# NEURAL CORRELATES OF MARITAL SATISFACTION AND WELL-BEING: REWARD, EMPATHY, AND AFFECT

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## Abstract

Numerous studies suggest that marital satisfaction is associated with psychological and physical health. Using fMRI, the present study explored the neural correlates of marital satisfaction to investigate the physiological markers potentially mediating these health effects. Seventeen middle-aged individuals (M= 52.85 years) in happy, stable, long-term, heterosexual pair-bonds (Mean length of marriage = 21.4 years) were scanned while viewing facial images of their spouses, as well as facial images of a familiar acquaintance and a close friend (to control for familiarity and social bonding). Participants' marital satisfaction scores (assessed with the Relationship Assessment Scale; Hendrick 1988) were correlated with brain activity in response to all of these facial images. Greater marital satisfaction (after controlling for Passionate Love Scale scores) was positively correlated with activation in several neural regions, including the ventral tegmental area (reflecting reward and motivation); the orbitofrontal cortex (associated with the evaluation of rewards); the anterior insula (associated with empathy); the inferior frontal gyrus (associated with the mirror system), the bed nucleus of the stria terminalis (associated with stress control); and the prefrontal cortex (associated with affective regulation). Greater marital satisfaction was also associated with decreased activation of the subcallosal cingulate gyrus, an area whose high activity is implicated in severe depression. These findings highlight key neural sites that may mediate the link between relationship quality with psychological and physical well-being and health.

**Key words**: marital satisfaction, Passionate Love Scale, reward, motivation, empathy, mirror system, affective regulation, affect

**Declaration of interest**: none

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The establishment and maintenance of social bonds have enabled survival and successful reproduction and parenting among humans and other mammalian species (e.g., Cacioppo & Patrick 2008, Silk 2007). The presence and quality of close relationships, namely attachment bonds, deeply affect human psychological and physical well-being; in fact, the link between marital quality and health has been shown by numerous studies over the past few decades (e.g., Kiecolt-Glaser et al. 1998). For example, a meta-analysis of 93 research studies reported a strong and significant association between marital quality and personal well-being (Proulx et al. 2007). Other studies echo this point suggesting that marital quality is positively correlated with physical health, stress-buffering, psychological well-being, life satisfaction, and self-esteem (e.g., Glenn & Weaver 1981, Voss et al. 1999, Riehl et al. 2003).

On the negative side, marital dysfunction is associated with a myriad of issues including depressive symptoms (e.g., Beach & O'Leary 1993, Frech & Williams 2007, Davila et al. 2003), poor health (e.g. Kiecolt-Glaser et al. 2005, Kiecolt-Glaser & Newton 2001), and partner aggression (e.g., Anderson et al. 2004). Marital strife has also been associated with relationship instability and poor outcomes for children. For example, children exposed to family violence often experience anxiety, aggression, troubles with emotion regulation, and difficulties in personal relationships (e.g., Carlson 2000, O'Leary et al. 2000). Thus, increasing understanding and awareness regarding outcomes associated with marital relations is important for general public health.

Although research has shown strong associations between relationship quality and individual well-being, little is known about the neural systems that may be the mediating factors. Several fMRI studies have investigated the neural correlates of pair-bonds in the context of new relationships (e.g., Aron et al. 2005, Bartels & Zeki 2000, Ortigue et al. 2007, Xu et al. 2010), dissolved (e.g., Fisher et al. 2011, Najib et al. 2004), and long-term relationships (Acevedo et al. 2011).

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Studies have also examined neural correlates in response to receiving and providing social support (hand-holding) from a romantic partner in the face of threat (receiving an electric shock) (e.g., Coan et al. 2006, Inagaki & Eisenberg 2012). However, the neural correlates of marital satisfaction have not been directly investigated for evidence of links with brain systems.

We applied functional magnetic resonance imaging (fMRI) to a group of long-term, happily married women and men recruited for a study on intense long-term romantic love (Acevedo et al. 2011). In the present report we used the same population to investigate correlations between neural activity and individuals' scores on a widely used measure of marital satisfaction, the Relationship Assessment Scale (Hendrick 1988). We have published the major findings about romantic love for this group of subjects (Acevedo et al. 2011). The paradigm used was based on our prior research on early-stage romantic bonds where neural activity was assessed in response to facial images of a partner versus a familiar acquaintance (e.g., Aron et al. 2005), permitting a direct comparison across studies. In the present research we also displayed images of a close, long-term friend as a control for social bonding. Although the close friend is a stronger control for human attachment and general social bonding than a familiar acquaintance, we examined activation differences between the partner and familiar acquaintance as it permitted a direct comparison to numerous previous studies of romantic love (e.g., Aron et al. 2005, Fisher et al. 2011, Xu et al. 2010). Four major hypotheses regarding the neural correlates of marital satisfaction were tested.

First, we predicted that marital satisfaction would be associated with neural activity in dopamine-rich reward regions. This hypothesis was based on research over several decades suggesting a strong, positive correlation between dopamine system activity (e.g. ventral tegmental area (VTA) and primary rewards like food (e.g., Hare et al. 2008). However, because we have already shown that passionate love scores are associated with dopamine rich region activation (Aron et al. 2005), we controlled for those scores in this report, thus identifying the unique aspects of relationship satisfaction over and above romantic love. Although love and marital satisfaction are highly correlated they are not entirely correlated (O'Leary et al. 2012).

