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(Citation)
Social Neuroscience,15(5):600-612

(Issue Date)
2020-10-22

(Resource Type)
journal article

(Version)
Accepted Manuscript

# Role of the Orbitofrontal Cortex in the Computation of Relationship Value

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## Author Note

We are grateful to Haruo Isoda, Akira Ishizuka, and Tamotsu Kawai (Brain and Mind Research Center, Nagoya University, Aichi, Japan) for their technical support. We also thank Adam Smith for his valuable comments on earlier manuscripts. This work was supported by the Japan Society for the Promotion of Science [KAKENHI 15H03447 to Y.O.]; and the John Templeton Foundation.

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**Abstract**

This research investigated whether the medial orbitofrontal cortex (OFC), which is known to code the value of various rewards, is involved in the relationship value recalibration process. Previous research suggests that people upregulate the relationship value of a specific friend in response to the friend's commitment signals. In a functional magnetic resonance imaging study (Study 1), participants imagined receiving high-cost commitment signals, low-cost commitment signals, or no signals from a particular friend. Participants' subjective rating of the relationship value upregulation was positively correlated with medial OFC activity. Subtraction analyses showed that high-cost commitment signals engaged the medial OFC more than did signal failures. An auxiliary analysis revealed that medial OFC activity in response to low-cost commitment signals was negatively correlated with loneliness. To follow-up these findings, we conducted an online vignette study (Study 2), in which participants rated the relationship value of a real friend before and after imagining receiving a series of low-cost commitment signals from that friend. Corroborating the upregulation hypothesis, perceived relationship value significantly increased after imagining a series of commitment signals. This effect was weaker among individuals high in loneliness.

**Keywords:** relationship value, commitment signal, orbitofrontal cortex (OFC), loneliness

Friendship is ubiquitous in human societies and is characterized by need-based transfers of costly support, which is important to one's fitness in pre-industrialized societies (Cronk et al., 2019; Dunbar, 2018; Hruschka, 2010). Accordingly, it has been hypothesized that the human mind has adapted to keep track of the relationship value of specific friends (Tooby, Cosmides, Sell, Lieberman, & Sznycer, 2008). Previous research has revealed that relationship value exerts various influences on interpersonal behavior; for example, participants in a resource allocation game behaved more generously toward more valuable partners than toward less valuable partners (Smith, Lieberman, Pedersen, Forster, & McCullough, 2017). Relationship value also influences the reconciliation process: Victims are more forgiving when they have been hurt by valuable partners (Burnette, McCullough, Van Tongeren, & Davis, 2012; McCullough, Bono, & Root, 2007; McCullough, Pedersen, Tabak, & Carter, 2014; Smith et al., 2019), and transgressors are more prone to feeling guilty and apologizing in a sincere fashion when they hurt valuable partners (Nelissen, 2014; Ohtsubo & Yagi, 2015).

Anthropological studies have shed light on how people keep track of the relationship value of specific friends. Bliege Bird, Ready, and Power (2018) focused on seemingly functionless social sharing in many pre-industrialized societies. For example, day-to-day sharing between specific partners of locally abundant resources, such as wild tubers and sardines, does not seem to enhance their fitness because the sharers could acquire the same resources without participating in dyadic sharing. Accordingly, Bliege Bird et al. (2018) proposed that the primary function of such sharing is to signal one's commitment to the relationship and thus reaffirm the existing relationship. A possible counterpart of such day-to-day sharing in modern, industrialized societies may be exchanges of pro-relationship behaviors (Yamaguchi, Smith, & Ohtsubo, 2015, 2017). For example, listening to a friend's personal problems for a long period and planning/throwing a surprise party for a friend's birthday serve as commitment signals; recipients of such pro-relationship behaviors, which are costly in terms of time spent by the signalers listening or planning, tend to upregulate the relationship value of the signalers (Yamaguchi et al., 2015, 2017). This result is reasonable because spending one's time on a particular friend prohibits the signalers from interacting with other potential partners, therefore clearly demonstrating their commitment to their friendship (Dunbar, 2018; Miritello et al., 2013; Sutcliffe, Dunbar, Binder, & Arrow, 2012; for the effect of cost involved in social signals, see Laidre & Johnstone, 2013).

However, relatively low-cost pro-relationship behaviors (e.g., just giving a birthday wish) are also known to facilitate upregulation of the relationship value, though to a lesser extent than do high-cost pro-relationship behaviors (Yamaguchi et al., 2015, 2017). This is likely because such low-cost pro-relationship behaviors still require constant attention on the target—it is easy to forget someone's birthday unless we are constantly paying attention to them (Ohtsubo et al., 2014). In line with this attention explanation, it has been revealed that people are not only attentive to their friends' needs (Clark, Mills, & Corcoran, 1989) but are also careful in monitoring whether their friends are paying attention to their needs (Clark, Dubash, & Mills, 1998; Ohtsubo et al., 2014). Moreover, people tend to increase their sense of intimacy toward someone who pays attention to them (Ohtsubo et al., 2014; Ohtsubo & Tamada, 2016; Ohtsubo & Yamaguchi, 2017).

Although psychological studies have accumulated evidence that people recalibrate their partners' relationship value in response to commitment signals (i.e., high- and low-cost pro-relationship behaviors), the neural underpinnings of such recalibration remain uninvestigated. In neuroeconomics literature, the orbitofrontal cortex (OFC) is implicated in representing the value of various rewards, such as food, money, and social rewards, as a “neural common currency” (Levy & Glimcher, 2012; see also Kringelbach, 2005). For example, in one study, hungry participants indicated how much they were willing to pay for several kinds of snacks (Plassmann, O’Doherty, & Rangel, 2007). Their willingness to pay was correlated with activity in the medial OFC (peak Montréal Neurological Institute [MNI] coordinates = 6, 30, and −17). Consistent with the common currency thesis, social neuroscience studies have also indicated the involvement of the OFC and ventral striatum (i.e., another important region of the reward system) in social reward processing (for a review, see Ruff & Fehr, 2014). For example, in the trust game experiment of Phan, Sripada, Angstadt, and McCabe (2010), when participants learned that their partner responded in a trustworthy manner to their entrustment decision, this information engaged both the OFC and ventral striatum. The OFC and ventral striatum were also engaged when participants learned that someone had made empathic comments about their past emotional events (Jones et al., 2011).

A recent functional magnetic resonance imaging (fMRI) study on costly apologies (Ohtsubo et al., 2018) also implied the involvement of the OFC in the relationship value upregulation process. After being hurt by a friend, the victim naturally downregulates the relationship value of the friend. Costly apologies (e.g., cancelling an important business so as to immediately apologize), which honestly communicate the transgressor’s commitment to the relationship with the victim (Ohtsubo & Watanabe, 2009; Ohtsubo & Yagi, 2015), facilitate the recipient’s upregulation (or restoration) of the relationship value with their transgressor (Forster & McCullough, 2017). Ohtsubo et al. (2018) asked participants in a magnetic resonance (MR) scanner to imagine that they had been hurt by a friend, but the friend subsequently apologized in a costly, sincere manner. In addition to brain regions associated with social cognition, the medial

OFC (peak MNI coordinates = 0, 46, and −18 for $x$, $y$, and $z$, respectively) was activated by costly apologies. However, in Ohtsubo et al.'s study, the ventral striatum was not activated. This lack of ventral striatum activation may be attributed to the fact that apologies per se do not involve tangible resources. Nevertheless, costly apologies still serve as a commitment signal and facilitate the upregulation of the relationship value of the apologizer.

