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Efficient brain connectivity reconfiguration predicts higher marital quality and lower depression

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Abstract

Social information processing is important for successful romantic relationships and protection against depression, and depends on functional connectivity (FC) within and between large-scale networks. Functional architecture evident at rest is adaptively reconfigured during a task, and there were two possible associations between brain reconfiguration and behavioral performance during neurocognitive tasks (efficiency effect and distraction-based effect). This study examined the relationships between brain reconfiguration during social information processing and relationship-specific and more general social outcomes in marriage. Resting-state FC was compared with FC during social information processing (watching relationship-specific and general emotional stimuli) of 29 heterosexual couples, and the FC similarity (reconfiguration efficiency) was examined in relation to marital quality and depression 13 months later. The results indicated that wives' reconfiguration efficiency (globally and in visual association network) during relationship-specific stimuli processing was related to their own marital quality. Higher reconfiguration efficiency (globally and in medial frontal, frontal-parietal, default mode, motor/sensory and salience networks) in wives during general emotional stimuli processing was related to their lower depression. These findings suggest efficiency effects on social outcomes during social cognition, especially among married women. The efficiency effects on relationship-specific and more general outcomes are, respectively, higher during relationship-specific stimuli or general emotional stimuli processing.

Key words: reconfiguration efficiency; social information processing; marital quality; depression; heterosexual couples

Introduction

As social beings, individuals seek connection with others (Lieberman, 2013), and such connections impact psychological and physical health (Buunk and Schaufeli, 1999; Corsano et al., 2006). Among social connections, marriage is typically the most intimate and enduring relationship; as such, marriage may promote life satisfaction and mitigate against depression (Holt-Lunstad et al., 2008; Cao et al., 2017). Social information–processing models propose that how individuals interpret and respond to social stimuli may predict better or worse social adjustment (such as social competence and depression, respectively) better than single or general social-cognition indices (Possel et al., 2006; Luebbe et al., 2010). How people process social information is important for successful romantic relationships and happiness, as well as unsuccessful romantic relationships

and depression (Joormann et al., 2007; Acevedo et al., 2012b). Therefore, investigating neural bases of social information processing may provide insight into mechanisms underlying marital and psychological well-being in marriages.

Prior studies of romantic couples have examined associations between relationship well-being and neural responses during information-processing tasks in which people mostly view relationship-specific stimuli (e.g. photographs of their partners). Romantic relationship status has been associated with differences in regional neural activations involved in processing rewards, motivation, empathy, stress and emotional regulation (Stoessel et al., 2011; Xu et al., 2012; Acevedo et al., 2012b).

Complex cognitive functions involving the processing of information from multiple domains depend on interactions across multiple brain areas, and these involve functional connectivity

(FC) within and between a set of domain-specific, distributed large-scale brain networks (Smith *et al.*, 2009; Heinzle *et al.*, 2012; Shirer *et al.*, 2012). Studies indicate that much of the brain's network structure is evident at rest and is typically adaptively reconfigured during task performance (Cole *et al.*, 2014; Krienen *et al.*, 2014). Although heterogeneity in experimental procedures may contribute to different directional associations, FC pattern reconfiguration has been found to relate to behavioral performance during neurocognitive tasks. Specifically, some studies have found individuals with smaller FC changes (higher reconfiguration efficiency) when performing the task (working memory, verbal comprehension, and reasoning) to show better cognitive performance (efficiency effect) (Vatansever *et al.*, 2015; Schultz and Cole, 2016; Zuo *et al.*, 2018). Other studies have found greater network reconfiguration relating to enhanced performance (distraction-based effect) (Braun *et al.*, 2015; Tommasin *et al.*, 2018; De Baene *et al.*, 2020). We thus aimed to examine the effects on social outcomes of brain reconfiguration during social cognition, an entity distinct from but possibly related to neurocognition and referring to the cognitive abilities involved in the processing and interpretation of socio-emotional information in oneself and others (Newman, 2001).