Second, we predicted that relationship quality would be associated with neural activity in regions associated with the evaluation of rewards and with decision-making (e.g., the orbitofrontal cortex). The ability to evaluate a partner is particularly important in a species such as *Homo sapiens*, in which highly interdependent partnership relationships are regularly employed to enhance overall well-being, and more broadly survival and reproduction (Fisher 2000).

Third, we hypothesized that marital satisfaction would be positively associated with neural regions implicated in empathy and responsiveness (e.g., the insula). Attachment theory and some major models of marital satisfaction emphasize the importance of empathizing with, and responding to, a partner's emotional signals in order to establish and maintain a secure, stable partnership (e.g., Bowlby 1969, Eisenberg & Miller 1987, Gable et al. 2004, Sullivan et al. 2010, Waldinger et al. 2004).

Fourth, we predicted that greater marital satisfaction would be correlated with areas implicated in depression and stress control. Several studies have reported on robust links between marital dissatisfaction and depressive symptoms (meta-analysis, Whisman 2001). Also, longitudinal research suggests that low quality marital bonds are associated with major depression and depressive symptoms (e.g., Beach & O'Leary 1993, Whisman & Bruce 1999). Thus, we predicted a significant correlation between marital satisfaction scores and activity in the subcallosal cingulate gyrus (SCG)—an area associated with affective disorders and the target of deep-brain stimulation for intractable depression (Lozano et al. 2008, Mayberg et al. 2005). In addition, research has shown that marital quality moderates the stress-buffering effects, reflected in brain systems, provided by receiving support from a romantic partner when faced with threat (e.g., Coan et al. 2006). Thus, we also predicted that marital satisfaction would be related to neural activation involved in stress and anxiety control (e.g., bed nucleus of the stria terminalis).

## Method

### *Participants*

Participants were 17 healthy, right-handed individuals (10 females and 7 males), ages 39-67 ($M$ = 52.85, $SD$ = 8.91) who self-reported being happily married, intensely in-love, and sexually exclusive with their spouse of 10 years or more ($M$ = 21.40, $SD$ = 5.89). Participants had between 0 and 4 ($M$ = 1.9) children residing with the couple at the time of the study. Seven participants were in a first marriage for both partners; the remaining had at least one previous divorce. The ethnic composition of the sample was 12% Asian-American 12% Latino, and 76% Caucasian. On average, participants completed 16 years ($SD$ = 1.09) of education. Participants were recruited from the New York metropolitan area and the study was approved by the human subjects committees at Stony Brook University and New York University. Individuals were screened for eligibility including relationship criteria, right-handedness, non-use of anti-depressants, and fMRI contraindications. As noted earlier, results for this group focusing just on romantic love have been published previously (Acevedo et al. 2011).

### *Questionnaires*

Participants completed a battery of questionnaires including the Relationship Assessment Scale (RAS; Hendrick 1988), a 7-item unifactorial measure of relationship satisfaction (M = 6.75, SD = 0.26). Sample RAS items include: "How well does your partner meet your needs?" and "In general, how satisfied are you with your relationship?" (alpha = .36). They also completed the Passionate Love Scale (PLS; Hatfield and Sprecher 1986) to measure romantic love (alpha =

**Table 1.** *Regional Neural Correlations of Relationship Satisfaction with Brain Responses to Images of Long-term Partner versus Controls for Familiarity and Social Bonding*

| **Brain region** | Left | | | | Right | | | |
|---|---|---|---|---|---|---|---|---|
| | x | y | z | P | x | y | z | P |
| ***Positive Correlation*** | | | | | | | | |
| VTA[a,e] | | | | | 2 | -12 | -12 | .01 |
| VTA/SN[a,b,e] | | | | | 8 | -12 | -16 | .01 |
| Bed nucleus of the stria terminalis[c] | -6 | 4 | -4 | .01 | | | | |
| Caudate tail[f] | -34 | -40 | 10 | .02 | 36 | -46 | 12 | .01 |
| Thalamus, medial dorsal[d] | -2 | -12 | 8 | .01 | | | | |
| Lateral orbitofrontal cortex[f] | -34 | 44 | -14 | .04 | 34 | 40 | -12 | .01 |
| Anterior insula[d,g] | | | | | 34 | 26 | -8 | .01 |
| Anterior insula[j] | | | | | 49 | 30 | -6 | .01 |
| Inferior frontal gyrus[i,k] | -50 | 20 | 16 | .02 | 53 | 20 | 20 | .01 |
| Inferior frontal gyrus[m] | | | | | 50 | 28 | -6 | .01 |
| Anterior intraparietal sulcus [l] | | | | | 38 | -44 | 44 | .01 |
| Anterior parietal region [k] | -30 | -47 | 65 | .01 | 42 | -48 | 60 | .03 |
| Parietal operculum [k] | | | | | 52 | -22 | 30 | .02 |
| Premotor cortex [l] | | | | | 46 | 6 | 42 | .02 |
| Temporo-parietal junction [l] | | | | | 50 | -50 | 24 | .01 |
| Medial prefrontal cortex [l] | -8 | 64 | 22 | .01 | 15 | 56 | 20 | .01 |
| | -10 | 38 | -12 | .01 | | | | |
| Angular gyrus[d] | | | | | 63 | -50 | 12 | .02 |
| Middle temporal gyrus[i] | -45 | -64 | 15 | .01 | | | | |
| Superior parietal lobe[h] | | | | | 15 | -75 | 60 | .01 |
| Subcallosal cingulate[f] | | | | | 12 | 42 | -3 | .03 |
| ***Negative Correlation*** | | | | | | | | |
| Subcallosal cingulate gyrus [f] | | | | | 6 | 20 | -10 | .02 |
| Medial Orbitofrontal cortex | | | | | 6 | 58 | -10 | .02 |

