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Connectome-based prediction of marital quality in husbands' processing of spousal interactions

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Abstract

Marital quality may decrease during the early years of marriage. Establishing models predicting individualized marital quality may help develop timely and effective interventions to maintain or improve marital quality. Given that marital interactions have an important impact on marital well-being cross-sectionally and prospectively, neural responses during marital interactions may provide insight into neural bases underlying marital well-being. The current study applies connectome-based predictive modeling, a recently developed machine-learning approach, to functional magnetic resonance imaging (fMRI) data from both partners of 25 early-stage Chinese couples to examine whether an individual's unique pattern of brain functional connectivity (FC) when responding to spousal interactive behaviors can reliably predict their own and their partners' marital quality after 13 months. Results revealed that husbands' FC involving multiple large networks, when responding to their spousal interactive behaviors, significantly predicted their own and their wives' marital quality, and this predictability showed gender specificity. Brain connectivity patterns responding to general emotional stimuli and during the resting state were not significantly predictive. This study demonstrates that husbands' differences in large-scale neural networks during marital interactions may contribute to their variability in marital quality and highlights gender-related differences. The findings lay a foundation for identifying reliable neuroimaging biomarkers for developing interventions for marital quality early in marriages.

Key words: connectome; gender differences; machine learning; marital interactions; marriage

Introduction

Marriages are often intimate and enduring interpersonal relationships and may influence the growth and development of individuals (Robles *et al.*, 2014; Cao *et al.*, 2017). However, as a particularly complex period, during the early years of marriage, marital quality often decreases (Markman, 1981; National Center for Health Statistics, 2001) and predicts future marital well-being (Dush *et al.*, 2008; Lavner and Bradbury, 2010). Thus, establishing imaging biomarkers that may be used to predict marital well-being at an individual level is of significant importance for timely and effective interventions at early marital stages.

The social learning model proposes that behavioral interactions are essential to marital relationships (Bandura and Walters, 1977; Laurenceau *et al.*, 1998). The vulnerability–stress–adaption model of marriage contends that marital interactions constitute the most proximal factor influencing marital outcomes (Karney and Bradbury, 1995). Marital interaction refers to the process of exchanging thoughts and feelings between husbands and wives, which includes both verbal and non-verbal information, involving emotional characteristics and content (Gottman *et al.*, 1977; Gottman, 1979; Levenson and Gottman, 1983; Geist and Gilbert, 1996; Eckstein and Goldman, 2001; Melby and Conger, 2001; Heyman, 2004; Coan and Gottman, 2007; Papp *et al.*, 2010; Yedirir and Hamarta, 2015). Positive marital interactions (e.g. spousal support, especially emotional support) have been correlated with higher marital satisfaction (Jensen *et al.*, 2013;

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Wang et al., 2015; Gadassi et al., 2016; Yazdani et al., 2016), while negative interactions (e.g. verbal or physical aggression, emotional dyscontrol, dominance, commands and withdrawal) have been linked to poorer marital well-being (Kurdek, 1995; Amato and Hohmann-Marriott, 2007; Ostrov and Collins, 2007; Carroll et al., 2010; Panuzio and DiLillo, 2010; Donato et al., 2014). Empirical studies have demonstrated that couples with higher marital quality, compared with those with lower marital quality, show more constructive vs destructive interactive behaviors and more positive rather than negative emotions during interactions (Gottman and Levenson, 1986; Papp et al., 2010; Cao et al., 2015; Yedirir and Hamarta, 2015). Marital interactive behaviors and emotions during interactions have also predicted marital well-being prospectively (Gottman and Krokoff, 1989; Noller et al., 1994; Heavey et al., 1995; Gottman et al., 1998; Bradbury et al., 2000b; Ostrov and Collins, 2007). Furthermore, research suggested that emotional characteristics of communication could better reflect the relationship quality than the actual content components of communication (Gottman et al., 1977; Gottman, 1979). Emotional rather than instrumental spousal support predicted better marital satisfaction regardless of gender and gender role attitudes (Mickelson et al., 2006). Thus, neural responses during marital interactions (especially emotional interactions) may provide insight into the neural underpinnings of marital well-being and its changes over time.

Historically, few studies have investigated relationships between marital well-being and neural responses to spousal interactive behaviors, and these studies have focused on a limited number of brain regions. Investigations using machine-learning-based prediction approaches have not been conducted to date. Furthermore, studies have typically utilized data from only one spouse. For example, wives' responses to electric shocks in the anterior insula when their husbands offered support were negatively correlated with marital well-being (Coan et al., 2006; Inagaki and Eisenberger, 2012). Gunther et al. (2009) reported that husbands exhibited higher activation in areas involved in theory of mind when processing their wives' suggestions and evaluations in important relative to unimportant fields. The current study adopted a classic social cognition task (Gunther et al., 2009; Stoessel et al., 2011; Acevedo et al., 2012; Xu et al., 2012), in which participants processed their spouse's representative interactive behaviors during scanning.

Functional brain imaging studies have revealed that human behavior depends on interactions between a set of domain-specific, distributed brain networks related to visual, auditory, motor, sensory and other processes (Fox and Raichle, 2007; Smith et al., 2009). Functional connectivity (FC) profiles (especially those within medial frontal and frontoparietal networks) can serve as a 'fingerprint' to characterize individual variability (Finn et al., 2015). Connectome-based predictive modeling (CPM) with built-in cross-validation has been developed to construct predictive models (Shen et al., 2017). CPM can not only identify networks underlying specific behaviors across the whole brain ('neural fingerprints') rather than focusing on a single edge, region or network of interest but also avoid some multiple comparison concerns (Power et al., 2011; Haufe et al., 2014; Whelan and Garavan, 2014). Using both resting-state and task-based functional magnetic resonance imaging (fMRI), CPM has recently been used to reliably predict intelligence (Jiang et al., 2020), divergent thinking (Beaty et al., 2018), personality and temperament traits (Hsu et al., 2018; Jiang et al., 2018) and loneliness (Feng et al., 2019). These publications provide foundations for future work to understand brain–behavior relationships, including with respect to marital quality. Currently, the field lacks studies investigating neural predictions of marital quality using whole-brain, machine-learning approaches and functional connectomes. Such approaches are important for increasing the likelihood of replication in future studies and generating reliable biomarkers of marital quality, providing brain-based information for intervention development to improve marital quality at early relational stages.