We considered two issues that may result in different directional associations and may offer guidance for our hypotheses. First, Schultz and Cole (2016) highlighted whole-brain overall effects, while studies about the effect of greater network reconfiguration mainly focused on the FC pattern of specific networks [e.g. frontal-parietal network (FPN)] or interactions between specific networks (e.g. FPN–default mode network connectivity) (Braun *et al.*, 2015; Tommasin *et al.*, 2018; De Baene *et al.*, 2020). Cole *et al.* (2013) demonstrated the FPN to be arguably the most flexible network; that is, the one displaying high variance in connectivity over different tasks or task complexities. This tendency may explain why studies have reported positive associations mostly between levels of task-evoked reconfiguration within the FPN and working memory task performance (Braun *et al.*, 2015; Tommasin *et al.*, 2018; De Baene *et al.*, 2020). This may contrast with nonfrontal modules (such as visual and somatomotor modules) that display relatively low flexibility across task conditions and provide a stable task-based core supporting higher-order cognitive functions (Bassett *et al.*, 2013). Additionally, some previous studies investigating efficiency effects have involved a large number of subjects from the Human Connectome Project dataset (Schultz and Cole, 2016; Zuo *et al.*, 2018), possibly identifying more subtle effects undetectable in smaller samples (Tommasin *et al.*, 2018). Moreover, previous results reflecting distraction-based effects may be confounded by concentration difficulties in brain tumor patients and may not generalize to healthy subjects (De Baene *et al.*,

2020). In our study, during natural viewing, brain activity was observed in widespread regions in lower- and higher-order sensory areas, corticolimbic emotion circuits, frontal and parietal cortices, and motor-planning regions of the brain (Hasson *et al.*, 2004; Nummenmaa *et al.*, 2012b; Abrams *et al.*, 2013). It may be reasonable to consider the global functional architecture or FC between a certain network and the remainder of other networks rather than FC patterns of specific networks or interaction between specific networks. Thus, we hypothesized efficiency effects during processing of social information on social outcomes, that is, higher reconfiguration efficiency when during processing of social-emotional stimuli would be related to better social outcomes. Specifically, we first investigated relationships between global reconfiguration efficiency (the similarity of whole-brain FC patterns between resting state and task) during the processing of relationship-specific stimuli and relationship-specific (marital quality) and more general (depression) measures. Next, we also investigated whether these effects were related to a subset of specific regions (the whole-brain FC configuration for each network) or reflected a general property across brain circuitry.

In marriages, dyadic data from husbands and wives are often interdependent but different from each other. First, people's responses would be expected to be simultaneously and independently associated with their own perceptions (actor effect) as well as their partners' (partner effect) (Kenny *et al.*, 2006). Second, differences often exist between husbands and wives in emotional perceptions and expressions, relationship evaluations and views, and interaction behaviors (Yin *et al.*, 2013; Burdwood and Simons, 2016). Thus, we aimed to utilize dyadic data to test the actor and partner effects related to brain reconfiguration efficiency and then investigate gender-related differences in these effects.

Social information processing may vary in different relationship situations (Burgess *et al.*, 2006; Peets *et al.*, 2007). Relationship-specific stimuli and other general stimuli may elicit different responses and have different social meanings (Lemerise and Arsenio, 2000; Butler, 2015). Given that ways in which people perceive and respond to emotional stimuli also relate importantly to aspects of intimate relationships and depression (Forgas, 2002; Leppanen, 2006), we also examined whether there were effects on marital quality and depression of brain reconfiguration efficiency during the processing of general emotional stimuli and whether these effects showed a different pattern with those during the processing of relationship-specific stimuli.

The current study utilized functional magnetic resonance imaging (fMRI) data from both partners of 29 early-stage heterosexual Chinese couples engaging in resting-state and social information processing, in which they watched relationship-specific and general emotional movies (Figure 1). We aimed to
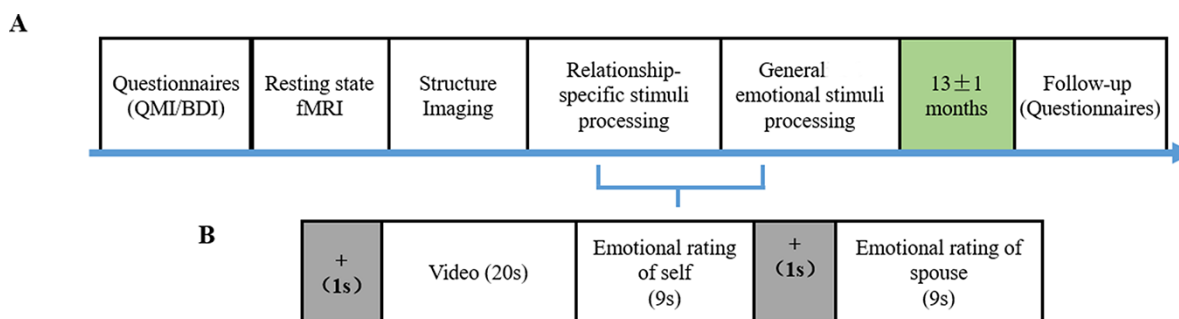
Fig. 1. Experimental protocols (A) and Schematic representation of the task (B).