**Note.** Regions of interest (ROIs) were identified as the highest intensity voxel in a cluster, for the Partner-versus-highly familiar neutral (HFN) contrast and Partner-versus-Close Friend (CF) contrast. MNI coordinates (x,y,z) are at the maximum value for the cluster, which may be elongated in any direction. P values (P) are for FDR correction.
Letters indicate origin of ROIs:
[a]Aron et al. (2005); [b] Bartels & Zeki (2004); [c]Coan et al. (2006); [d] Ortigue et al. (2007); [e]Acevedo et al. (2011); [f] Xu et al. (2010); [g] Fan et al. (2010); [h] Lamm et al. (2011) ; [i] Mazzola et al. (2010); [j] Singer et al. (2004); [k] Iacoboni et al. (1999); [l]VanOverwalle et al. (2009); [m]Liakakis et al. (2011). VTA, ventral tegmental area; SN, substantia nigra.

.81). Sample PLS items include: "I possess a powerful attraction for my partner." and "I yearn to know all about my partner".

## Stimuli

Stimuli for each participant (four facial photographs and 4-digit numbers for a countback task) were digitized and presented using E-Prime 2.0 software (Psychological Software Tools, Inc., Pittsburgh, PA). Facial photographs were of the Partner and three controls, a Highly-Familiar Neutral (HFN), a Close Friend (CF), and a Low-Familiar Neutral (LFN). In the present analysis, we focused on HFN and CF controls for familiarity and social affiliation and did not utilize the LFN to investigate familiarity effects. Controls were the same sex and approximately the same age as the partner. The HFN was a relatively neutral acquaintance known about as many years as the Partner (repeated measures *t*-test, $t$ (16), = 0.66, *ns*), and selected to control for facial familiarity. Subjects selected someone they interacted with frequently and for which they reported feeling neither strong positive nor negative affect (examples included friends of the spouse and co-workers). The CF was someone with whom the participant had a close, positive, non-romantic relationship. In this sample, three were siblings 1 was a cousin 2 were in-laws, 9 were friends, and 2 were co-workers.

To reduce carry-over effects, all facial images were followed by a count-back distraction task, replicating procedures in Aron et al. (2005). For example, a high number (e.g. 2,081) was displayed on the screen and participants were instructed to begin with this number and mentally count backwards in increments of seven.

Attractiveness and image quality. All photos were rated for facial attractiveness and image quality by six independent raters (3 females and 3 males) of around the same age as the participants. Attractiveness coder-ratings were adequately inter-correlated (alpha = 0.66 for female raters and 0.91 for male raters). Regarding attractiveness and image quality, independent coder-ratings did not differ significantly across types of target stimuli (F (3, 64) = 0.94, ns and F (3, 64) = 0.63, ns, respectively). There were no significant associations between Partner-minus-HFN coder-rated attractiveness difference scores with Partner-versus-HFN brain activations, and Partner-minus-CF coder-rated attractiveness difference scores with Partner-versus-CF brain activations. Thus, it is unlikely that Partner-versus-HFN and Partner-versus-CF effects were due to objective differences in facial attractiveness.

## fMRI protocol

The experimental protocol consisted of two 12-minute sessions consisting of four tasks in an alternating block design. Participants viewed alternating face images (starting image counterbalanced across individuals), interspersed with a count-back task for 30-seconds each, for 6 repetitions. They were instructed to think about experiences with the stimulus person that were not sexual in nature. All face images were followed by a count-back task. Immediately after each 12-minute session, while still in the scanner, participants rated emotions elicited by each stimulus.

## Data Acquisition and Analysis

Data were acquired with a 3T Siemens magnetic resonance imaging system located in the Center for Brain Imaging at New York University. First, anatomical scans were obtained. Next, functional images were obtained. The first four volumes were discarded to allow for proper calibration, resulting in 360 functional images, in volumes of thirty; 3mm axial slices (0 mm gap) covering the whole brain. A repetition time (TR) of 2,000-ms was used, with a TE of 30-ms, a 90° flip, resulting in a voxel size of functional images of 3X3X3mm.

Data were analyzed using SPM2 (http://www.fil.ion.ucl.ac.uk/spm). For preprocessing, functional EPI volumes were realigned to the fist volume, smoothed with a Guassian kernel of 6mm, and then normalized to the EPI template. Images were inspected for motion and no participant showed movement greater than 3 mm (whole voxel) motion. After preprocessing, activation contrast images were created: Partner-versus-HFN and Partner-versus-CF. The contrast images were used to create second level, group effects of regions more active while viewing images of the Partner versus HFN or versus the CF. Next, we conducted correlations between each participant's relationship satisfaction score (controlling for passionate love scores) and brain responses for the P-versus-HFN and the P-versus-CF contrasts independently.