Drawing from the results of Ohtsubo et al.'s (2018) study, we predicted that commitment signals (i.e., pro-relationship behaviors) would also activate the OFC. The vignette study of Yamaguchi et al. (2017) revealed that both high-cost and low-cost commitment signals promote the upregulation of relationship value more than commitment signal failures (e.g., failing to express interest in a friend's photo) but also that high-cost commitment signals are more effective than low-cost ones in promoting upregulation. Therefore, we predicted that the OFC would be activated more by high-cost commitment signals than by low-cost commitment signals and signal failures and more by low-cost commitment signals than by signal failures. As for the ventral striatum, we did not have any a priori predictions because Ohtsubo et al.'s (2018) costly apology study did not observe its significant activation and, like costly apologies, some commitment signals (e.g., giving a birthday wish) do not involve tangible resources.

After corroborating the significant OFC activity in response to commitment signals in Study 1, we conducted a follow-up vignette study (Study 2) to measure the relationship value *change*: Participants of Study 2 rated the relationship value of a particular friend before and after imagining that they have received a series of commitment signal from the friend. We predicted that the relationship value change (i.e., post-signal relationship value minus pre-signal relationship value) would be greater than zero.

A subsidiary purpose of the present study was related to an intriguing observation that individuals high in loneliness are less responsive to commitment signals from their friends (Yamaguchi et al., 2017). Participants in Yamaguchi et al.'s (2017) study were presented with a series of hypothetical vignettes each describing a friend's commitment signal (either high- or low-cost) and rated the extent to which the event would confirm their bond with the friend (i.e., subjective evaluation of relationship value upregulation). The results showed that the commitment-confirming effect of both high-cost and low-cost signals was weaker among individuals high in loneliness. This finding is consistent with the notion that loneliness causes individuals to withdraw from social interactions and interpret the behaviors of others more negatively (Cacioppo & Hawkley, 2009; Qualter et al., 2015). For example, an experience sampling study showed that individuals high in loneliness perceived positive social interactions less favorably than did individuals low in loneliness (Hawkley, Preacher, & Cacioppo, 2007). Notably, in the fMRI study of Cacioppo, Norris, Decety, Monteleone, and Nusbaum (2009), lonely individuals exhibited weaker activation of the ventral striatum in response to positive social stimuli compared to positive non-social stimuli. To our knowledge, however, no study has revealed a diminished OFC response to commitment signals (i.e., one type of positive social stimuli) among lonely individuals. Therefore, we conducted an auxiliary analysis to explore whether medial OFC responses to commitment signals would be weaker among individuals high in loneliness. In Study 2, we also tested whether the degree of relationship value upregulation would be smaller in individuals high in loneliness than in individuals low in loneliness.

## Study 1: fMRI study

### *Methods*

*Participants*. Twenty-six healthy volunteers (23 females and 3 males, 20.35 ± 1.44 years old) participated in the study. On the basis of a previous study that included 19 participants in the data analyses and revealed the involvement of the medial OFC in encoding economic values (Plassmann et al., 2007), we aimed to collect analyzable data from at least 20 participants. Two female participants were excluded due to excessive head movement (more than 3 mm) during the fMRI scan, one female participant was excluded due to left-handedness, and one male participant was excluded due to a mechanical problem. Consequently, 22 participants were retained for data analyses. After providing informed consent, participants were asked to fill out a set of questionnaires, including a Japanese version of the Revised UCLA Loneliness Scale (Moroi, 1991; Russell, 1982). The loneliness score of each participant was computed by averaging their responses on a 4-point scale to the 20 items (Cronbach's $\alpha = .85$, $M = 1.57$, $SD = .31$), and thus it ranged from 1 to 4.

*Task*. The task was adapted from Yamaguchi et al.'s (2015, 2017) vignette studies. Participants were exposed to 30 commitment-signal-related scenarios and asked to imagine that the events described in each scenario had occurred with a real friend. Each scenario consisted of a situation section and a commitment signal section. There were 10 situations (e.g., you passed a test for an important qualification). Each situation was combined with three commitment signal sections: the high-cost commitment signal condition (e.g., your friend treated you to dinner to celebrate your achievement), the low-cost commitment signal condition (e.g., your friend sent you a short message of congratulations), and the signal failure condition (e.g., your friend did not notice your achievement), resulting in 30 scenarios (i.e., 10 situations × 3 signal conditions). The full list of these 30 scenarios is presented in the Supplementary Online Materials.

Before starting the imaging session, participants were asked to think of one particular friend throughout the fMRI experiment. Although participants were asked to assume that the real-life friend was the protagonist of every scenario, they were also asked to treat each scenario as an independent event by ignoring previous scenarios when reading a new one. In each trial of the imaging study (Figure 1), participants were first presented a situation scenario for 10 seconds (situation phase), which was followed by a friend's behavior scenario for 10 seconds (signal phase). Participants then rated the extent to which each event would improve or deteriorate the bond with their friend by using a visual analogue scale (VAS) slider within 5 seconds (rating phase). The two poles of the slider were denoted as "deteriorate it very much" (converted to 0) and "improve it very much" (converted to 100). This VAS score is considered as a subjective rating of upregulation of the relationship value of the friend. After 10 seconds (resting phase), the next trial was started. Three functional imaging runs (each consisting of 10 trials and lasting about 6 minutes) were performed for each participant. After each run, participants were asked whether they needed a brief interval before proceeding to the next imaging session.

The 30 scenarios (10 situations × 3 conditions) were presented to participants in one of two orders: As each of the three runs consisted of 10 trials, we distributed the 10 situations pertaining to each run. Within each run, the 10 situations were randomly ordered. The three signal conditions (high-cost vs. low-cost vs. signal failure) were distributed nearly evenly across the three runs (i.e., the ratio of high-cost, low-cost, and signal failure scenarios was either 3:3:4, 3:4:3, or 4:3:3). One order (Order 1) was prepared using this scheme. The second order (Order 2) was created by reversing Order 1. Participants were assigned to either Order 1 or Order 2 to mitigate possible order effects.

*fMRI data acquisition, processing, and analyses*. Functional neuroimaging was conducted using a 3-Tesla MRI scanner (Verio; Siemens Ltd., Erlangen, Germany) at the Brain and Mind Research Center, Nagoya University, Japan. Each participant's head was immobilized within a 32-element phased-array head coil. Imaging was performed using an echo-planar imaging (EPI) gradient-echo sequence (echo time [TE] = 30 ms, repetition time [TR] = 2,500 ms, field of view [FOV] = 192 × 192 mm$^2$, flip angle = 80°, matrix size = 64 × 64, 39 slices, slice thickness = 3 mm, total number of volumes = 148). A whole-brain, high-resolution T1-weighted anatomical magnetization-prepared rapid-acquisition gradient echo (MP-RAGE) MRI was also acquired for each participant (TE = 1.98 ms, TR = 1,800 ms, FOV = 256 × 256 mm$^2$, flip angle = 9°, matrix size = 256 × 256 pixels, and slice thickness = 1 mm).

To analyze the functional images, we used Statistical Parametric Mapping (SPM) software (SPM12 revision 6225; The Wellcome Trust Centre for Neuroimaging, London, UK) implemented in MATLAB 2014b (MathWorks Inc., Massachusetts). The first four volumes of each fMRI run were discarded due to unsteady magnetization. After all of the volumes were realigned, differences in slice timing within each image volume were corrected. The reference image was the center of the volume. The whole-brain 3D MP-RAGE volume was co-registered with the EPI volumes and normalized to the MNI T1 image template (ICBM152) through a nonlinear basis function. Subsequently, normalization parameters were applied to all the EPI volumes. The normalized EPI images were then spatially smoothed in three dimensions by using an 8-mm full-width at half-maximum Gaussian kernel. After completing the realignment processes, we checked for head movements (> 3 mm) during the experimental run.

Task-related activation was statistically evaluated on a voxel-by-voxel basis by using the general linear model at the individual level to generate contrast images. The situation (10 s), friend's commitment signal (10 s), and rating phases (5 s) were separately modeled by a block design convolved with a canonical hemodynamic response. The situation and rating phases were considered covariates of no interest in order to partial out their contribution to brain activation in single participant analyses. We decided to focus on the signal phase instead of the evaluation phase to more strictly test the hypotheses from signaling theory, which presumes that exposure to signals would elicit upregulation of the relationship value. Although the evaluation phase might be associated with comparable OFC activity (e.g., OFC activity is greater in the high-cost condition), it could be an experimental artifact because participants were explicitly asked to evaluate the relationship value on the basis of the preceding signal scenarios. Accordingly, we decided to analyze the blood-oxygen-level-dependent (BOLD) responses in the signal phase.