(i) examine relationships between brain reconfiguration efficiency during social information processing and their own/partner's relationship-specific outcome (i.e. marital quality) and a more general measure (i.e. depression); (ii) investigate gender-related differences in these effects; and (iii) determine whether these effects showed different patterns between stimuli types. We hypothesized that there are efficiency effects during the processing of social-emotional stimuli on social outcomes. We also hypothesized that the efficiency effects would differ between genders and types of stimuli (in a context-related fashion).

Materials and methods
Participants
This study was approved by the Institutional Review Board of the State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, with all participants providing written informed consent prior to study participation. Thirty-four heterosexual couples were recruited via advertisements posted online. Inclusion criteria included the couples being in the early stage (less than 4 years) of a first marriage and without children, having no history of psychiatric or neurological illness, and being suitable for MRI scanning. Three couples did not complete scanning during the relationship-specific information-processing task due to not generating the requisite videos. Two subjects with head motion exceeding 3.0 mm were excluded (Acevedo *et al.*, 2012a, 2012b). Thus, data from 29 couples (29 husbands and 29 wives) were analyzed, and the demographic characteristics and questionnaire measures are displayed in Table 1.

Stimuli and questionnaire measures
Relationship-specific stimuli (spousal videos)
Unlike previous studies using static photos, the current research used arguably more ecologically valid experimental stimuli (video of one another's marital partners). Each husband and wife were instructed to record typical positive (praise and understanding), negative (criticism and dominance), and neutral (unrelated to marital relationship) behaviors, which were displayed as relationship-specific stimuli for their spouses (see examples in Supplementary Table S1). When recording the videos, participants were asked to describe their spouse's virtues (praise) and shortcomings (criticism), to express their understanding of their spouse's feelings and thoughts (understanding), to tell their spouse what they should to do (dominance), and to describe

laboratory items (neutral) in the first and second person (Lee *et al.*, 2015). Each type of behavior included five videos, with the most representative 20 s selected as stimuli.

General emotional stimuli
Given the importance of emotions in marriage and depression (Gottman *et al.*, 1998), we selected emotional videos as general stimuli. We edited positive (happy) and negative (sad and angry) videos from the Chinese emotion video system (Xu *et al.*, 2010) and supplemented some neutral videos, and then cut them into 20 s clips. Fifty-one college students were recruited to assess the emotional types and intensities of these video clips (Gross and Levenson, 1995). We chose clips with more than 80% agreement (i.e. the number of subjects who agreed that the video belonged to one emotional type accounting for more than 80% of the total number of subjects).

Quality of Marriage Index
The Quality of Marriage Index (QMI) included five 7-point items ranging from 1 (strongly disagree) to 7 (strongly agree) and one 10-point item ranging from 1 (very unsatisfied) to 10 (very satisfied). A higher total score suggests higher marital quality (Norton, 1983). Cronbach's alpha was 0.98 for husbands and 0.96 for wives.

Beck Depression Inventory
The Beck Depression Inventory (BDI) is a 21-item self-report measure designed to evaluate the severity of depression in the past two weeks (BDI; Beck *et al.*, 1961). The total scores range from 0 to 63, with each item scored from 0 to 3, and a higher score indicating more severe depression. Cronbach's alpha was 0.921 for husbands and 0.876 for wives.