**Region of Interest Analysis.** For this report we focus on results of the marital satisfaction correlations only. Regions of interest were based on previous studies showing participants face images of a romantic partner in the context of new relationships (Aron et al. 2005, Bartels & Zeki 2004, Ortigue et al. 2007, Xu et al. 2011) and published findings for the present sample of individuals in long-term, in-love relationships (Acevedo et al. 2011). In addition, we also examined regions found for the attenuation of stress in the context of partner contact (Coan et al. 2006); two meta-analyses reporting on fMRI studies of empathy (Fan et al. 2010, Lamm et al. 2011); two studies of empathy in the context of a romantic partner (Mazzola et al. 2010, Singer et al. 2004); and meta-analyses and research on the mirror neuron system (Iacoboni et al. 1999, Liakakis et al. 2011, Van Overwalle & Baetens 2009) and depression (Mayberg et al. 2005). We adopted a false discovery rate (FDR) for multiple comparisons correction (Genovese et al. 2002) with a threshold of $p < .05$, placing the ROI coordinates at the center of activations and extending for a 3-mm radius. Anatomic regions were confirmed with the "Atlas of the Human Brain" (Mai et al. 2008).

**Whole brain analysis.** For the correlation of marital satisfaction scores (controlling for passionate love scores) with brain activation, exploratory whole-brain analyses were conducted adopting a threshold of $p \leq .001$ (uncorrected for multiple comparisons) with a minimum spatial extent of $\geq 15$ contiguous voxels.

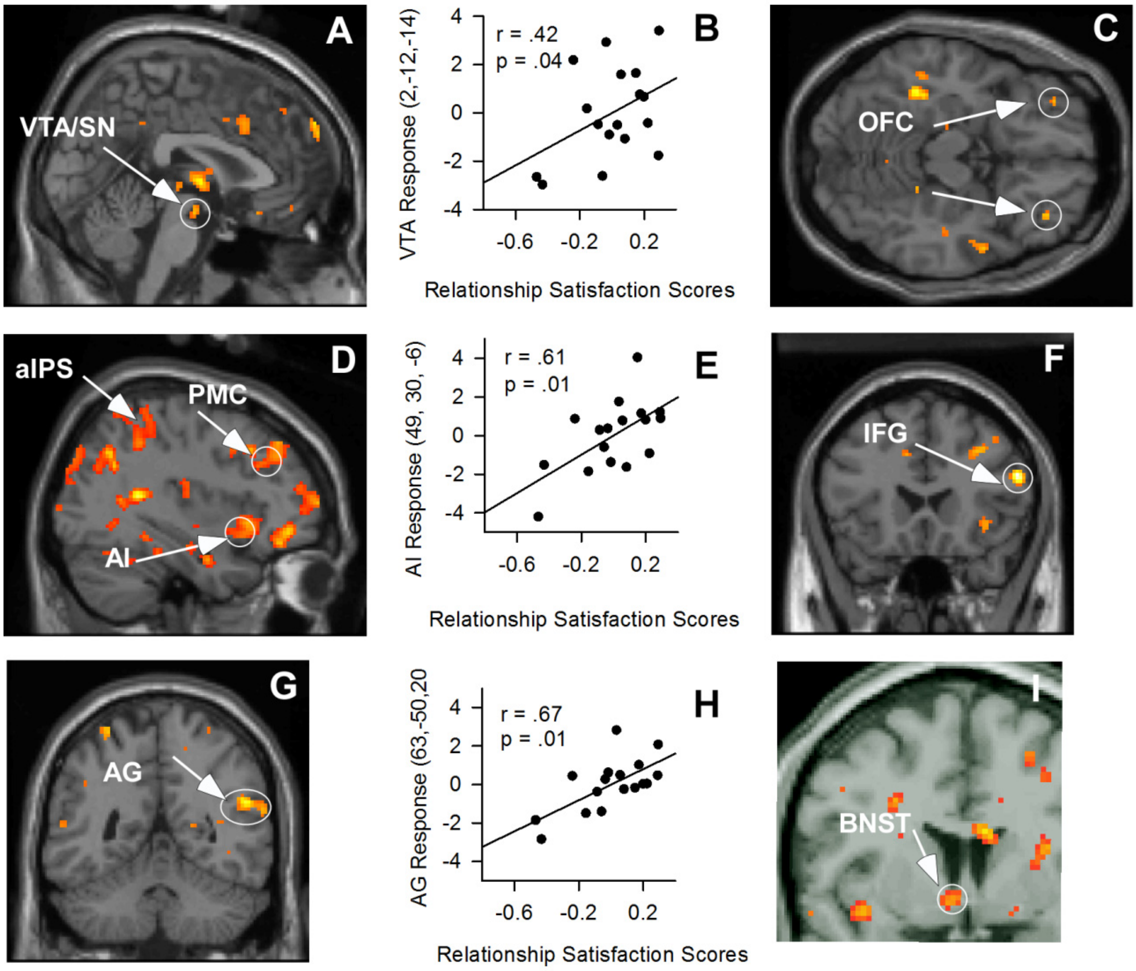


**Figure 1A&B.** *Sagittal brain image of the VTA (arrow and circle) and scatter plot showing the association between brain response in the VTA and relationship satisfaction scores for the Partner-versus-HFN contrast. Greater marital satisfaction was associated with greater response in the VTA for the partner versus a familiar acquaintance*