Marriage typically consists of dyadic relationships between husbands and wives, and it is important to consider both husbands' and wives' FC patterns that may simultaneously and independently associate with their own marital quality (actor effects) as well as their partners' (partner effects) (Kenny et al., 2006). Differences often exist between husbands and wives in perceptions of marital well-being and interactive behaviors. For example, husbands have reported higher levels of marital satisfaction than wives (Ng et al., 2009; Rostami et al., 2014), reported lower active involvement and less negative interactive behaviors (Ball et al., 1995) and received greater spousal support than wives (Xu and Burleson, 2001). Thus, we aimed to examine whether one's own and one's partner's marital quality may be reliably predicted from an individual's unique pattern of brain FC when responding to their spousal interactive behaviors and to evaluate gender specificity in predictability.

Furthermore, perceiving and responding to emotional stimuli may also contribute to the functioning of intimate relationships (Forgas, 2002). During task-free resting states, FC within reward, motivation, emotional regulation and social cognition networks has been observed to be increased in 'in-love' vs 'ended-love' and 'single' groups (Song et al., 2015). Thus, to investigate the model specificity on predicting individuals' marital quality from their FC, we compared a prediction model using FC responding to their spousal interactive behaviors with that during generalized emotional stimuli processing and resting state.

The current study used CPM to interrogate fMRI data from 25 recently married Chinese husband–wife pairs. The fMRI data obtained during the processing of relationship-specific stimuli (involving neural responses to spousal interactive behaviors) and general emotional stimuli and while at rest were examined to determine whether brain FC patterns during responding to spousal interactive behaviors could reliably predict individuals' own and their partners' marital quality after 13 months. Specificity involving gender (husband and wife) and condition (spousal interactive stimuli, emotional stimuli and rest) was examined. We hypothesized that data relating to the processing of spousal interactions would be most likely to be predictive of marital quality, given the relevance of spousal interactions to marital quality (Karney and Bradbury, 1995; Bradbury et al., 2000a). Given gender-related differences in marital well-being and interactive behaviors (Ng et al., 2009; Rostami et al., 2014), we hypothesized that CPM would show gender specificity in predictability.

Materials and methods

Participants

The study was approved by the Institutional Review Board of the State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University. All subjects provided written informed consent prior to participation. Twenty-five couples completed both fMRI scanning and follow-up measurements 13 months later, and the demographic characteristics and questionnaire measures are displayed in Table 1.

Table 1. Demographic characteristics

	Wives (n = 25)		Husbands (n = 25)			
	M	s.d.	M	s.d.	t	P
Age (years)	28.72	2.24	29.24	2.90	−1.14	0.264
Education (number with master's degree or above)	11	–	12	–	–	0.845[a]
Months of marriage	17.49	12.49	17.49	12.49	–	–
Time interval to follow-up (months) questionnaire (months)	12.85	0.69	12.85	0.69	–	–
T1 marital quality	36.44	8.15	38.44	7.71	−1.80	0.084
T2 marital quality	36.76	8.57	37.04	10.00	−0.27	0.787
Marital quality change (△marital quality)	0.32	6.84	−1.40	8.49	−1.00	0.350

T1 marital quality: marital quality at Time 1 (scanning); T2 marital quality: marital quality at Time 2 (13 months after scanning).
[a]McNemar's test.

Experimental process and tasks

To measure brain responses to their spousal interactions, reflecting a classical paradigm of social cognition, the current study adopted several representative positive or negative interactive behaviors, frequently occurring and suitable to display during scanning, as stimuli. This process also facilitates comparisons with general emotional videos. Each husband and wife was scanned in a random sequence (wife or husband was scanned first). First, subjects were scanned during resting state, eyes open, looking at a black screen, staying awake and not thinking of anything in particular. Then, participants watched relationship-specific stimuli [typical positive (praise and understanding), negative (criticism and dominance) behaviors and neutral clips of their spouse] and rated their emotional reactions and their spouse's emotions in the videos, consisting of 25 blocks (order of the stimuli involved 5 × 5 Latin squares for the relationship-specific stimuli processing task). Finally, participants watched the general emotional stimuli [positive (happy), negative (sad and angry) and neutral videos] and rated their own responses and speculated regarding their spouse's emotional reactions to these videos; these consisted of 16 blocks (order of the stimuli used 4 × 4 Latin squares in the general emotional stimuli processing task) (Yuvaraj et al., 2014).

A Quality of Marriage Index was assessed around scanning time and 13 months (±1 month) after the scans. Details regarding participants, stimuli, questionnaire measures and emotional responses to the scanner stimuli can be found in our prior study (Ma et al., 2021) and Supplementary Material.

Image acquisition and preprocessing

Data were acquired using a Siemens 3T TrioTim MRI scanner (Siemens, Erlangen, Germany; see Supplementary Material) (Ma et al., 2021). Spatial processing of resting and task-based data was performed using standard processes in DPABI version 4.2 (Data Processing & Analysis for Brain Imaging, http://rfmri.org/dpabi), which included slice-timing, realignment, normalization to $3 \times 3 \times 3\,mm^3$ Montreal Neurological Institute space, nuisance regression (linear drifts, mean cerebrospinal fluid signal, mean white-matter signal and 24-parameter motion), smoothing with a Gaussian kernel of 6 mm at full width half maximum and a filter at 0.01–0.15 Hz (Sun et al., 2004; Bassett et al., 2015) to task-related and 0.01–0.10 Hz resting-state data (Yan et al., 2016; Feng et al., 2019; Marin-Marin et al., 2021).

Analysis of functional connectome

The FC matrix (i.e. connectome) for each subject during resting state and each task was estimated by correlating (Pearson's r) all possible pairs of 268 regions of interest (ROIs) of a functional brain atlas involving 10 functional networks (Shen et al., 2013; Finn et al., 2015; Yip et al., 2019). The functional connectome was Fisher's r-to-z transformed (Rosenberg et al., 2018; Yip et al., 2019). We calculated the FC after removing average task-related signals from the task-based data by using residuals of finite impulse response task regression, fitting the cross-block mean response for each time point (window length = 40 s, order = 7) (Liu et al., 2017; Cole et al., 2019). For missing FC data within ROI pairs, values were imputed as the average value for that FC from all remaining subjects with same gender. To maximize the amount of data used to calculate correlations and thus the reliability of FC estimates (Birn et al., 2013; Shah et al., 2016) and to facilitate comparisons with the resting-state model, we generated one task matrix rather than five condition-specific matrices (e.g. prize and criticism) for each individual (Rosenberg et al., 2018; Yip et al., 2019).