Neural responses associated with individual VAS ratings of relationship value upregulation (or downregulation) were first analyzed using a parametric modulation analysis, wherein, collapsing the three within-participant conditions, participant's ratings associated with all scenarios were entered as covariates in the individual-level analysis. A random-effects analysis at the group level using a one-sample *t*-test design was conducted. The statistical threshold was set as $< .001$ at the voxel level for an uncorrected *p*-value and $< .05$ at the cluster level (whole brain) for a familywise-error-corrected (FWE-corrected) *p*-value.

After corroborating the positive correlation between relationship value upregulation and OFC activity by the first whole-brain analysis, we focused on the OFC in the subsequent second and third analyses to avoid committing type I errors in other regions. Therefore, we defined an anatomical region of interest (ROI) to cover the bilateral medial OFC (Frontal_Med_Orb_L + Frontal_Med_Orb_R + Rectus_L + Rectus_R) using the Automated Anatomical Labeling (AAL) Atlas (Tzourio-Mazoyer et al., 2002) in the Wake Forest University PickAtlas Toolboxes (Maldjian, Laurienti, Kraft, & Burdette, 2003) for SPM12. The OFC ROI was used as an explicit mask in the second and third analyses. In the second analysis, using contrast images related to the signal phases of the three conditions (i.e., high-cost commitment signal, low-cost commitment signal, and signal failure conditions), we conducted a random-effects analysis at the group level. A series of one-way within-participant ANOVAs tested whether the OFC activity was greater in the high-cost commitment signal condition than in the low-cost commitment signal and signal failure conditions and whether it was greater in the low-cost commitment signal condition than in the signal failure condition. The statistical threshold was set as < .001 at the voxel level for an uncorrected *p*-value and < .05 at the cluster level (ROI) for an FWE-corrected *p*-value.

The third analysis examined the association between OFC activity and loneliness. We conducted a group analysis with a multiple regression design that uses contrast images related to the signal phase of the two conditions (high-cost and low-cost commitment signal conditions). The statistical threshold was set as < .001 at the voxel level for an uncorrected *p*-value and < .05 at the cluster level (ROI) for an FWE-corrected *p*-value.

*Ethical statement and data availability*. Studies 1 and 2 were approved by the ethical review board at the first author's institute. This research was conducted in accordance with the Helsinki Declaration. Behavioral data and analytical codes for Study 1 and all data and codes for Study 2 are available in the Open Science Framework (https://osf.io/kp4r3/).

*Results and discussion*

*Behavioral data analyses: Commitment-confirming effect and loneliness*. We first analyzed subjective ratings of the commitment-confirming effect of the friend's behaviors (ranging from 0 = "would deteriorate [the relationship] very much" to 100 = "would improve it very much") with a one-way repeated ANOVA. This dependent variable was measured using VAS during the fMRI session and was supposed to reflect participants' subjective ratings of relationship value upregulation. Corroborating previous research findings, the effect of commitment signals on perceived confirmation of the relationship bond was significant, $F(2, 42) = 184.34$, $p = 1.60^{-21}$, generalized $\eta^2 = 0.87$. Post-hoc tests by the Ryan procedure, which secures high statistical power while keeping familywise error rate at .05 (Howell, 2010), indicated that the three levels of means were all significantly different from one another at the .001 level. As shown in Figure 2A, high-cost pro-relationship behaviors were most effective in confirming participants' perception of their friend's commitment ($M = 86.60$, $SD = 8.43$), followed by low-cost pro-relationship behaviors ($M = 75.40$, $SD = 9.53$). Signal failures were associated with rather low ratings ($M = 33.37$, $SD = 9.12$).

We then computed the correlation coefficient between loneliness score and subjective rating of the perceived commitment-confirming effect for the three conditions separately. Corroborating Yamaguchi et al.'s (2017) results, participants high in loneliness were less sensitive to low-cost signals ($r = -.45$, $p = .035$, Figure 2C). The comparable correlation was only marginally significant in the high-cost signal condition ($r = -.39$, $p = .073$, Figure 2D), which could be due to a relatively small sample size. Consistent with Yamaguchi et al.'s (2017) results, loneliness was not significantly correlated with the reaction to signal failures ($r = .26$, *ns*, Figure 2B).

*OFC activity and commitment signals*. The fMRI data were first analyzed to examine whether OFC activity was positively correlated with the perceived commitment-confirming effect (i.e., subjective sense of upregulation of the relationship value). In this analysis, we collapsed the within-participant condition (high-cost signal, low-cost signal, and signal failure conditions) and used participants' responses to the 30 vignettes as the parametric modulator. The statistical threshold was set at an uncorrected $p < .001$ at the voxel level and an FWE-corrected $p < .05$ at the cluster level (whole brain). We found that BOLD responses in the medial OFC were positively correlated with participants' perceived commitment-confirming effect (Table 1 and

Figure 3). Significant correlations were also found in other regions (i.e., parahippocampal gyrus, occipital gyrus, and temporal gyrus) but not in the ventral striatum. Therefore, this analysis revealed that the subjective sense of relationship value upregulation was positively associated with medial OFC activity.

We then used the subtraction method to test whether commitment signals would engage the medial OFC and if this effect would be affected by their costliness. In particular, three comparisons were conducted: High-Cost Signal > Signal Failure, Low-Cost Signal > Signal Failure, and High-Cost Signal > Low-Cost Signal. The statistical threshold was set at an uncorrected $p < .001$ at the voxel level and an FWE-corrected $p < .05$ at the cluster level (OFC as the ROI). The predictions were only partially supported (Table 2). We observed significant increases in BOLD responses in the OFC for the first comparison (Figure 4A). For illustrative purposes, we used the first eigenvariate as a BOLD signal summary of the ROI. As shown in Figure 4B, the regional BOLD responses to the commitment signals (or signal failures) showed the predicted pattern (i.e., High-Cost Signal > Low-Cost Signal > Signal Failure). However, the increases in BOLD responses in the OFC for the second and third comparisons failed to reach statistical significance.

*OFC activity and loneliness*. We then examined whether BOLD responses to commitment signals in the medial OFC were negatively correlated with the loneliness score for the high-cost and low-cost signal conditions separately. The negative correlation between loneliness and the BOLD responses to low-cost commitment signals was significant (MNI peak coordinates = 8, 50, and −18; $p < .05$, FWE corrected [ROI]; cluster size = 35; $T = 4.98$; Figures 5A). However, the negative correlation between loneliness and the BOLD responses to high-cost commitment signals was not significant at the FWE-corrected threshold. For illustrative purposes, we used the first eigenvariate as a BOLD signal summary of the ROI. Figure 5B visually exemplifies the significant negative correlation between loneliness and the BOLD responses to low-cost commitment signals in the OFC. The comparable correlation was not significant in the high-cost commitment signal condition. However, we also extracted eigenvariates of the cluster by loosening the statistical threshold to the uncorrected $p$-value set at $< .005$ for the peak level (MNI peak coordinates = 0, 34, and −24; $p = .49$; cluster size = 4; $T = 3.08$). Figure 5C visually corroborates that the loneliness–OFC activity (operationalized as the first eigenvariate) correlation also tended to be negative in the high-cost commitment signal condition, though it failed to reach statistical significance. This result (i.e., the correlation failed to reach statistical significance in the high-cost condition but was significant in the low-cost condition) was consistent with the results of the behavioral data analysis (Figures 2C and 2D).