Experimental process and tasks
Each husband and wife were scanned in a random sequence (wife or husband scanned first). We used a within-subject design. First, participants were instructed to look at a black screen, stay awake, lie motionless, and not to think of anything in particular. Next, participants watched the relationship-specific stimuli {relationship-specific stimuli-processing task; consisting of 25 blocks [5 (praise/understanding/neutral/criticism/dominance) × 5 Latin squares]}, rated their emotional reactions and rated their spouse's emotions in the videos. Finally, participants watched the general emotional stimuli {general-emotional-stimuli-processing

Table 1. Demographic characteristics

		Wife		Husband			
	n	*M*	s.d.	*M*	s.d.	$t_{(28)}/t_{(24)}$	*P*
Age	29	28.67	2.11	29.27	2.85	−1.42	0.166
Education (number of master's degree or above)	29	14.00	–	14.00	–	–	1.000[a]
Married duration (months)	29	17.81	12.45	17.81	12.45	–	–
T1 Marital quality	29	36.59	8.28	37.83	7.83	1.16	0.256
T1 Depression	29	7.24	6.75	6.59	7.59	−0.36	0.720
Time of interval to follow-up questionnaire (months)	25	12.85	0.69	12.85	0.69	–	–
T2 Marital quality	25	36.76	8.57	37.04	10.00	−0.27	0.787
T2 Depression	25	5.40	6.33	6.16	7.543	−0.44	0.667

[a]McNemar test;
T1 Marital quality: marital quality at Time 1 (around the time of scanning);
T1 Depression: Depression at Time 1 (around the time of scanning);
T2 Marital quality: marital quality at Time 2 (13 months after scanning);
T2 Depression: depression at Time 2 (13 months after scanning).

task; consisting of 16 blocks [4 (happy/sad/angry/neutral) × 4 Latin squares]}, rated their own emotional reactions and estimated their spouse's emotional reactions to these videos (Yuvaraj *et al.*, 2014).

The QMI and BDI were used to assess marital quality and depression at scanning and 13 months (±1 month) after scanning. Twenty-five of 29 couples completed the follow-up measurement. Analysis indicated that missing data were completely at random, and full information maximum likelihood was used to estimate and replace missing values.

Image acquisition and preprocessing

A Siemens 3 T MRI scanner (Siemens, Erlangen, Germany) was used to collect imaging data. Scanning sessions included the acquisition of the localizer images, a high-resolution structural image (magnetization-prepared rapid-gradient echo) and functional images from resting-state and social information–processing tasks. The resting-state fMRI data comprised 200 continuous echo-planar imaging (EPI) whole-brain functional volumes. The task-based fMRI data consisted of 523 EPI whole-brain functional volumes when watching the relationship-specific stimuli and 336 EPI when processing general emotional stimuli.

Structural images were collected with $1 \times 1 \times 1$ resolution using a sagittal three-dimensional T1-weighted sequence with a repetition time (TR) of 2.530 ms, time-to-echo (TE) of 2.96 ms, flip angle of 7° and inversion time (TI) of 1100 ms. Functional images were acquired using an asymmetric spin-echo echo-planar sequence: volume TR = 2 s, TE = 30 ms, flip angle = 90° and field of view = 224 mm. A single acquisition was composed of 33 transverse slices, 3.5 mm thick (0.7 mm gap), and an in-plane resolution of 3.5×3.5 mm.

Spatial processing of resting-state and task-based data was performed using the standard process in DPABI version 4.2 (Yan *et al.*, 2016), which included slice timing, realignment, nuisance regression (such as cerebral-spinal-fluid and white-matter signals and 24-parameter motion), normalization to $3 \times 3 \times 3$ mm³ Montreal Neurological Institute (MNI) space, smoothing with a Gaussian kernel of 6 mm full-width half-maximum, and filtering temporally.

We found that head motion [mean frame-wise displacement of head position (mean FD Power)] was not significantly correlated with social outcomes (with Bonferroni correction for the number of motion indexes, $P < 0.05/6 = 0.008$; Supplementary Table S2). To further control for the effects of head motion on FC measures, we implemented a motion-scrubbing regression strategy. The time points with frame-wise displacement of head position equal or higher than 0.5 were assigned values of 0, and other time points were assigned values of 1 (Power *et al.*, 2012). Thus, scrubbing regression allows for the same number of time points across participants while controlling for excess head motion at specific time points (Lemieux *et al.*, 2007; Power *et al.*, 2013; Satterthwaite *et al.*, 2013).