Because the current study utilizes data from both partners of married couples, CPM was employed to examine how person A's connectivity pattern simultaneously and independently predicted his or her own as well as his or her partner's (person B's) report of marital quality.

Prediction analysis using CPM during relationship-specific task

In each CPM process, leave-one-out cross-validation (LOOCV) was applied, in which data from one subject were set aside as the test set, and data from the remaining $n-1$ subjects were used as the training set. Each iteration consisted of three steps. (i) Feature selection, in which edges and behavioral data from the training data set were correlated using partial Spearman's correlation (because of the non-normality of marital quality and small sample size) and separated into positive and negative networks (at threshold of $P < 0.01$) (Shen et al., 2017; Beaty et al., 2018; Jiang et al., 2020), was conducted first. Positive networks are edges with FC strength positively associated with marital quality, and negative networks are those negatively associated with marital quality. (ii) Model building, in which training data were used to fit simple linear regression between marital quality and a summary of FC connectivity strength of positive-, negative-, and combined positive- and negative-feature networks, was performed next. (iii) Prediction, in which the resultant model coefficients were applied to the test data set to predict marital quality, was conducted last. To control for influences of head motion and marriage duration, feature selection in CPM analysis was conducted controlling for head motion and months of marriage.

Model performances were assessed using Spearman's correlations between predicted and actual values (Yip et al., 2019), and a significant positive correlation demonstrated a good prediction (Shen *et al.*, 2017). Thus, to account for non-independence, we conducted a permutation test by randomly shuffling the marital quality and connectivity matrices 1000 times and rerunning the CPM to create a null distribution of r and *MSEM* values for prediction (Rosenberg *et al.*, 2016). Based on their corresponding null distribution, the *P*-values of the empirical correlation values were computed using the following formula: (1 + the number of permutated *r* values ≥ the empirical *r*)/1001 (Beaty *et al.*, 2018; Feng *et al.*, 2019). The *P*-values of the empirical MSE values were computed using the following formula: (1+the number of permutated *MSE* values≤ the empirical *MSE*)/1001 if the r and MSE value couldn't be computed in certain permutation iterations, that is, the *r* and *MSE* is NaN, the denominator is 1+ the number of permutated *r* or *MSE* values that are not NaN (Feng *et al.*, 2019).

Contributing network in the prediction

The edges appearing across all iterations of the LOOCV (i.e. with a 100% occurrence rate) were defined as the contributing network (Rosenberg *et al.*, 2016; Shen *et al.*, 2017). Cognitive constructs may arise from a collection of brain areas acting together as large-scale networks (Fox and Raichle, 2007; Smith *et al.*, 2009; Shen *et al.*, 2013). Thus, the importance of each network contributing to the prediction was measured by the number of connections within and between 10 canonical neural networks for the positive and negative networks (Feng *et al.*, 2019; Yip *et al.*, 2019).

Gender specificity in the predictability of own and partner's marital quality

We examined gender specificity in CPM by applying wife-specific (or husband-specific) contributing networks to husbands' (or wives') FC and behavioral data. If the contributing network is gender-specific, the wife-specific FC pattern should be only able to predict their own or their partners' marital quality using wives' FC data, instead of using husbands' FC data. For husbands, it would be vice versa (Jiang *et al.*, 2020).

Testing of prediction model specificity

To test the model specificity, we reran the prediction model using FC data from the general emotional processing task and task-free resting state (Beaty *et al.*, 2018).

Results

Connectome-based prediction of marital quality after 13 months when responding to spousal interactive behaviors

The overall CPM model in husbands when responding to spousal interactive behaviors significantly predicted their own

