractive condition (moral commitment score: r = 0.10, t(36) = 0.59, adjusted p = 1.00, 95% CI for the coefficient = [−0.23, 0.41]; enthusiastic commitment score: r = 0.23, t(36) = 1.43, adjusted p = 0.48, 95% CI for the coefficient = [−0.10, 0.51]) or between the attractive and unattractive condition (moral commitment score: r = −0.01, t(36) = −0.07, adjusted p = 1.00, 95% CI for the coefficient = [−0.33, 0.31]; enthusiastic commitment score: r = −0.10, t(36) = −0.62, adjusted p = 1.00, 95% CI for the coefficient = [−0.41, 0.22]).

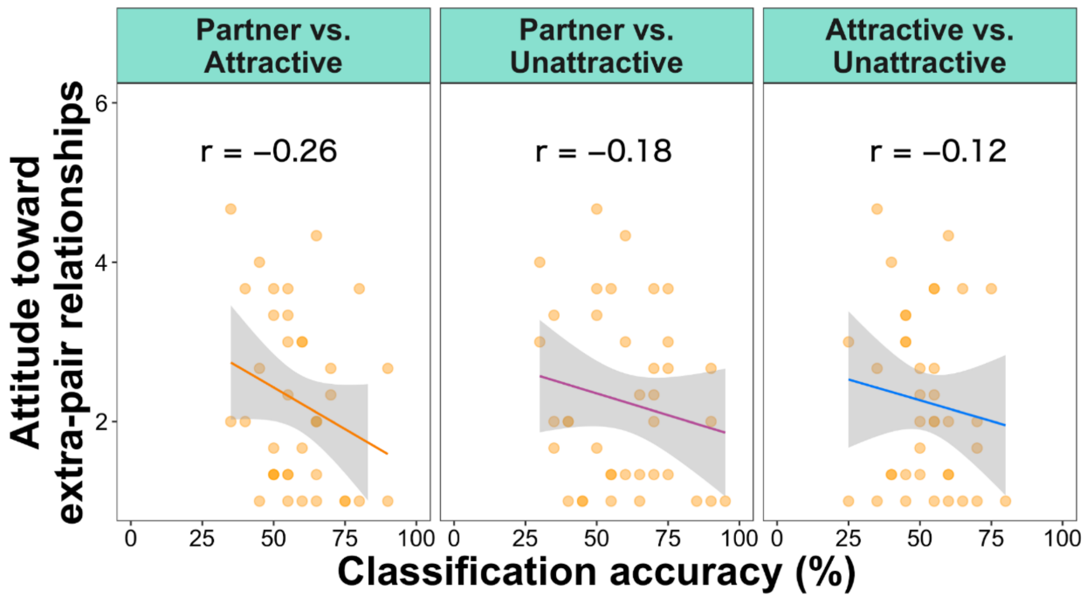


Supplemental Figure 3

Scatter plots for the relationships between classification accuracy for the NAcc activity patterns during the anticipatory delay phase and relationship commitment across participants. Each dot denotes a participant, and the lines with shaded areas represent the results of the regression analysis and the 95% confidence intervals. The purple dots denote one participant whose commitment scores were winsorized. $^{**}p < 0.01$

7. Exploratory correlation analyses between neural activity patterns in the NAcc and attitudes toward extrapair relationships

We explored whether neural activity patterns in the NAcc during the anticipatory delay phase were associated with attitudes toward extrapair relationships assessed by a questionnaire. As illustrated in Supplemental Figure 4, no significant correlations were observed in all conditions (partner vs. attractive: r = −0.26, t(36) = −1.61, adjusted p = 0.35, 95% CI for the coefficient = [−0.53, 0.07]; partner vs. unattractive: r = −0.18, t(36) = −1.09, adjusted p = 0.85, 95% CI for the coefficient = [−0.47, 0.15]; attractive vs. unattractive: r = −0.12, t(36) = −0.74, adjusted p = 1.00, 95% CI for the coefficient = [−0.43, 0.21]; p-values were adjusted by multiplying 3).



Supplemental Figure 4

Scatter plots for the relationships between the classification accuracy of the NAcc during the anticipatory delay phase and attitudes toward extrapair relationships. Each dot denotes a participant, and the lines with shaded areas represent the results of the regression analysis and the 95% confidence intervals.

8. Classification between obtaining positive feedback from social and nonsocial stimuli

To determine whether mOFC activity could discriminate the control condition from the other experimental conditions, we performed a pairwise classification analysis between the social (partner, attractive, and unattractive) and nonsocial (control) conditions during the outcome phase. We used a bootstrap sampling procedure (see Section 5) and observed above-chance classification accuracy, similar to the finding in the NAcc during the anticipatory delay phase (one-sample t-test compared with 50%; mean = 61.9%, SD = 11.7%, $t(37) = 6.22$, $p < 0.001$, $d = 0.99$, 95% CI for the mean = [58.6%, ∞], one-tailed).

9. Supplemental Discussion

Here, we present some future directions in this line of research. First, sex differences are important topics to be pursued. Because we limited our study to only heterosexual male volunteers to avoid possible confounding effects, our results do not indicate whether similar neural mechanisms would be observed in females or homosexual individuals. Males have been reported to express a desire for romantic relationships with more potential partners than females (Buss and Schmitt 1993; Wiederman 1997). Additionally, the probability of extramarital sex experiences is believed to be higher in males than in females (e.g., Atkins et al. 2001). In addition to relationship maintenance, other studies have focused on sex differences in behaviors of mate switching, which potentially reflects that the cost of mate switching is likely to be higher in females (e.g., damage to reputational components of her mate value or loss of support from her partner; Buss et al. 2017). According to the theoretical framework that these sex differences may be deeply related to different strategies for mate selection (Buss 1989; Buss and Schmitt 1993), females can be expected to exhibit a more significant difference in decoding accuracy relative to their long-term partner or alternative partners than males, which might represent a greater motivation to maintain a committed relationship.

Second, longitudinal assessment could provide further insight into how dissociable neural representations of the long-term partner and other opposite-sex individuals are formed. It is well known that relationship quality dynamically changes over time. The early stages of a romantic relationship usually involve limerence, the involuntary romantic infatuation with the partner (Tennov 1979; Fisher et al. 2016; Ueda et al. 2018), which is believed to be sustained by the limbic reward system (Aron et al. 2005). However, this sort of addictive passionate love generally loses intensity over time

(Traupmann and Hatfield 1981; Sternberg 1986; Tucker and Aron 1993). Several studies have found neurochemical changes associated with relationship quality (Marazziti et al. 1999; Marazziti and Canale 2004). We, therefore, expect to find linear or nonlinear temporal changes in neural representations related to the partner over time. In support of this hypothesis, one study that surveyed relationship quality in marital relationships reported a U-shaped association between happiness and relationship duration, characterized by the highest happiness in the earliest and latest years of marriage (VanLaningham et al. 2001).

Third, investigations of cultural differences would also be valuable. It has been reported that 84% of the 853 societies tabulated in Murdock's Ethnographic Atlas permit polygyny, and 44% of those cultures regard polygyny as the preferred marriage form (Van den Berghe 1979). Attitudes toward single-minded romantic relationships might be different in those societies and would be expected to involve different neural mechanisms. Furthermore, some researchers have hypothesized that attitudes about romantic relationships can alter over time, which could be modulated by social factors such as social norms and exposure to media (Buss et al. 2001; Hatfield et al. 2010). For instance, initiating a romantic relationship from online dating has recently been prevalent in the United States (Rosenfeld et al. 2019), which may have influenced our attitude toward romantic relationships.

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