In sum, the results generally corroborated the prediction that the medial OFC is activated in response to commitment signals. The subjective rating of the relationship value upregulation was significantly positively associated with BOLD responses in the medial OFC. High-cost commitment signals activated the medial OFC more strongly than did signal failures. These results suggest the involvement of the medial OFC in the relationship value recalibration process. An exploratory analysis showed that OFC activity in response to low-cost commitment signals was negatively correlated with loneliness.

## Study 2: Vignette Study

### *Overview*

Study 1 and other previous studies (e.g., Yamaguchi et al., 2017) only measured participants' perceptions of the extent to which their bond with a friend was confirmed by hypothetical commitment signals. No prior study directly measured the change in relationship value in response to commitment signals. Therefore, it is not clear whether exposure to commitment signals from a particular friend actually causes the upregulation of the relationship value (i.e., whether the change score is positive and different from zero). The evidence for this assumption is necessary if we want to argue that the medial OFC is involved in the relationship value upregulation process. Therefore, in Study 2, we assessed the change score by having participants rate the relationship value of a particular friend twice: before and after imagining that they received the 10 low-cost commitment signals from their friend. Low-cost commitment signal scenarios were used because the results of Study 1 suggested that high-cost commitment signal scenarios may be associated with a weaker effect size, possibly due to a ceiling effect. In addition, we tested whether the change score would be negatively correlated with loneliness.

*Methods*

*Participants*. Before collecting the data, we conducted a power analysis under the assumption that the correlation between relationship value upregulation and loneliness is around .20 (cf. Yamaguchi et al., 2017). As the power analysis indicated that approximately 200 participants would be required to achieve the power of .80, we aimed to include at least 200 participants in Study 2. Participants, who were students at either a university, college, or vocational school, were recruited through an online survey service provided by Cross Marketing Inc., Japan. We focused on the student sample because the 10 low-cost commitment signal scenarios involved situations relevant to students. By the end of the data collection, 412 participants had accessed the online survey site. Of the 412 participants, 54 participants failed to pass an attention check item (i.e., an item requiring a certain response), 29 failed to follow a specific instruction (i.e., they thought about their best friend; see the Procedure section of Study 2), and 86 responses were excluded due to the survey company’s quality control rules (e.g., some responses were from the same IP address; some left nonsense syllables in open-ended sections; and some provided implausible responses to the demographic questions, such as having 99 children). Therefore, the final data set contained 243 participants (126 women and 117 men, mean age ± *SD* = 20.49 ± 1.81 years).

*Procedure*. After providing their demographic information, participants completed the Revised UCLA Loneliness Scale (Cronbach's α = .94, *M* = 2.12, *SD* = .58). Participants were then asked to think about a particular friend. To avoid a ceiling effect, we explicitly instructed participants to think about one of their regular friends but avoid choosing a best friend or a mere acquaintance who does not qualify as a friend. Participants typed the friend's initials and then rated the friend's relationship value by using five relationship value items adapted from Burnette et al.'s (2012) Relationship Value and Exploitation Risk scale. Sample items include "He/she plays a key role in my life" and "He/she is worthless to me" (reverse coded), which were rated on a 5-point scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). Cronbach's α coefficient was .79 for the pre-task relationship value. Participants were then exposed to the 10 low-cost commitment signal scenarios used in Study 1, each of which was presented for 30 seconds. They were asked to imagine that all 10 events happened with the same friend whose initials they had entered at the outset of the study. To have participants imagine that each scenario actually happened to them as vividly as possible, we told them that they would take memory quizzes about the scenarios later in the study and that their memory would be enhanced if they vividly imagined the scenarios. After being exposed to the 10 scenarios, participants rated the friend's relationship value again by using the same five items (Cronbach's α = .84 for post-task relationship value). They were then presented with one new and one old scenario and were asked to determine whether they had seen each scenario. This task was a filler task. Table 3 summarizes correlations among these variables of interest.

*Results and discussion*

We subtracted the pre-task relationship value from the post-task relationship value to obtain the relationship value change score (ΔRV). Mean ΔRV ± *SD* was 0.46 ± 0.57, which was significantly greater than 0, $t(242) = 12.61$, $p = 2.2 \times 10^{-16}$. Therefore, participants upregulated the relationship value after imagining that the 10 scenarios had actually happened. This result provides firm evidence for relationship value upregulation in response to commitment signals. Moreover, ΔRV was negatively correlated with loneliness, $r(241) = -.16$, $p = .016$ (Figure 6). Therefore, individuals high in loneliness were less prone to upregulating the relationship value in response to low-cost commitment signals.

However, as shown in Table 3, pre-task relationship value (Pre-RV in Table 3) was also negatively correlated with loneliness. Therefore, to test the robustness of the above result, we examined the association between post-task relationship value and loneliness by controlling for the effect of pre-task relationship value. A multiple regression analysis with post-task relationship value as the outcome variable and loneliness, pre-task relationship value, age, and gender as the predictor variables revealed that the negative association between loneliness and post-task relationship value was significant ($\beta = -.25$, $SE = .049$, $p = 1.06 \times 10^{-6}$) after controlling for the effect of pre-task relationship value ($\beta = .57$, $SE = .049$, $p < 2 \times 10^{-16}$). The effect of gender was marginally significant ($\beta = -.01$, $SE = .048$, $p = .060$; dummy coding with male = 1 and female = 2; see the Supplementary Online Materials for more analyses exploring possible gender differences in the Study 2 data), and the effect of age was not significant.

**General Discussion**

Studies 1 and 2 conjointly support the idea that people upregulate the relationship value of social partners in response to the partner's pro-relationship behaviors, and the medial OFC is involved in this recalibration process. As discussed in the Introduction section, pro-relationship behaviors serve as commitment signals, and people upregulate the relationship value of their social partners upon receipt of the partners' commitment signals (Yamaguchi et al., 2015, 2017). We predicted that the medial OFC, which is implicated in the valuation of various types of rewards, is also involved in the valuation of social relationships. Study 1 exposed participants to hypothetical commitment signals while in an MR scanner. Corroborating our predictions, (1) the BOLD responses in the medial OFC were positively correlated with subjective ratings of the commitment-confirming effect (i.e., a sense of upregulation of relationship value). (2) High-cost pro-relationship behaviors engaged the medial OFC more strongly than did signal failures, though differences in the other two comparisons (i.e., Low-Cost Signal > Signal Failure; High-Cost Signal > Low-Cost Signal) failed to reach statistical significance. An auxiliary analysis revealed that BOLD responses in the medial OFC to low-cost commitment signals were negatively correlated with loneliness. Study 2 attempted to obtain direct evidence of the upregulation of relationship value in response to commitment signals. By having each participant rate the relationship value of a real friend twice (i.e., before and after imagining that they had received a series of low-cost commitment signals from the friend), Study 2 showed that participants upregulated the relationship value of a particular friend in response to commitment signals. Study 2 also showed that individuals high in loneliness were also less prone to upregulating the relationship value of the signaler.

These findings underscore the role of OFC in the relationship value recalibration process. Montague and Berns (2002) maintained that the OFC is involved in the process of "conversion of disparate types of future rewards into a kind of internal currency, that is, a common scale used to compare the valuation of future behavioral acts or stimuli” (p. 265). The results of the present research are congruent with this thesis. As noted in the Introduction, previous social neuroscience studies indicated that the OFC and ventral striatum responded to social rewards (Ruff & Fehr, 2014). However, no studies examined the correlation between subjective rating of upregulation (i.e., perceived commitment-confirming effect) and medial OFC activity. Therefore, the present research provides direct evidence of the OFC’s involvement in the relationship value recalibration process.

This research has several limitations. First, both Studies 1 and 2 relied on hypothetical vignettes. Although it is difficult to manipulate a real friend’s commitment signals in the MR scanner, it may be desirable to use participants’ real experiences as stimuli. Such stimuli may be collected through an experience sampling study (e.g., Hawkley et al., 2007) conducted prior to an fMRI study. This issue is associated with the second limitation: Study 1 failed to observe significant activity in the ventral striatum in response to commitment signals. We speculated that this result might be attributable to the absence of tangible resources in some commitment signals, but an alternative explanation is that the rewarding effect was weak because the stimuli were hypothetical scenarios. Significant activity may be observed in the ventral striatum if we use more realistic stimuli.