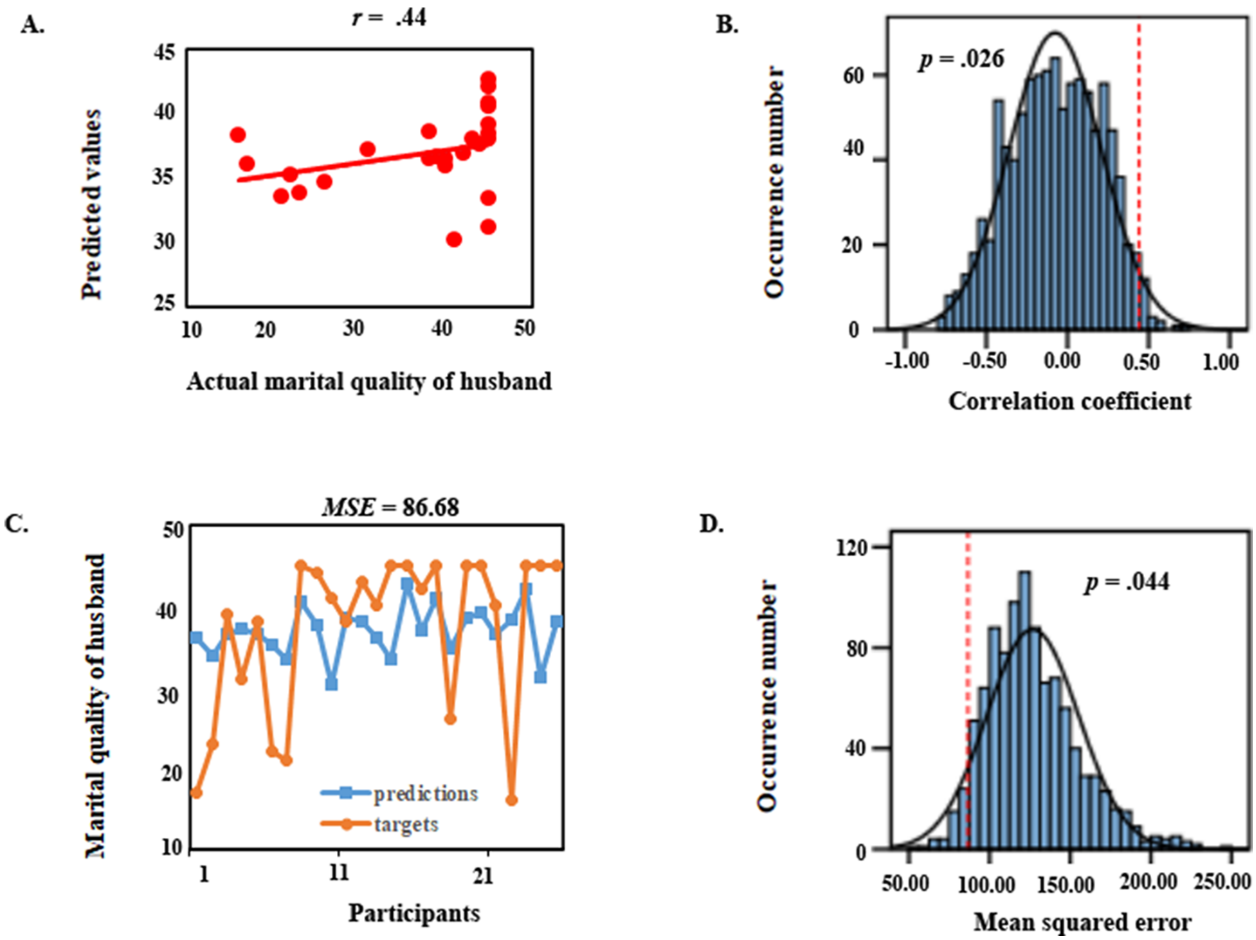

Fig. 1. Prediction of husbands' marital quality by brain connectivity patterns during responses to spousal interactive behaviors of husbands. (A) Correlation between actual and predicted loneliness scores; (B) permutation distribution of the correlation coefficient (*r*); (C) consistency between actual and predicted marital quality and (D) permutation distribution of the MSE. The values obtained using the real scores are indicated by the dashed line in (B) and (D).

marital quality (actor effect; combined positive and negative networks) and their wives' marital quality (partner effect; negative networks) after 13 months (Figures 1 and 2; Tables 2 and 3).

Contributing networks in the prediction

Figures 3A and 4A summarize the positive and negative networks based on connectivity between macroscale brain regions. In the prediction of husbands' marital quality from husbands' functional connectome, the highest-degree nodes for the positive network included prefrontal nodes with connections to occipital nodes; connections within motorstrip nodes; cerebellar nodes with connections to brainstem nodes; and limbic nodes with connections to insula nodes. The highest-degree nodes for the negative network included temporal nodes with connections to prefrontal, temporal, parietal, motorstrip and limbic nodes; prefrontal nodes with connections to prefrontal and cerebellar nodes; and cerebellar nodes with connections to parietal nodes. In the prediction of wives' marital quality from husbands' functional connectome, the highest-degree nodes for the negative network included temporal nodes with connections to prefrontal and limbic nodes, and motorstrip nodes with connections to prefrontal and temporal nodes.

To facilitate the characterization of identified contributing networks, we summarized connections within and between canonical neural networks. In the prediction of husbands' marital quality from husbands' functional connectomes, the positive network implicated connections between motor/sensory and salience networks, between visual b and salience networks and within the cerebellum/brainstem network. The negative network implicated connections between frontal–parietal and visual association networks, within the motor/sensory and frontal–parietal networks, and between frontal–parietal and medial frontal networks (Figure 3B). In the prediction of wives' marital quality from husbands' functional connectome, the negative network implicated connections involving the motor/sensory network and between motor/sensory and frontal–parietal networks (Figure 4B).

Gender specificity in the predictability of marital quality

We examined gender specificity in CPM by applying the husband-specific contributing network to wives' FC and behavioral data. Wives' summary connectivity strengths within positive and negative networks were entered into correlation analyses with their own or their partner's marital quality; negative network