**Figure 1C.** *Horizontal brain image showing brain regions where there was a positive association between activation of the orbitofrontal cortex (OFC) and marital satisfaction scores for the Partner-versus-Close Friend contrast. Greater marital satisfaction was associated with greater response in the OFC*

**Figure 1D.** *Image showing brain regions where there were positive correlations between relationship satisfaction scores and activations in regions of the anterior insula (AI) and parts of the proposed mirror system: the anterior intraparietal sulcus (aIPS) and premotor cortex (PMC), for the Partner-versus-Close Friend contrast*

**Figure 1E.** *Scatter plot showing the association between brain response in the AI and relationship satisfaction scores for the Partner-versus-Close Friend contrast. Greater marital satisfaction was positively correlated with response in the AI, an area consistently found activated in empathy studies*

**Figure 1F.** *Coronal brain image showing regions where there was a positive correlation between activation of the right inferior frontal gyrus (IFG) and marital satisfaction scores for the Partner-versus-Close Friend contrast. Greater marital satisfaction was associated with greater response in the right IFG, and area proposed to be part of the human mirror system*

**Figure 1G&H.** *Image and scatter plot showing the association between brain response in the right angular gyrus (AG) and relationship satisfaction scores for the Partner-versus-Close Friend contrast. Greater marital satisfaction was associated with greater response in the AG*

**Figure 1I.** *Image showing the association between brain response in the bed nucleus of the stria terminalis (BNST) and marital satisfaction scores for the Partner-versus-Close Friend contrast. Greater marital satisfaction was associated with greater response in the BNST, and area important for the regulation of stress and anxiety*

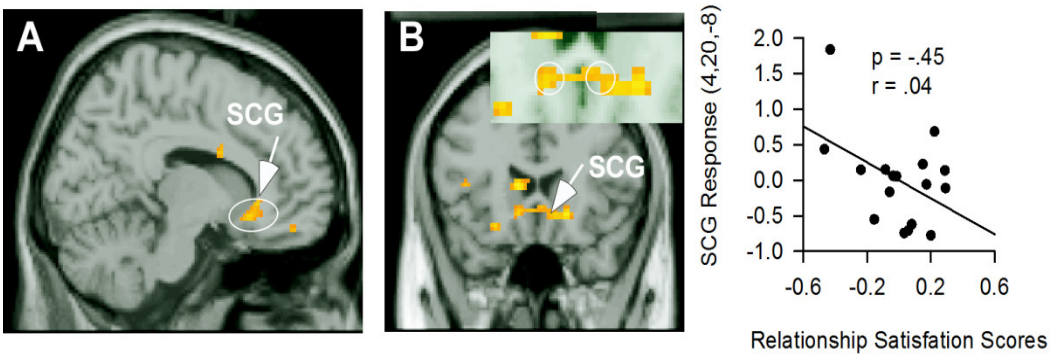


**Figure 2A&B.** *Images show the region where there is a negative correlation between relationship satisfaction scores and activation in the subcallosal cingulate gyrus (SCG) for the Partner-versus-HFN contrast in a sagittal section (A) and coronal section (B). Lower marital satisfaction was associated with greater activation of the SCG, an area which shows increased activation for severe depression*
**Figure 2C.** *Scatter plot showing the negative correlation between brain response in the SCG and relationship satisfaction scores for the Partner-versus-HFN contrast*

## Results

### *Marital satisfaction and brain activation*

**Regions of Interest.** As shown in **table 1**, positive correlations between marital satisfaction scores (controlling for Passionate Love Scale scores) for the Partner-versus-HFN and Partner-versus-CF were similar in regions of the right VTA, right substantia nigra (SN), left bed nucleus of the stria terminalis (BNST), bilateral caudate tail, left medial dorsal thalamus, bilateral lateral orbitofrontal cortex, left prefrontal cortex, right anterior insula (AI), bilateral inferior frontal gyrus (IFG), bilateral anterior parietal region (aIP), right parietal operculum, right premotor corerx (PMC), right temporo-parietal junction (TPJ), bilateral medial prefrontal cortex (MPFC), left middle temporal gyrus, and right angular gyrus (AG), left middle temporal gyrus, right superior parietal lobe, and right subcallosal cingulate gyrus (SCG).

**Whole-brain analyses.** Only the Partner-versus-HFN contrast correlations yielded significant activations in the whole-brain, exploratory analyses ($p \leq .001$, uncorrected 15 voxel minimum). Results showed a positive correlation between marital satisfaction scores (controlling for passionate love) and activity in the right anterior putamen (MNI coordinates: 26 20, 4), right dorsolateral prefrontal cortex (MNI coordinates: 48, 30 28), and the left midbrain reticular formation (MNI coordinates: -6, -18, -8).

**Negative correlations.** Only the Partner-versus-HFN contrast yielded significant negative correlations. As predicted, marital satisfaction scores were negatively correlated with activity in the right subcallosal cingulate gyrus (SCG) in response to the partner versus the familiar acquaintance (**figure 2**). The SCG has been implicated in affective processing and disorders (e.g., Drevets et al. 2008).