Third, we admit that the small sample size of this study (especially of Study 1) imposed constraints on some conclusions (e.g., whether low-cost commitment signals engage the medial OFC more than do signal failures, whether high-cost commitment signals engage the medial OFC more than do low-cost signals). Although some automated fMRI power calculators are available, their adequate use requires some pilot fMRI data (Mumford, 2012), which we were unable to collect due to time and budget constraints. Now, however, Study 1 can be used to calculate the adequate sample size for future studies. We conducted such power analyses by using NeuroPower (Durnez et al., 2016; http://neuropowertools.org/). For the comparison of OFC activity in response to the high- vs. low-cost commitment signals, a sample size of 44 was required to achieve the power of 80%. However, this required sample size was twice as large as that of the current study. Therefore, we need high-power replication studies of Study 1, which could also address two additional shortcomings of Study 1—unbalanced gender composition and possible cultural differences (Study 1 was conducted only in Japan). Women are known to be more relationship-oriented than men (e.g., Cross & Madson, 1997), and the above effect size based on our mostly female sample may be overestimated. In a recent cross-cultural study, Japanese anticipated experiencing negative emotions, such as shame and guilt, upon receiving social support from their friends, whereas European Americans anticipated experiencing positive emotions, such as pride (Ishii, Mojaverian, Masuno, & Kim, 2017). Therefore, cross-cultural replication studies involving balanced gender composition need to be conducted.

Fourth, we admit that the loneliness part of this study (i.e., the finding from auxiliary analyses) is weak and needs further studies. In Study 1, the loneliness score was associated with the range restriction problem; the maximum value of the loneliness score in Study 1 was 2.15 (the possible range was 1–4). Moreover, the correlation based on the small sample size of 22 was far from decisive. Although Study 2 ($N = 243$) confirmed the negative association between loneliness and relationship value upregulation, it might have been still underpowered to detect some moderation effects, such as gender difference: A recent meta-analytic review revealed that gender difference in loneliness is small (Hedge's $g = .08$; Maes, Qualter, Wanhalst, van den Noortgate, & Goossens, 2019). Given these problems associated with the current study, we refrain from drawing any strong conclusions about the loneliness–insensitivity to commitment signal association.

In conclusion, the two studies converged on the notion that commitment signals (i.e., pro-relationship behaviors of social partners) trigger an upregulation of relationship value toward the signaler. Study 1 showed that the medial OFC is involved in this process. This line of research is likely to deepen our understanding of friendship formation and maintenance.

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**Table 1**. Brain regions that were significantly correlated with perceived bond confirmation in response to the friend's commitment signals (and signal failures) collapsing the three conditions.

| Region | Peak Coordinates | | | | Cluster size | Cluster *p*-value (FWE-corrected) |
|---|---|---|---|---|---|---|
| | *x* | *y* | *z* | *T* | | |
| OFC | 12 | 44 | −10 | 6.55 | 688 | < .001 |
| Parahippocampal Gyrus (left) | −32 | −26 | −14 | 6.70 | 5598 | < .001 |
| Occipital Gyrus | −34 | −90 | 16 | 4.90 | 415 | .001 |
| Temporal Gyrus | −52 | −44 | −10 | 4.49 | 288 | .005 |

**Table 2**. The results of three subtraction analyses (High-Cost Signal > Signal Failure; Low-Cost Signal > Signal Failure; High-Cost Signal > Low-Cost Signal) using the OFC as the ROI.

| Comparison | Peak Coordinates | | | | Cluster size | Cluster *p*-value (FWE-corrected) |
|---|---|---|---|---|---|---|
| | *x* | *y* | *z* | *T* | | |
| High-Cost > Signal Failure | 6 | 38 | −12 | 5.66 | 738 | < .001 |
| Low-Cost > Signal Failure | 12 | 44 | −10 | 3.58 | 3 | .166 |
| High-Cost > Low-Cost | 0 | 30 | −24 | 3.74 | 14 | .100 |

**Table 3**. Correlation matrix of variables of interest in Study 2.

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1. Pre-RV | | | | | |
| 2. Post-RV | .63 *** | | | | |
| 3. ΔRV | −.44 *** | .42 *** | | | |
| 4. Loneliness | −.27 *** | −.40 *** | −.16 * | | |
| 5. New Item Accuracy | .07 | .10 | .03 | −.05 | |
| 6. Old Item Accuracy | .10 | .19 ** | .10 | −.13 * | .21 *** |

Notes. Items 5 and 6 are the accuracy scores of the filler task, which were coded as 0 = inaccurate, 1= accurate.

* < .05

** < .001

*** < .001

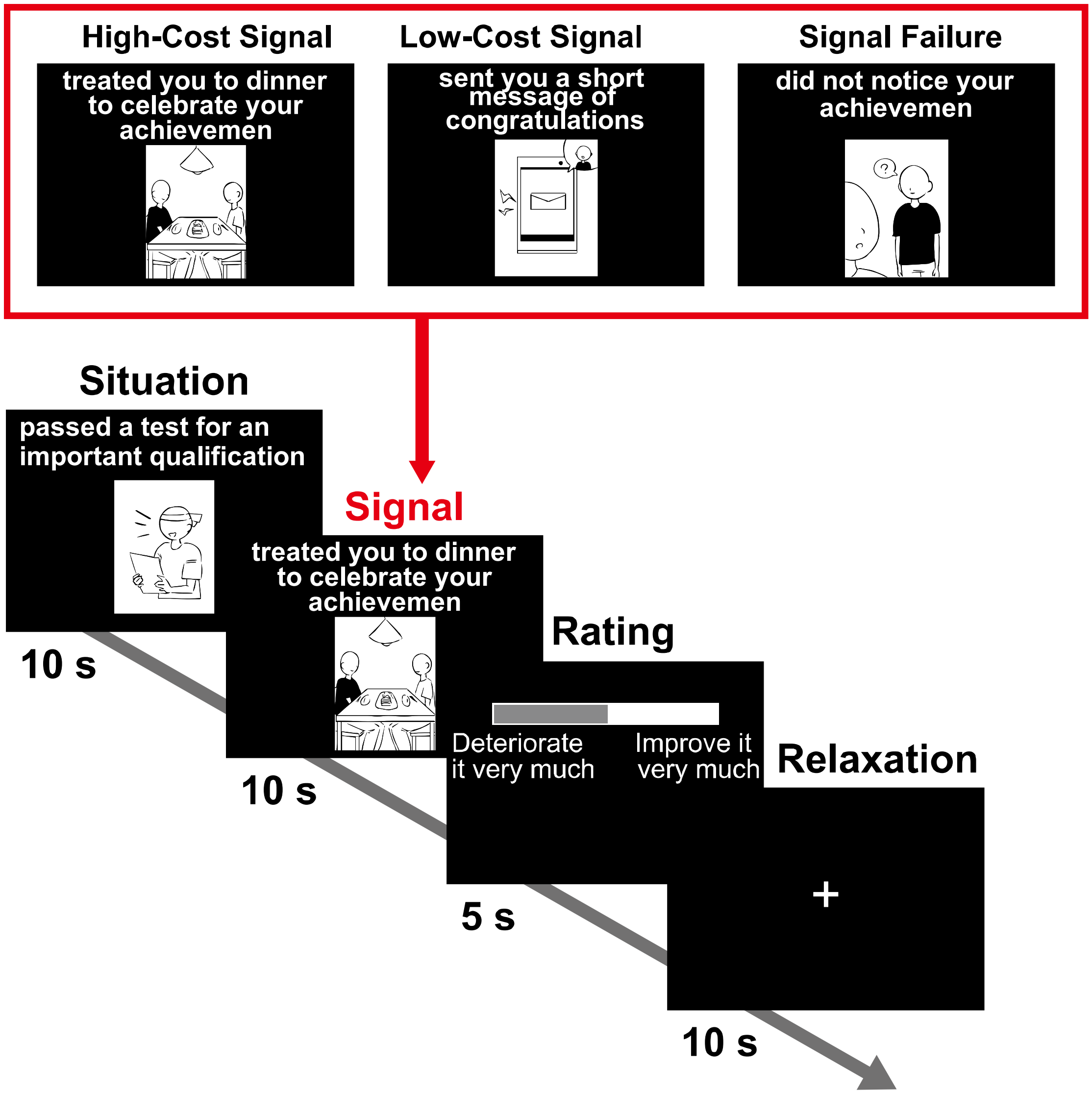


*Figure 1*. Time course of Study 1. Each situation was followed by a high-cost commitment signal scenario, a low-cost commitment signal scenario, or a signal failure scenario. After observing the signal scenario, participants rated how much the event would improve/deteriorate the relationship with the friend. After a 10 sec relaxation phase, the same procedure was repeated.