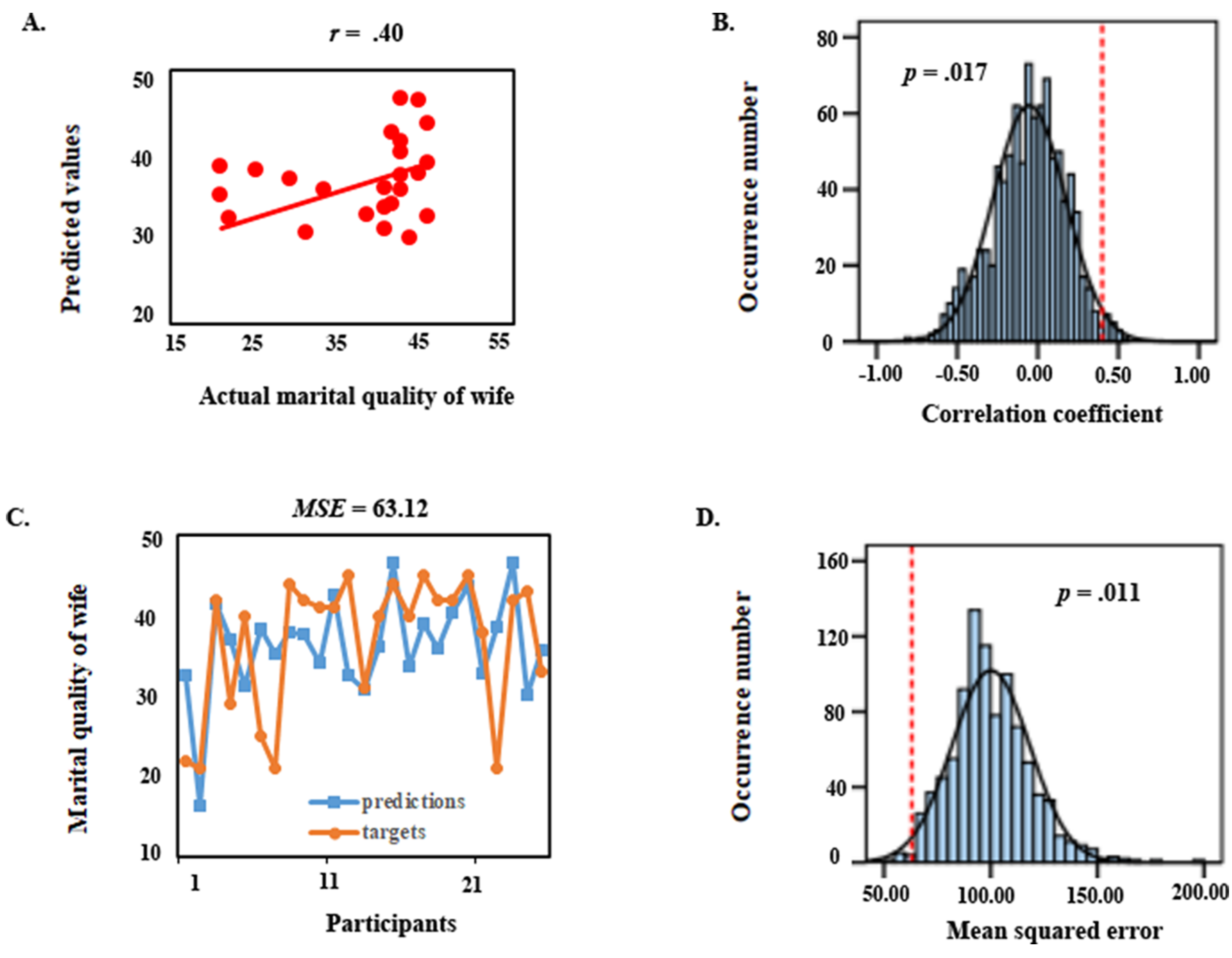

Fig. 2. Prediction of wives' marital quality by brain connectivity patterns during responses to spousal interactive behaviors of husbands. (A) Correlation between actual and predicted loneliness scores; (B) permutation distribution of the correlation coefficient (r); (C) consistency between actual and predicted marital quality and (D) permutation distribution of the MSE. The values obtained using the real scores are indicated by the dashed line in (B) and (D).

Table 2. Summary of CPM for husbands' marital quality after 13 months, controlling for head motion and months of marriage

		Marital quality of husbands											
		$r_{(positive)}$	$p_{r\ (positive)}$	$MSE_{\ (positive)}$	$p_{MSE\ (positive)}$	$r_{(negative)}$	$p_{r\ (negative)}$	$MSE_{\ (negative)}$	$p_{MSE\ (negative)}$	$r_{(combined)}$	$p_{r\ (combined)}$	$MSE_{\ (combined)}$	$p_{MSE\ (combined)}$
Spousal interaction	Husbands' FC	−0.30	0.849	151.28	0.750	0.32	0.060	95.17	0.058	0.44	0.026	86.68	0.044
	Wives' FC	−0.31	0.820	169.84	0.854	0.28	0.084	118.90	0.288	−0.10	0.509	144.82	0.748
	Husbands' FC	−0.20	0.715	154.14	0.765	0.25	0.100	113.10	0.178	0.10	0.280	102.29	0.201
Generalized emotion	Wives' FC	−0.48	0.940	179.76	0.908	0.31	0.063	106.51	0.125	−0.06	0.487	129.30	0.621
	Husbands' FC	−0.15	0.635	160.00	0.767	−0.08	0.598	140.73	0.620	−0.31	0.742	132.33	0.689
Resting-state	Wives' FC	−0.39	0.897	177.55	0.875	0.17	0.184	100.18	0.072	−0.07	0.443	110.67	0.373

r(positive) and *pr (positive)*: the value and significance of correlation between actual and predicted marital quality by the positive network;
r(negative) and *pr (negative)*: the value and significance of correlation between actual and predicted marital quality by the negative network;
r(combined) and *pr (combined)*: the value and significance of correlation between actual and predicted marital quality by the combination of positive and negative network;
MSE (positive) and *pMSE (positive)*: the value and significance of MSE between actual and predicted marital quality by the positive network;
MSE (negative) and *pMSE (negative)*: the value and significance of MSE between actual and predicted marital quality by the negative network;
MSE (combined) and *pMSE (combined)*: the value and significance of MSE between actual and predicted marital quality by the combination of positive and negative network.

Table 3. Summary of CPM for predicting wives' marital quality after 13 months, controlling for head motion and months of marriage

		Marital quality of wives											
		$r_{(positive)}$	$p_{r\ (positive)}$	$MSE_{\ (positive)}$	$p_{MSE\ (positive)}$	$r_{(negative)}$	$p_{r\ (negative)}$	$MSE_{\ (negative)}$	$p_{MSE\ (negative)}$	$r_{(combined)}$	$p_{r\ (combined)}$	$MSE_{\ (combined)}$	$p_{MSE\ (combined)}$
Spousal interaction	Husbands' FC	−0.57	0.987	132.30	0.931	0.40	0.017	63.12	0.011	0.22	0.140	75.02	0.169
	Wives' FC	−0.58	0.966	163.89	0.974	0.22	0.146	95.03	0.417	−0.43	0.852	139.93	0.965
	Husbands' FC	−0.57	0.968	149.19	0.964	0.22	0.121	83.74	0.200	−0.43	0.864	109.90	0.862
Generalized emotion	Wives' FC	0.09	0.306	89.42	0.356	−0.04	0.531	94.18	0.453	0.21	0.188	70.08	0.128
	Husbands' FC	−0.19	0.709	110.91	0.713	0.01	0.410	93.68	0.370	0.00	0.390	84.54	0.397
Resting-state	Wives' FC	−0.03	0.493	90.19	0.309	−0.11	0.615	95.61	0.412	−0.12	0.520	78.91	0.340

r(positive) and *pr (positive)*: the value and significance of correlation between actual and predicted marital quality by the positive network;
r(negative) and *pr (negative)*: the value and significance of correlation between actual and predicted marital quality by the negative network;
r(combined) and *pr (combined)*: the value and significance of correlation between actual and predicted marital quality by the combination of positive and negative network;
MSE (positive) and *pMSE (positive)*: the value and significance of MSE between actual and predicted marital quality by the positive network;
MSE (negative) and *pMSE (negative)*: the value and significance of MSE between actual and predicted marital quality by the negative network;
MSE (combined) and *pMSE (combined)*: the value and significance of MSE between actual and predicted marital quality by the combination of positive and negative network.