## Discussion

The present study is the first to examine the neural correlates of marital satisfaction. It is important to note that the sample was recruited for a study of long-term intense romantic love. The sample provided an opportunity to examine the physiology of stable and highly rewarding pair-bonds and valuation processes related to a natural, complex reward—marital satisfaction. We utilized a well-established paradigm where neural responses to partner images versus highly familiar, neutral persons and close friends were assessed. Marital satisfaction scores, over and above passionate love, showed significant associations in brain regions implicated in reward and motivation, goal-based evaluation, empathy, regulation of affect and stress, and mood disorders (such as depression and anxiety).

Our first prediction was that marital satisfaction would be associated with activation of dopamine-rich brain regions implicated in reward and motivation found in previous research with romantic partners focusing on romantic love (e.g., Acevedo et al. 2011, Aron et al. 2005, Ortigue et al. 2007, Xu et al. 2011). Our second hypothesis was that marital satisfaction scores would be associated with neural activity in regions associated with evaluation and decision making. This premise was partly based on the likelihood that the ability to accurately evaluate a romantic partner using cortical as well as subcortical systems is important for well-being, survival, reproduction, and offspring viability.

Both were confirmed. Marital satisfaction (controlling for passionate love) showed significant correlation effects ($p < .05$, FDR correction) in cortical and subcortical brain regions supporting reward, motivation, and reward evaluation behaviors, specifically the VTA/SN, caudate tail, PFC, OFC, and medial dorsal thalamus.

The midbrain (VTA/SN) and cortical areas (such as the OFC and PFC) mediate motivation, reward, and action (e.g., Knuston & Cooper 2005, Glimcher & Rustichini 2004). In the present study, greater activation of the right VTA/SN was correlated with marital satisfaction (when controlling for passionate love) in response to the partner. In a previous report of the present sample of individuals in long-term love (Acevedo et al. 2011) VTA activation was found: (a) in response to the partner versus the familiar acquaintance and close friend controls; (b) with correlations of passionate love and romantic love scales; and (c) extending into the SN in association with closeness scores (measured by the Inclusion of Other in the Self scale; Aron et al. 1992). Numerous studies have found activation of the right VTA in response to images of romantic partners among individuals in early-stage romantic love (e.g., Aron et al. 2005). However, the activation from the present study in the VTA/SN was most similar to that found in correlation with Inclusion of Other in the Self (IOS) scores seen by Acevedo et al. (2011), suggesting that signals may be reflecting positive valuations of the partner, the relationship and self-inclusion factors.

Correlations of activity in the caudate tail, mOFC and subcallosal cingulate are particularly interesting as they were found in association with relationship stability (together versus apart at 40 months follow-up) among individuals scanned in the early stages of romantic love (Xu et al. 2011, personal communication). The OFC is a key site involved in goal-directed behavior, affect, and selective memory retrieval. Knowledge about the OFC's functions has increased substantially over the past decade. It has been associated with a range of human behaviors and emotions, such as flexibly updating the incentive value of rewards, comparing relative value options, making decisions (e.g., Mar et al. 2011) and social evaluations of a close other (Hughes and Beer 2011). Research with humans and other primates suggests that the mOFC monitors and adjusts the incentive value of stimuli, and the lateral region is implicated in suppression of rewarded responses following contingency change (e.g., Elliott et al. 2000, Kringelbach & Rolls 2004, McClure et al. 2007, O'Doherty et al. 2001) as well as social evaluations (Beer and Hughes 2011). Across a range of studies the OFC has been associated with valuation of positive stimuli, such as pleasant foods (e.g., Rolls et al. 2003, Small et al. 2003), pleasant odors (Rolls, Grabenhorst, & Parris 2010), taste (Kringelbach et al. 2003, O'Doherty et al. 2002), imagined rewards (Bray et al. 2010), attractive faces (e.g., O'Doherty et al. 2003), and monetary rewards (e.g, Knutson et al. 2001). It has also been found to be active in response to aversive outcomes such as monetary losses and disliked foods (e.g., O'Doherty et al. 2003, Plassmann et al. 2010). Specifically, we found activation in the medial and lateral region of the OFC that have been associated with positive evaluation of the self and close others (Hughes and Beer 2011). In the present study, strength of OFC signals may be reflecting valuation of a positive stimulus—a highly rewarding long-term partner.

The medial dorsal thalamus has been shown to be important for reward-based decision making through its interaction with the OFC and amygdala (e.g., Baxter et al. 2000). Lesion studies with macaque monkeys suggest that the medial dorsal thalamus (in concert with the amygdala and OFC) support reward-based decision making, particularly choosing of objects when faced with selective satiation (Izquierdo & Murray 2010). Interestingly animal studies have suggested the importance of the medial thalamus (as well as other key regions) in relation to monogamous pair-bonding in mammals (e.g., Lim & Young 2004).

The present findings exemplify how the perceived level of natural reward (degree of relationship satisfaction) is processed in the brain; and suggest how positive valuations of a partner (marital satisfaction) are both inherently gratifying (as evidenced by reward-related signals) and evoke brain systems that influence choices and guide behaviors that may serve to promote relationship well-being and stability (such as delaying gratification and decreased impulsivity).