Resting-state FC is often examined using filters at 0.01–0.1 Hz of the standard process in DPABI version 4.2 (Yan *et al.*, 2016; Feng *et al.*, 2019; Marin-Marin *et al.*, 2021). Cordes *et al.* (2001) showed that over 90% of their connectivity measure is due to low-frequency (below 0.1 Hz) fluctuations in a block-design paradigm. Similarly, findings with event-related designs demonstrated that functional associations between 0 and 0.15 Hz can be attributed to task-related FC (Sun *et al.*, 2004; Bassett *et al.*, 2015). To remove low-frequency signal drift, a high-pass filter (1/128 = 0.008 Hz) is also applied in a general linear model. Thus, to allow the comparison of resting-state and task-based data, we applied a filter at 0.01–0.10 Hz that is sensitive to both resting-state and task-based FC.

Brain reconfiguration efficiency and the actor–partner interdependence model

FC was assessed using a functional brain atlas consisting of 268 nodes defined based on a separate population of healthy subjects (Shen *et al.*, 2013). This atlas covered the brain globally and consisted of 10 functional networks (Finn *et al.*, 2015; Yip *et al.*, 2019).

The FC (i.e. connectome) for each subject during resting state and each task was estimated using REST version 1.8 (Song *et al.*, 2011) by extracting and correlating (Pearson r) the mean time series of all possible pairs of 268 ROIs and then using Fisher's r-to-z transformations. 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, and order = 7) (Liu *et al.*, 2017; Cole *et al.*, 2019). Finally, the whole-brain connectome similarity between each information processing task and resting state was assessed by Fisher's z-transformed correlation between the vectorized upper triangular part of the connectivity matrix between task–rest pairs of each individual. A higher similarity value represents a higher global reconfiguration efficiency, namely a more efficient reconfiguration of whole brain.

Because the current study utilized data from both partners of a married couple, the Actor–Partner Interdependence Model (APIM; Kenny *et al.*, 2006) was employed using Mplus8.0 to examine first how one's global functional architecture reconfiguration efficiency during each social information processing task simultaneously and independently statistically predicted his or her own as well as his or her partner's report of marital quality/depression.

Next, to investigate whether brain reconfiguration efficiency of certain specific networks might predict marital and psychological well-being, we also calculated whole-brain FC configuration efficiency for each network separately, based on task–rest similarity of all the connections involving each network within the entire brain (Cole *et al.*, 2013; Schultz and Cole, 2016). We investigated the statistical predictions of marital quality/depression from these brain reconfiguration efficiencies during each social information processing task (with Bonferroni correction for the number of networks, $P < 0.05/10 = 0.005$).

Testing contributing variance and relevance of brain reconfiguration efficiency

Furthermore, it is possible that variance relating to resting-state and task-related FC may underlie the effects of brain reconfiguration efficiency. To test this possibility and the relevance of brain reconfiguration, the source of variance of resting-state or task-related FC was held constant using a leave-one-subject-out approach, that is, we compared one's resting-state (or task-based) FC pattern with the mean task-based (or resting-state) FC pattern of the remaining 28 same-gender participants and calculated predictions between this measure and marital quality/depression.