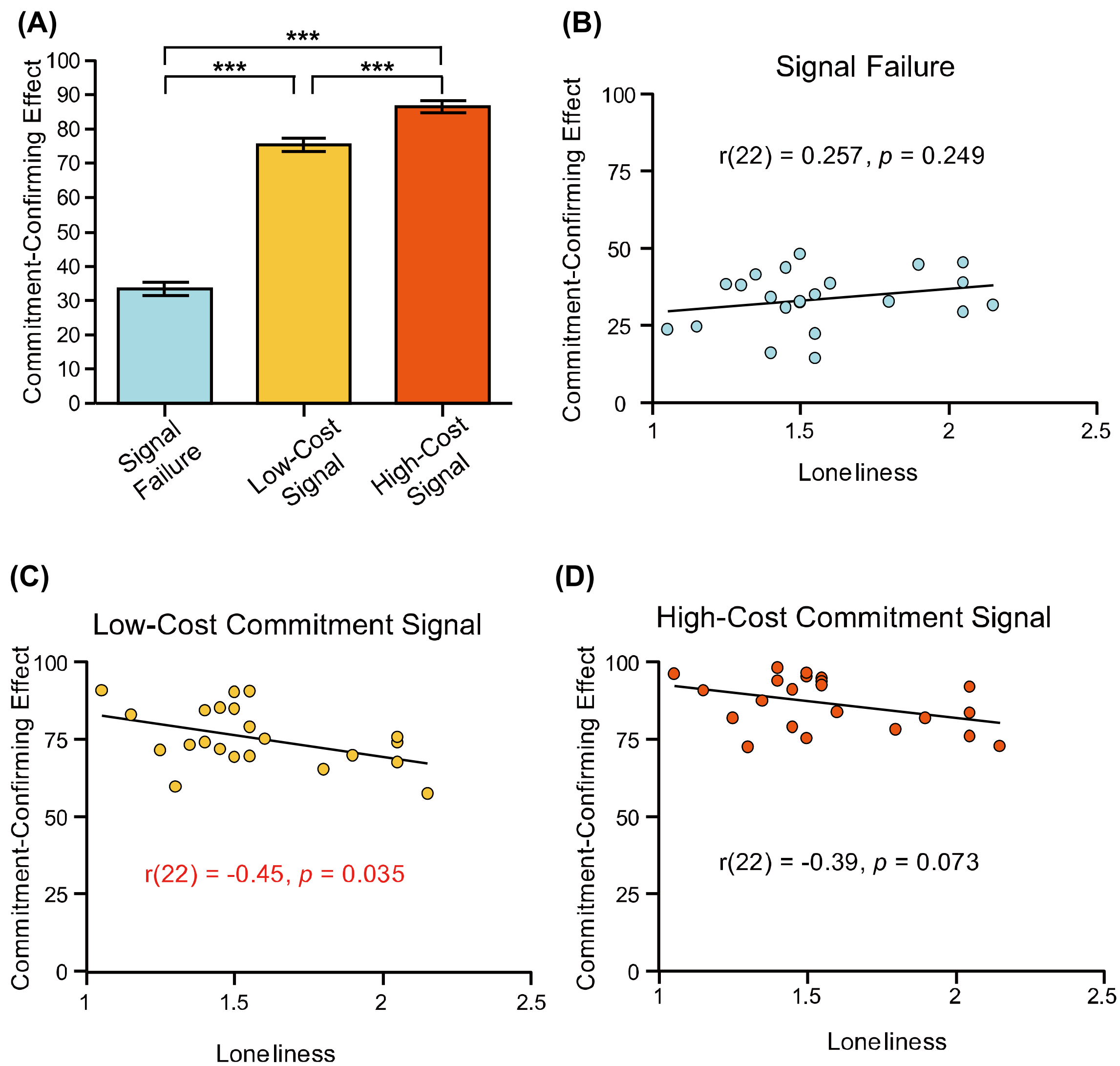


*Figure 2*. Commitment-confirming effect of three types of signals (operationalized as the extent to which the friend's behavior would improve or deteriorate the relationship: 0 = "deteriorate it very much" and 100 = "improve it very much") and loneliness. (A) Mean commitment-confirming effect as a function of signal type (signal failure vs. low-cost vs. high-cost). (B) Scatter plot showing the non-significant correlation between the commitment-confirming effect of signal failures and loneliness. (C) Scatter plot showing the negative correlation between the commitment-confirming effect of low-cost commitment signals and loneliness. (D) Scatter plot showing the negative (marginally significant) correlation between the commitment-confirming effect of high-cost commitment signals and loneliness.

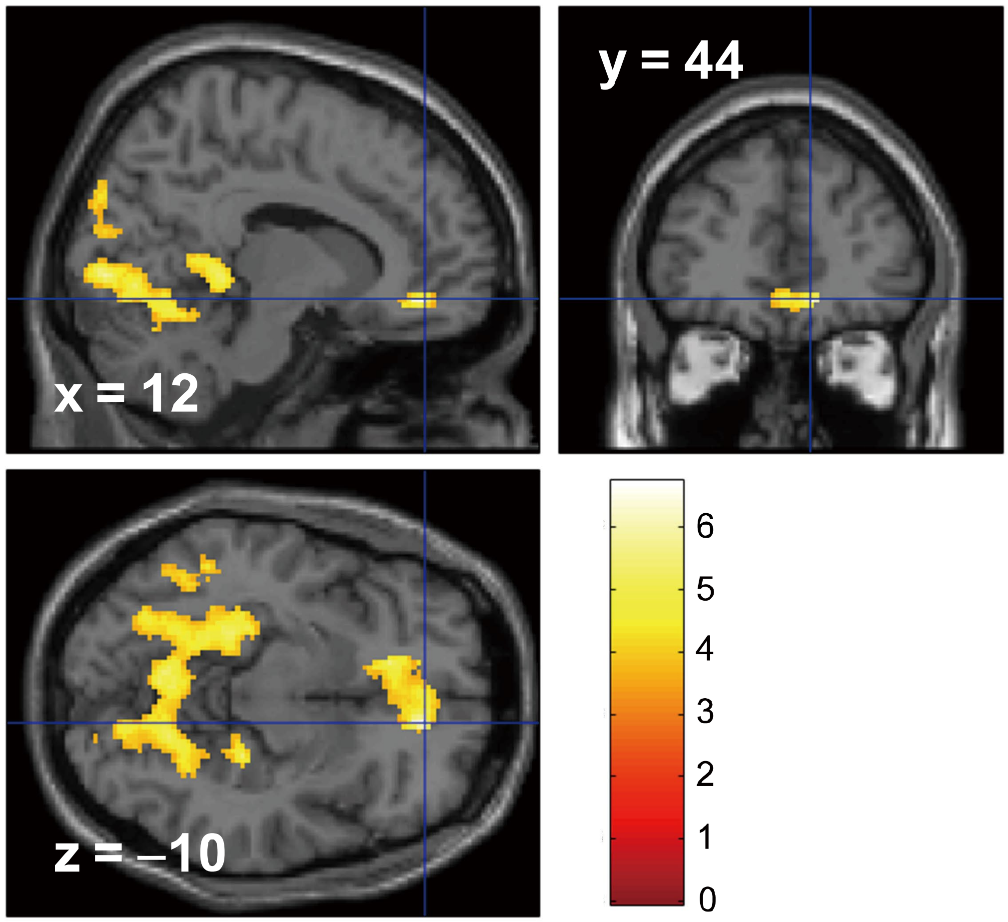


*Figure 3*. Brain regions that were positively correlated with upregulation of perceived commitment in response to three types of signals (signal failures, low-cost commitment signals, and high-cost commitment signals) in the parametric modulation analysis (see Table 1 for regions and associated statistics). The bar graph shows *T* values corresponding to color coding. Crosshairs show the OFC peak coordinates [12, 44, −10].