## *Marital satisfaction and empathy*

Our third hypothesis was that marital satisfaction ratings would be positively correlated with brain activity associated with empathy. We examined regions of interest based on two separate meta-analyses of empathy studies, two studies examining empathic responses to a loved one's pain, and three studies examining the mirror neuron system.

A positive association between brain activity and individual marital satisfaction scores (controlling for passionate love scores) was shown in areas of the right anterior insula (AI) similar to those found in 2 meta-analyses of 40 and 32 empathy studies respectively (Fan et al. 2010, Lamm et al. 2011) and a study involving perception of a romantic partner's pain (Singer et al. 2004). The AI has been associated with numerous functions ranging from emotional recognition to olfactory sensory processing (Kurth et al. 2010). The AI is important for subjective emotion processing, and the representation of feeling states in internal viscera (e.g., Kurth et al. 2010). It shows connectivity with other regions of the brain associated with emotion detection and interpretation, such as the inferior frontal gyrus (Jabbi & Keysers 2008). More generally, the insula integrates information from various systems and has been proposed to engender human awareness (Craig 2009, Klein et al. 2007).

Marital satisfaction was also correlated with activation of areas proposed to be part of the mirror system, such as the inferior frontal gyrus (IFG), anterior intraparietal sulcus (aIPS), and premotor cortex (PMC) (e.g., Iacoboni et al. 1999, Van Overwalle & Baetens 2009). It is suggested that the mirror system permits humans to rapidly and intuitively sense others' goals on the basis of simple behavioral input, but is limited to familiar executed actions (e.g., Cross et al. 2006, Van Overwalle & Baetens 2009). Activation of the IFG was found in an area similar to that reported in a study investigating neural responses to a loved one's pain (Mazzola et al. 2010) and research on human imitation (Iacoboni et al. 1999). Numerous studies have shown activation of the inferior frontal gyrus while the subject observed and executed movements (e.g., Decety et al. 1997) and it has been proposed that neurons in the IFG are part of a "mirror neuron system" (e.g., Kilner et al. 2009). These hypotheses are based on research with monkeys showing that neurons in the IFG analogue in humans fire when monkeys perform and observe hand actions (e.g., Rizzolatti & Craighero 2004, Nelissen et al. 2005). Thus, it has been suggested that activation of the IFG is implicated in imitation and understanding others' intentions (Gallese & Goldman 1998).

A separate mentalizing system has been proposed for understanding others' goals of more abstract and complex forms, allowing humans (and perhaps some primates) to make self-other distinctions in mental perspective (e.g., Amodio & Frith 2006, Mitchell 2006). In the present study, we found evidence for involvement of the mentalizing system in regions of the temporo-parietal junction and medial prefrontal cortex.

In addition, we found activation of the angular gyrus which has been implicated in studies involving the understanding of metaphors, cognition (specifically internal dialogue), left-right hand awareness, and abstract representation of the self (e.g., Arzy et al. 2006, Blanke et al. 2002). In a study of romantic love, activation of the angular gyrus was associated with subliminal presentation of a partner's name and individuals' scores on the Passionate Love Scale (Ortigue et al. 2007). The authors suggested that it may be involved in integration of abstract representation of the partner into individuals' self-concepts. Somewhat similarly, the middle temporal gyrus has been implicated in a wide range of processes, from extracting word meaning to recognition of faces. We found activation of the middle temporal gyrus similar to that reported in a study of perceiving a loved one in pain (Mazzola et al. 2010) and in a meta-analysis of emotion face perception (Sabatinelli et al. 2011). These results suggest a neural mechanism by which marital satisfaction could benefit both the individual and couple. The association between relationship satisfaction with neural regions implicated in empathy and the mirror system suggest greater attunement to a relationship partner's signals—an important component for maintaining a secure and stable relationship (e.g., Bowlby 1969, Collins & Ford 2010).

## *Affective regulation, stress, and well-being*

Marital satisfaction scores were also correlated with activity in several regions implicated in affective regulation and stress control. For example, activation was shown in the left side of the bed nucleus of the stria terminalis (BNST), a region which regulates the hypothalamic-pituitary-adrenal (HPA) axis responses to stress. The BNST has been implicated in mediating anxiety-like behavior to chronic, negatively-valenced threats in humans and organizing stress responses via projections brainstem regions (e.g., Hammack et al. 2010, Walker et al. 2009). Lesion studies with rats have shown immobilization in response to stress suggesting that the BNST may modulate coping in response to uncontrollable stress (Schulz & Canbeyli 2000).

One positive correlation was found in the dorsomedial prefrontal cortex (PFC) which serves a wide range of functions, such as cognitive control, emotion regulation, and rational decision making (e.g., Bunge et al. 2002, Casey et al. 2005, Ochsner & Gross 2005), as well as perspective – taking and self-referential thinking (e.g., Mitchell et al. 2006, Tamir & Mitchell 2010). One study showed increased prefrontal activity in association with making a safe choice versus a risky choice (e.g., Cristopoulos et al. 2009). Developmental studies suggest the strengthening of connections between prefrontal regions (engaged in cognitive control) and striatal regions (involved in motivation and reward processing) from adolescence into adulthood (e.g., Casey et al. 2007). In the present context, activation of the PFC and striatum in relation to marital satisfaction may reflect adaptive emotion regulation, known to be associated with positive interpersonal functioning (e.g., Gross & John 2003).