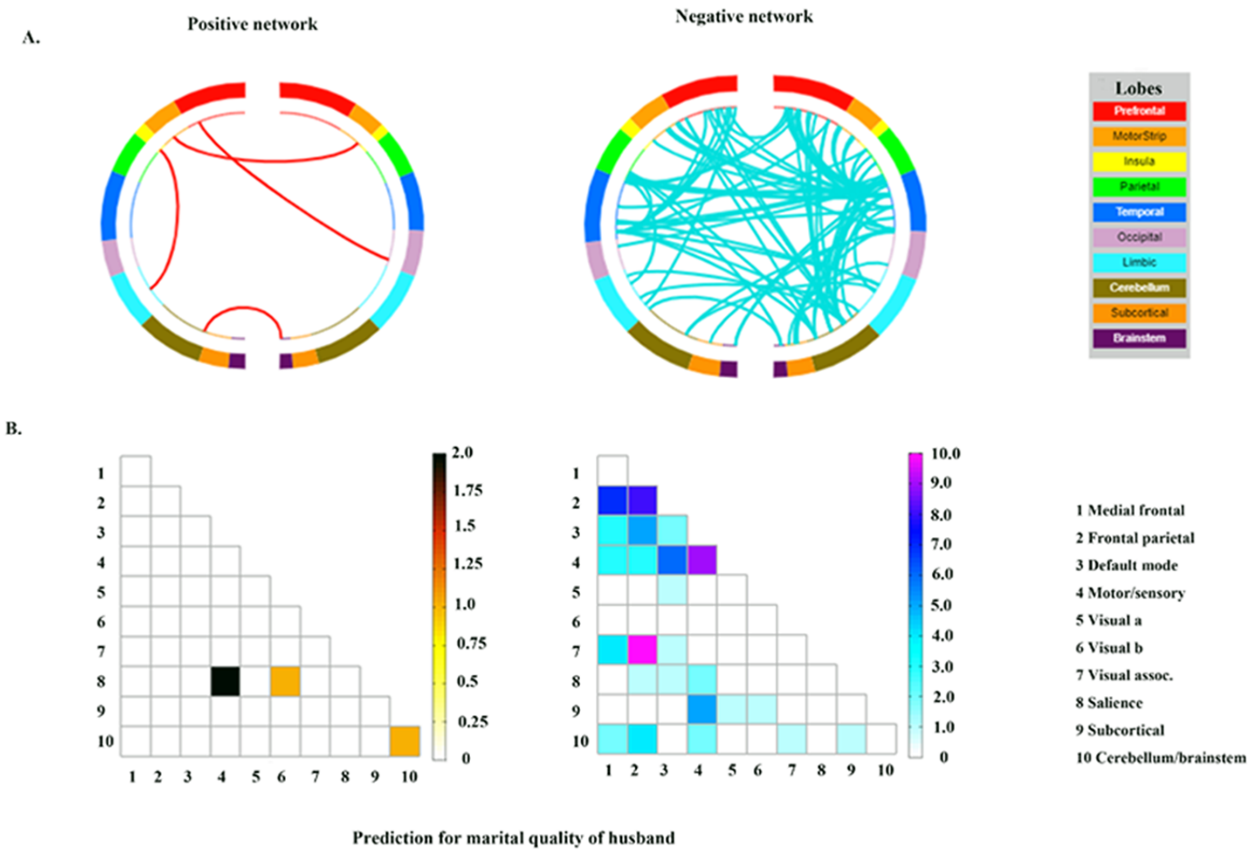

Fig. 3. Positive and negative networks summarized by overlap with macroscale brain regions (A) and large neural networks (B) in the prediction of husbands' marital quality using husband's FC responding to spousal interactive behaviors. In the panels designated 'Positive network' and 'Negative network', cells represent the number of edges within (and between) each network.

values were first sign-flipped so that higher correlation values indicated 'better' prediction (Yip *et al.*, 2019). The results showed no significant prediction when predicting their own or their partners' marital quality with male-specific FCs using females' data [their own: $r = 0.22$, $P = 0.283$ (connectivity of positive minus negative network); their husbands: $r = -0.07$, $P = 0.726$ (negative connectivity of negative network)], suggesting gender specificity in the predictability of their own and their partners' marital quality.

Prediction model specificity

To test the model specificity, we reran the prediction model using FC data from the general emotional processing task and task-free resting-state data. However, the brain connectivity patterns during responding to general emotional stimuli and during the resting state did not predict marital quality after 13 months (Tables 2 and 3). These results suggest the specificity of the prediction model for marital quality to the husbands' processing of spousal interactions.

Discussion

By using the recently developed approach of CPM, we found that the functional connectome during husbands' responses to wives' interactive behaviors predicted their own (actor effect) and their wives' (partner effect) marital quality after 13 months. However, the brain connectivity patterns responding to general emotional stimuli and during resting state were not predictive. These findings indicate that the predictability of marital quality showed gender specificity (husbands' brain responses) and model specificity [brain responses to spousal (wives') interactions]. Implications are discussed below.

The role of husbands' FCs and gender specificity in the prediction of marital quality when responding to spousal interactive behaviors

The significant prediction model based on husbands' but not wives' FC is in accord with previous evidence of the critical role of husbands in marriages. Husbands' but not wives' sensitive support provision was related to both spousal marital outcomes (Jensen *et al.*, 2013). Similarly, husbands' emotional regulation and impulse control have been found to be more important than wives' for marital satisfaction (Noller and Fitzpatrick, 1988; Velotti *et al.*, 2016; Frye *et al.*, 2020). Gender-related considerations may provide a potential explanation for these results. Women are often more attentive to relationship quality (Acitelli, 1992; Nolen-Hoeksema and Jackson, 2001). They are more likely to take an active role in seeking change and managing disagreements, maintaining closeness and enhancing the well-being of their partners (Strazdins and Broom, 2004; Erickson, 2005; Christensen *et al.*, 2006; Denton and Burleson, 2007). However, husbands relative to wives have displayed lower active involvement in marital interactions (Samter, 2002; Markman *et al.*, 2010; Ju *et al.*, 2015), shown more difficulty in emotional expression (Gross and John, 1998; Cyranowski *et al.*, 2000; Croyle and Waltz, 2002; Burdwood and Simons, 2016) and used more frequently expression suppression as compared with cognitive reappraisal (Gross and John, 2003b; Duarte *et al.*, 2015b).