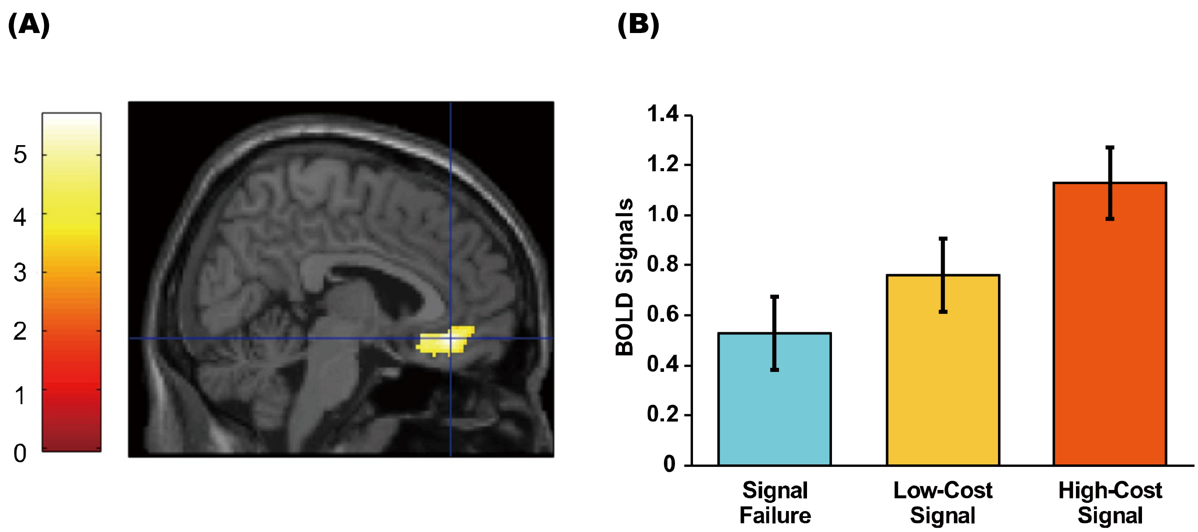


*Figure 4*. Results of subtraction analyses. (A) Brain region within the medial OFC that was significant in the "High-Cost Signal > Signal Failure" subtraction analysis (the OFC ROI was used as an explicit mask). The bar graph shows *T* values corresponding to color coding. Crosshairs show the OFC peak coordinates [6, 38, −12]. (B) BOLD signal summary of ROI (the first eigenvariate of the cluster) as a function of signal type.

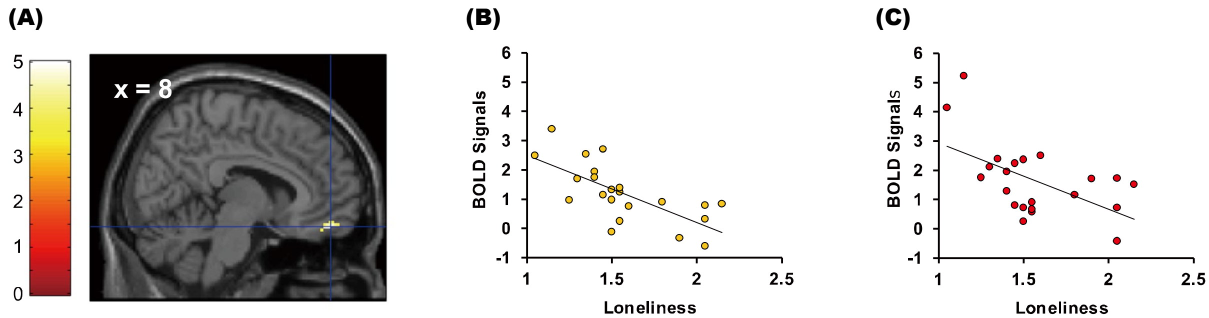


*Figure 5*. Association between loneliness and OFC responses to commitment signals (the OFC ROI was used as an explicit mask). (A) Brain region within the medial OFC whose responses to low-cost commitment signals were significantly correlated with loneliness. The bar graph shows *T* values corresponding to color coding. Crosshairs show the OFC peak coordinates [8, 50, −18]. (B) Scatter plot showing the negative correlation between OFC responses to low-cost commitment signals (the first eigenvariate of the cluster) and loneliness. (C) Scatter plot showing the relationship between OFC responses to high-cost commitment signals (the first eigenvariate of the cluster) and loneliness.

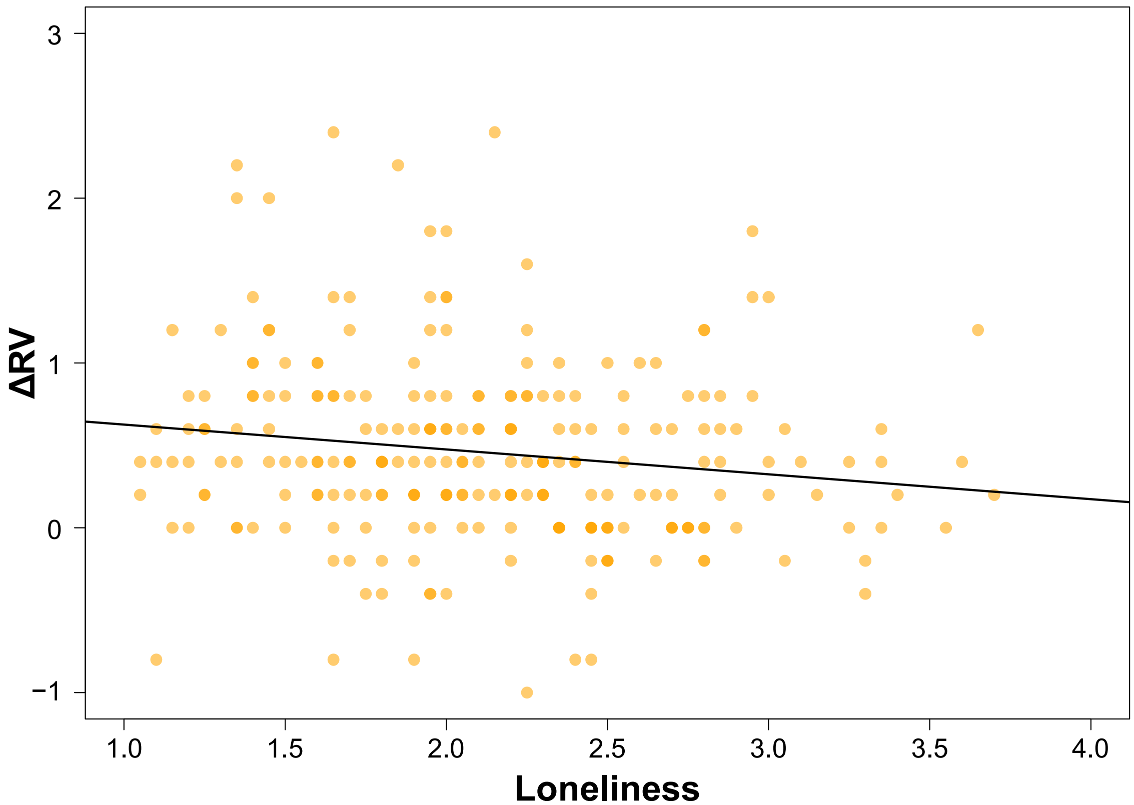


*Figure 6*. Scatter plot showing the negative correlation between relationship value change scores and loneliness, $r(241) = -.16$, $p = .016$.