Last, marital satisfaction was negatively correlated with activation of the SCG; hyperactivation of the SCG has been linked with major depression and has been a target for deep-brain stimulation treatment of intractable depression (Lozano et al. 2008). Studies with patients suffering from affective disorders suggest co-activation of the medial prefrontal cortex, SCG, and related striato-pallido-thalamic structures (e.g., Drevets et al. 2008). The SCG area was also less active among individuals in early-stage romantic love that stayed together versus those that broke up 40 months after the initial scan (Xu et al. 2012, personal communication). It's interesting to note that a separate, more anterior area of the SCG was positively correlated with marital satisfaction in the present study of long-term coupled individuals, as was found in correlation with relationship happiness among a sample in early-stage romantic love (Xu et al. 2010). Thus we have replicated an effect for relationship satisfaction in the SCG. Correlations of relationship satisfaction with neural activity in regions implicated in affective regulation are in line with research suggesting links between marital dissatisfaction and depressive symptoms (meta-analysis, Whisman 2001). On the positive side, the present results suggest that satisfying relationships are associated with affective regulation and may also protect individuals from stress, anxiety and depression. However, we are not suggesting causality, as negative affectivity, stress, and other physical and psychological ailments are negatively associated with marital satisfaction.

## *Implications, strengths, and limitations*

The present study is the first to assess the neural correlates of marital satisfaction within a population of highly satisfied and in-love individuals. This population was selected because they were highly likely to exhibit the physiology and neural circuitry associated with rewarding marital bonds. The results suggest that brain regions and pathways associated with reward, motivation, decision-making, empathy, and affective and stress regulation are involved in perceived marital satisfaction.

The significant contribution of positive social bonds to an individual's well-being is well-known. In the 1950's, Harlow demonstrated the striking effects of social isolation on monkeys' physical and psychological well-being. Since then, numerous studies with humans have shown strong links between marital quality and health outcomes (e.g., meta-analysis, Proulx et al. 2007).

In this report we extended previous research and showed that marital satisfaction is associated with brain regions implicated in reward, motivation, evaluation of rewards, empathy, and emotional regulation. These findings also support theories suggesting the important role of the attachment system in regulating psycho-biological systems and behavior (e.g., Sbarra & Hazan 2008). The results also highlight the association between relationship satisfaction with neural activity of systems implicated in empathy and imitation. Thus, suggesting processes that enable humans to respond to a partner's needs. In sum, these findings suggest some of the neural mechanisms that may permit happily long-time married individuals to behave in ways that enhance their relationships and promote marital stability.

It is important to note that by examining only highly satisfying marriages, it is not feasible to generalize across the spectrum of different types of relationships (e.g. content but not highly satisfying marriages or even unsatisfying ones). However, by selecting only those in highly satisfying relationships we have constrained the variability of our key factor, marital satisfaction, thus likely considerably under-estimating the degree of correlations. That is, as there were small differences in relationship satisfaction scores only substantial effects were likely to be found. Indeed, it is likely that if we recruited a sample with greater variability in marital satisfaction scores, correlations with brain activity could potentially be even stronger. These results are also likely conservative because all correlations controlled for passionate love scores, a variable with typically considerable overlap with marital satisfaction. At the same time, this control permits a more fine-grained interpretation of the aspects of marital quality specifically associated with the identified patterns of activations.

There are some limitations that should be addressed in future research. In addition to exploring these issues in a larger sample and with a broader range of marital satisfaction, it would be useful to test samples in earlier marital stages and a broader age-range and across cultural contexts, and to include those in long-term same-sex relationships. Another methodological issue that limits interpretation of results is task-selection, such that participants were asked to recall events with their partners, familiar acquaintances, and friends. The flexibility of the experimental procedure leave many things open to interpretation. Also, although we conducted post-experimental interviews, there were no objective measures of task adherence. Future research would benefit from measuring the associations of neural patterns to assessments of marital quality that are not based on self-report, such as implicit cognitive measures and observational coding of marital discussions.

These findings are particularly valuable for public health issues as they show how relationship quality may impact health, through systems implicated in affect, stress, and depression. Thus, public health programs might aim to raise awareness and educate the public about the significant influence that relationship functioning has on couples' psychological and physical health, as well as their offspring (e.g., Amato & Sobolewski 2001, Barry & Kochanska 2010, Ha et al. 2009). For example, program and policy makers may focus resources to increase relationship functioning among existing relationships, and by providing youth with relationship and parenting skills. Also, increasing knowledge about the many benefits and factors associated with satisfying relationships might inspire those in dissatisfying relationships to work on issues or exit highly dysfunctional relationships.

## Conclusions

Satisfying pair-bonds are adaptive and provide benefits for individuals, couples, and their children. The present findings suggest that perceived marital satisfaction, even after controlling for degree of passionate love, is strongly associated with neural activation in multiple brain areas involved in reward, motivation, self-concept, empathy, and affective regulation. The present report suggests how relationship quality may be deeply affect human psychological and physical health, mediated through several neural systems at cortical and subcortical levels. Some of the more important brain regions involved may be the brainstem VTA (reward), substantia nigra, bed nucleus of the stria terminalis (stress), subcallosal cingulate (mood) and inferior frontal gyrus (empathy).

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