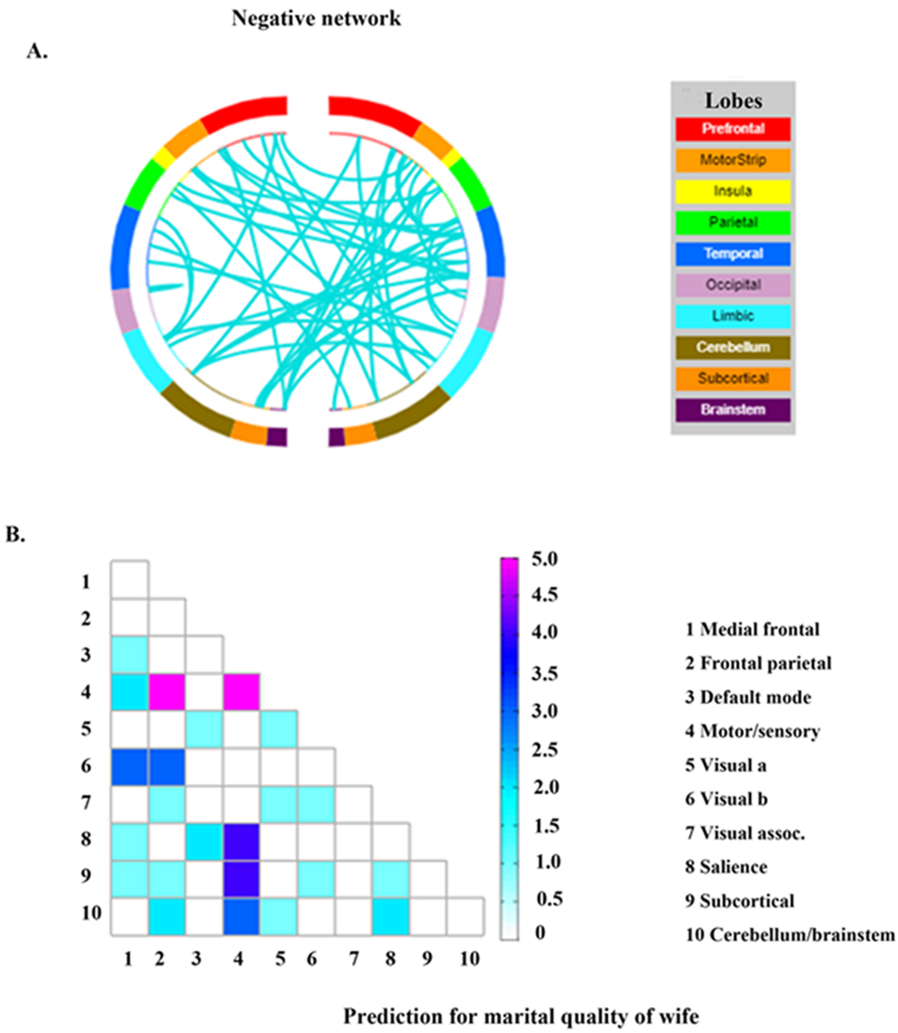

Fig. 4. Negative network summarized by overlap with macroscale brain regions (A) and large neural networks (B) in the prediction of wives' marital quality using husband's FC responding to spousal interactive behaviors. In the panel designated 'Negative network', cells represent the number of edges within (and between) each network.

Therefore, in interactions between partners, wives may show more sensitive but smaller ranges of FC responses, and the restricted variability may suggest that wives' FC may be less likely than husbands' to contribute to variations in marital outcomes for either spouse. Husbands who may better perceive and respond to their wives' interactions may experience greater benefits in marriage. Given that females relative to males have also been reported to be affected more by responses from their partners (Cyranowski *et al.*, 2000; Croyle and Waltz, 2002; Shirao *et al.*, 2005; Burdwood and Simons, 2016), these benefits may not be limited to the husbands but may also extend to their wives. Correspondingly, during problem-solving, the marital quality of wives in the group whose husbands were more negative than their wives was found to be significantly lower than that in the group whose wives were more negative than their husbands (Ju *et al.*, 2013).

We also examined gender specificity; that is, whether the wives' FC of the husband-specific contributing network could predict their marital quality. The results showed no significant predictions, suggesting gender specificity. This is consistent with gender-related differences in relationship evaluations and views, interactive behaviors and detecting, understanding, expressing and regulating emotions (Cyranowski *et al.*, 2000; LaFrance *et al.*, 2003; Harenski *et al.*, 2008; Yin *et al.*, 2013; Burdwood and Simons, 2016). This finding highlights potential concerns regarding generalizing findings across genders and the importance of collecting data from both partners in marriages.

The marital quality-related network during processing of spousal interactive behaviors

Cognitive constructs may arise from a collection of brain areas acting together as large-scale networks (Fox and Raichle, 2007; Smith *et al.*, 2009; Shen *et al.*, 2013). The current study revealed that when responding to spousal interactive behaviors, a marital quality-related network was complex and included connectivity between multiple well-established neural networks that are important for processing social information and valuations (Nummenmaa *et al.*, 2012; Lee *et al.*, 2015; Schmalzle *et al.*, 2015; Miedl *et al.*, 2016; Saarimaki *et al.*, 2018; Esmenio *et al.*, 2019). These networks included the visual system implicated in the processing of complex, emotional stimuli (e.g. faces and films) and actions (Laird *et al.*, 2011); salience network contributing importantly to allocating and switching attentional resources (Sridharan *et al.*, 2008; Menon and Uddin, 2010; Menon, 2011); cerebellum and brainstem involved in reactions to different emotions (Critchley, 2005; Linnman et al., 2012); somatosensory cortices contributing not only to emotional perception but also to emotional regulation (Schutter and van Honk, 2009; Nummenmaa et al., 2012, 2014); medial prefrontal regions involved in mentalizing and emotional regulation (Amodio and Frith, 2006; Hensel et al., 2015; Nagels et al., 2015; Miedl et al., 2016) and frontal–parietal circuitry implicated in exteroceptive processes related to cognitive control and goal-directed attention (Ochsner and Gross, 2005; Dosenbach et al., 2007).

Considering the functions of the above networks, when responding to their wives' interactive behaviors, husbands' marital quality prospectively was positively correlated with their own stronger connectivity within networks mostly linked to emotional processing. Husbands' and wives' marital quality prospectively were negatively correlated with their stronger connectivity within networks mostly linked to cognitive/attentional control and emotional regulation and between networks implicated in (i) cognitive/attentional control and visual processing and (ii) emotional regulation and cognitive/attentional control.

These findings suggest multiple interpretations that resonate with and build upon prior findings. First, husbands may detach themselves from their wives' influences and promote their marital well-being by minimizing cognitive control processing related to spousal evaluations (e.g. by stopping their thinking about criticism). Such an interpretation resonates with findings that youth showed decreased responses in cognitive control regions to maternal criticism (Lee et al., 2015).