**Role of the Orbitofrontal Cortex in the Computation of Relationship Value**

**Supplementary Online Materials**

Table S1 summarizes the English translations of the 30 scenarios used in Study 1. Table S2 summarizes the original Japanese versions of the 30 scenarios.

Table S1

*Scenarios used in Study 1. In Japanese, subject(s) of a sentence can be omitted and thus the subject(s) in parentheses were omitted in the Japanese scenarios.*

| | |
|---|---|
| Situation 1 | (You and the friend) went out for dinner on your birthday. |
| High-Cost | (Your friend) wished you "Happy Birthday" and paid for dinner. |
| Low-Cost | (Your friend) wished you "Happy Birthday." |
| Signal Failure | (Your friend) did not mention anything about your birthday. |
| Situation 2 | (You) were absent from a lecture. |
| High-Cost | (Your friend) brought the handout and notes from the lecture to your home. |
| Low-Cost | (Your friend) took an extra copy of the handout from the lecture to give to you later. |
| Signal Failure | (Your friend) did not take a handout from the lecture to give to you. |

Table S1 *cont'd*

| | |
|---|---|
| Situation 3 | (You) had a personal problem, and wanted to talk about it. |
| High-Cost | Despite (your friend) being busy, (he/she) took a long time to listen to the personal problem. |
| Low-Cost | (Your friend) listened to the personal problem. |
| Signal Failure | (Your friend) said "I'm busy. Let's talk about it later." |
| Situation 4 | (You) were accused by an acquaintance of causing a misunderstanding. |
| High-Cost | (Your friend), took your side, explaining it was just a misunderstanding, even though this led him/her to also be accused. |
| Low-Cost | (Your friend) helped explain it was a misunderstanding. |
| Signal Failure | (Your friend) kept silent although he/she knew it was just a misunderstanding. |
| Situation 5 | (You) got a personal best record at an athletic event. |
| High-Cost | (Your friend) wished you "congratulations," and bought you some sweets to celebrate. |
| Low-Cost | (Your friend) wished you "congratulations." |
| Signal Failure | (Your friend) appeared to have little interest in your achievement. |
| Situation 6 | (You) passed a test for an important qualification. |
| High-Cost | (Your friend) treated you to dinner to celebrate your achievement. |
| Low-Cost | (Your friend) sent you a short message of congratulations. |
| Signal Failure | (Your friend) did not notice your achievement. |

Table S1 *cont'd*

| | |
|---|---|
| Situation 7 | (You) lost your favorite watch. |
| High-Cost | (Your friend) spent many hours helping you search for the watch. |
| Low-Cost | (Your friend) comforted you saying "you will find it." |
| Signal Failure | (Your friend) simply said "that's too bad." |
| Situation 8 | (You) make a big mistake on a project at work. |
| High-Cost | (Your friend) bought you some fancy sweets, and came to comfort you. |
| Low-Cost | (Your friend) comforted you saying "everyone makes mistakes." |
| Signal Failure | (Your friend) did not do anything special to comfort you. |
| Situation 9 | (You) invited your friend to spend some time together on the weekend. |
| High-Cost | (Your friend) took the time to reschedule his/her other plans, and the two of you were able to go out together on the weekend. |
| Low-Cost | (You and your friend) went out together on the weekend. |
| Signal Failure | (Your friend) already had plans and was unable to join you. |
| Situation 10 | Someone asked your friend about something you were keeping secrete. |
| High-Cost | (Your friend) went out of his/her way to protect your secret. |
| Low-Cost | (Your friend) simply said "I don't know about that." |
| Signal Failure | (Your friend) carelessly disclosed your secrete. |

Table S2

*The original Japanese scenarios used in Study 1.*

| | |
|---|---|
| Situation 1 | あなたの誕生日に一緒に食事に行きました |
| High-Cost | 誕生日おめでとうといっておごってくれました |
| Low-Cost | 誕生日おめでとうと言いました |
| Signal Failure | 誕生日のことは何も話しませんでした |
| Situation 2 | あなたは講義を欠席しました |
| High-Cost | 講義の資料とノートを届けてくれました |
| Low-Cost | プリントをとっておいてくれました |
| Signal Failure | プリントをとっておいてくれませんでした |
| Situation 3 | あなたは悩みを相談したいと言いました |
| High-Cost | 忙しいのに長時間つきあってくれました |
| Low-Cost | 悩みを聞いてくれました |
| Signal Failure | 忙しいのでまた今度聞くと言いました |
| Situation 4 | 別の知り合いから誤解をうけ非難されました |
| High-Cost | 自分も非難されても必死で弁護してくれました |
| Low-Cost | 誤解だと一緒に説明してくれました |
| Signal Failure | 誤解だと知っていただけれど黙っていました |
| Situation 5 | あなたはスポーツで自己ベストを出しました |
| High-Cost | お祝いといってお菓子をくれました |
| Low-Cost | おめでとうと言いました |
| Signal Failure | 特に関心なさそうでした |
| Situation 6 | あなたは資格試験に合格しました |
| High-Cost | 合格祝いにと夕食をおごってくれました |
| Low-Cost | あなたの友人は合格おめでとうというメールをくれました |
| Signal Failure | そのことに気づいていませんでした |
| Situation 7 | あなたはお気に入りの時計を落としました |
| High-Cost | 何時間も一緒に外を探してくれました |
| Low-Cost | そのうち出てくるよと慰めてくれました |
| Signal Failure | ご愁傷さまと言いました |
| Situation 8 | あなたは大きな仕事で失敗してしまいました |
| High-Cost | 高級なお菓子を買って慰めにきてくれました |
| Low-Cost | 誰でも失敗はあるよと慰めてくれました |
| Signal Failure | 特に慰めてくれませんでした |
| Situation 9 | あなたは週末に遊びに行こうと誘いました |
| High-Cost | 予定を調整してくれ、一緒に遊びにいきました |
| Low-Cost | 一緒に週末に遊びにいきました |
| Signal Failure | 別の用事があって遊びに行けませんでした |
| Situation 10 | Aさんがあなたの秘密について聞かれました |
| High-Cost | 知らないと上手にとりつくろってくれました |
| Low-Cost | 知らないといいました |
| Signal Failure | うっかりあなたの秘密を話しました |

**Study 2: Exploratory Analyses of Gender Differences**

For an exploratory purpose, we examined possible gender differences in the Study 2 data because most participants in Study 1 (20 of the 22 analyzed participants) were females. The gender difference in loneliness was not significant: $M_{\text{female}}$ = 2.06 (*SD* = 0.60) vs. $M_{\text{male}}$ = 2.19 (0.56), $t(241) = 1.69$, $p = .092$. The gender difference in ΔRV was also not significant: $M_{\text{female}}$ = 0.52 (0.57) vs. $M_{\text{male}}$ = 0.39 (0.55), $t(241) = 1.70$, $p = .091$. The correlations between loneliness and ΔRV were $r(124) = -.18$, $p = .046$ and $r(115) = -.11$, $p = .258$ for females and males, respectively. Although the difference between the two correlations was not significant ($Z = .57$, *ns*), the effect size is apparently greater for females. As we already noted, females outnumbered males in Study 1. Therefore, it is desirable to replicate Study 1 including more male participants, and replicate Study 2 with a larger sample size that is sufficient to detect the (possibly subtle) gender difference in the ΔRV–loneliness correlation.