Results
Statistical results of brain reconfiguration efficiency

For global reconfiguration efficiency, although there was no significant interaction between gender and stimuli type (two-way repeated measures ANOVA, two-sided: $F_{(1, 28)} = 0.33$, $P = 0.568$, partial $\eta^2 = 0.01$), a significant main effect of stimuli type
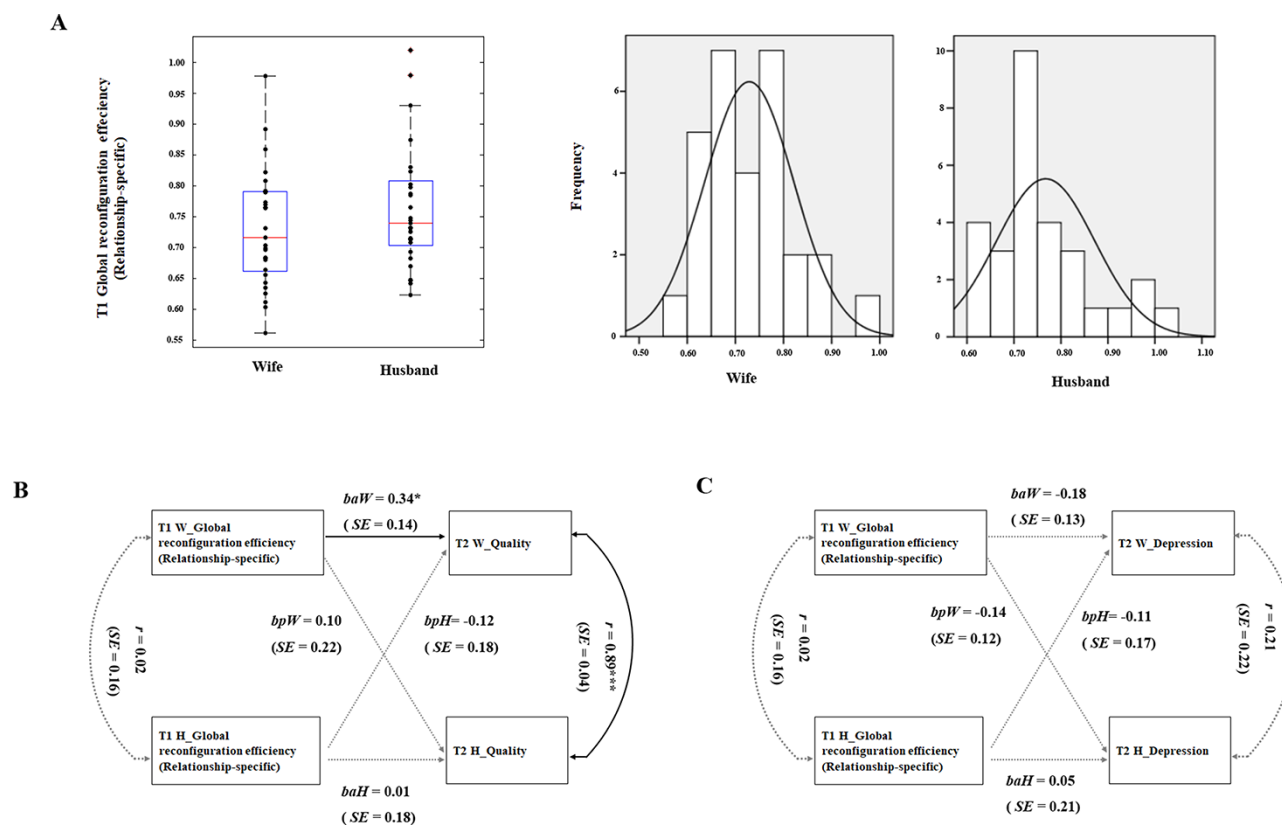
Fig. 2. Global reconfiguration efficiency during the processing of relationship-specific stimuli (A) predicts marital quality (B) and depression (C) ($n = 29$). Boxes represent the interquartile range (IR) between the 25th and 75th percentiles. The red line in the center of each box represents the median. The upper and lower error bars display the largest and smallest values within 1.5 times IR above the 75th percentile and below the 25th percentile, respectively. Each black dot represents one participant. T1 H_Global reconfiguration efficiency (Relationship-specific): global reconfiguration efficiency of husbands while watching relationship-specific stimuli (videos of spouse); T1 W_Global reconfiguration efficiency (Relationship-specific): global reconfiguration efficiency of wives while watching relationship-specific stimuli (videos of spouse); T2 H_Quality: marital quality of husbands at Time 2 (13 months after scanning); T2 W_Quality: marital quality of the wives at Time 2 (13 months after scanning); T2 H_Depression: depression of husbands at Time 2 (13 months after scanning); T2 W_ Depression: depression of wives at Time 2 (13 months after scanning). b_{pW}: standardized beta value of regression from index of wives to index of husbands (partner effect of wives); b_{aH}: standardized beta value of regression from index of husbands to index of husbands (actor effect of husbands); b_{aW}: standardized beta value of regression from index of wives to index of wives (actor effect of wives); b_{pH}: standardized beta value of regression from index of husbands to index of wives (partner effect of husbands). Numbers in parentheses are standard errors. Black solid lines indicate $P < 0.05$, and gray dotted lines indicate nonsignificant regressions.

($F_{(1, 28)} = 51.48$, $P < 0.001$, partial $\eta^2 = 0.65$; processing of relationship-specific stimuli > processing of general emotional stimuli) was observed.