Second, males relative to females may use expression suppression (vs cognitive reappraisal) more frequently (Gross and John, 2003a; Spaapen et al., 2014; Duarte et al., 2015a). Emotional suppression may not only lead couples to ignore conflicts and problems and hinder them from resolving conflicts or disagreements but also lead to perceptions of hostility by their partner, and this may aggravate discordant interactions (Fruzzetti and Iverson, 2006; Waldinger and Schulz, 2006). Furthermore, emotional suppression by husbands has been found to be negatively related to their own and their spousal marital satisfaction (Klein et al., 2016; Velotti et al., 2016; Frye et al., 2020).

Third, males relative to females typically express less emotions (positive and negative) and with a lower intensity (Gross and John, 1998). Husbands' difficulties describing and personalizing their emotions have been found to be negatively related to their marital satisfaction; even when husbands have lower levels of emotional expressiveness than their wives, their marital satisfaction may be negatively influenced (Yelsma and Marrow, 2003). Thus, appropriate emotional perception and awareness are beneficial to their own marital quality. More study is needed to support these currently speculative notions, particularly given the complexities of brain interactions and their relationships to behavior.

Connectome-based prediction model specificity

The brain connectivity patterns responding to general emotional stimuli and during resting state showed no predictivity. Previous research has found that CPM derived from task-based data has typically outperformed that derived from resting-state data (Greene et al., 2018). This result might add to emerging evidence that the manipulation of brain states (e.g. via task) may be necessary for detecting individual differences in brain–behavior relationships (Finn et al., 2017). Furthermore, the absence of predictivity during responding to general emotional stimuli may reflect the important role of marital interactions in relation to marital outcomes (Karney and Bradbury, 1995; Bradbury et al., 2000a). However, future studies with larger populations are needed to examine this finding.

Post hoc explorations

Given the significant prediction during spousal interaction processing, we further explored prediction using FC matrices by extracting signal from each ROI in positive or negative conditions (each of 10 blocks) during spousal interaction processing. The results showed the prediction of husbands' FC during the positive condition for marital quality of wives ($r = 0.42$, $P = 0.010$; MSE = 63.26, $P = 0.017$; negative network) and husbands ($r = 0.39$, $P = 0.041$; MSE = 90.23, $P = 0.072$; combined positive and negative networks).

From the perspective of positive psychology, the effect of positive interactions on intimate relationships may not be obvious in the short term, but over time, the effect of positive behaviors on intimate relationships may develop, while the impact of negative behaviors may be more immediate and short-lived (Fredrickson, 2001; Reis and Gable, 2003; Fincham and Beach, 2010; Ju et al., 2015). Prior research suggests that positive interactions (such as warm support) between newlyweds predicted their marital quality after the birth of child (Shapiro et al., 2000; Dush and Taylor, 2012).

FC did not predict current marital quality at the time of scanning (Supplementary Table S4). Although there were medium to large correlations between marital quality at the time of scanning and that after 13 months (husbands: $r = 0.68$, $P < 0.001$; wives: $r = 0.63$, $P = 0.001$), marital relationships, like individuals, are not static over time; rather, they may follow a developmental trajectory (VanLaningham et al., 2001). It may have taken time for the effects of marital interactions on intimate relationships to accumulate (Fredrickson, 2001; Reis and Gable, 2003; Fincham and Beach, 2010; Ju et al., 2015). In the current study, marital quality in the early stage of marriage was high with smaller variance, with marital quality variance gradually expanding over time (Table 1; the s.d. of marital quality at T2 is greater than that at T1). Thus, FC may have demonstrated a better prediction effect at T2.

Strengths and limitations

There are several strengths. First, we utilized CPM to construct predictive models. CPM can accommodate complex interactions of multiple regions and large-scale networks. We measured marital quality 13 months after scanning, which enabled us to examine predictive effects. Second, we applied CPM not only to relationship-specific stimuli processing of marital interactions but also to general emotional processing and resting-state data. This approach enabled us to test the prediction model in different task contexts and to demonstrate model specificity. Third, in marriages, there are dyadic data from each partner, which may be interdependent but different. However, previous neuroimaging studies have only collected fMRI data from one partner. The current study utilized dyadic data to simultaneously test actor and partner effects and gender specificity.

This study has practical implications. The findings lay a foundation for identifying reliable biomarkers relating to marital quality prospectively and perhaps for identifying couples who might benefit from timely interventions. They also provide potential targets for developing interventions (e.g. using brain stimulation) to promote marital well-being.

However, there are several limitations. First, couples were recently wed, well-educated Chinese husband and wife pairs without children, so the findings may not generalize to other groups. Second, given the small sample, future studies should enroll larger samples and more types of couples to confirm and extend the current findings. Third, we focused mainly on emotional interactive behaviors in the present study. As instrumental and emotional factors may predict well-being in social interactions (Morelli *et al.*, 2015), future studies should consider also studying instrumental behaviors. Fourth, to obtain whole-brain FC data, we utilized a classic task during fMRI. Future studies should collect other imaging data (e.g. using near-infrared spectroscopy during natural interactions) to place our results into further context and provide additional information about the individualized prediction. Fifth, limited out-of-the-magnet assessments were collected. Future studies should gather additional personal and marital data to link to the observed brain findings. Sixth, strictly speaking, our results are not predictive *per se*, and testing the extent to which the FC patterns generalize to novel samples is needed (Shen *et al.*, 2017; Yip *et al.*, 2019).

Conclusions

The current study found that husbands' and wives' marital quality after 13 months may be predicted by the husbands' FC patterns when responding to their spousal interactive behaviors. That is, individual differences in large-scale neural networks during husbands' processing of their wives' interactions directed at them contributed to variability in marital quality. As the findings did not generalize across genders, it is important to collect data during marital interactions from both partners when investigating marital quality.

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Conflict of interest

The authors declared that they had no conflict of interest with respect to their authorship or the publication of this article.

Supplementary data

Supplementary data are available at *SCAN* online.

Author contributions

X.-Y.F. provided funding for the study. S.-S.M. and X.-Y.F. designed the study. S.-S.M., R.-H.F., L.-B.W., S.-T.Y., Y.-F.H. and X.-Y.J. contributed to the data collection. S.-S.M., J.-T.Z., K.-R.S. and R.Z. completed the data analysis and interpretation of findings. S.-S.M. drafted the manuscript. J.-T.Z., M.N.P. and X.-Y.F. provided critical revisions of the manuscript.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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