Similar to global reconfiguration efficiency, regarding reconfiguration efficiency of specific networks, significant interaction between gender and stimuli type were only found in default mode network (two-way repeated measures ANOVA, two-sided: $F_{(1, 28)} = 4.95$, $P = 0.034$, partial $\eta^2 = 0.15$; during the processing of relationship-specific stimuli, husbands' > wives' reconfiguration efficiency), and significant main effects of stimuli type were observed in other networks (Supplementary Table S3).
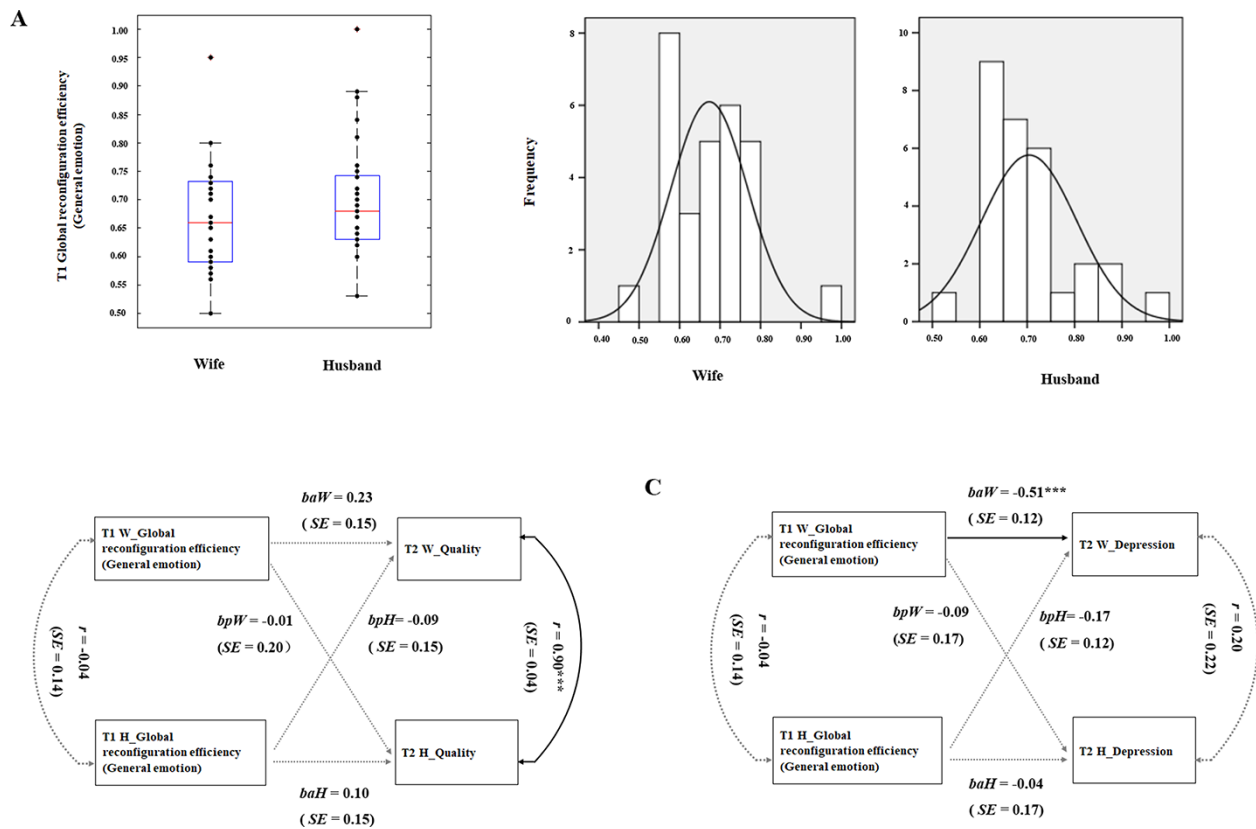
Predictions of marital quality and depression from global reconfiguration efficiency

APIM analyses showed significant efficiency effects on social outcomes during social information processing. During the processing of relationship-specific stimuli, global reconfiguration efficiency among wives predicted their own higher marital quality 13 months later (actor effect; Figure 2). During the processing of general emotional stimuli, wives' higher global reconfiguration efficiency was related to their own lower depression 13 months later (actor effect; Figure 3).

To investigate the robustness of the findings, we explored alternate data analytic approaches. First, we reran APIM controlling for QMI and BDI scores at the time of scanning. Second, we removed the task-evoked activations using a standard general linear model regression of task events, which was often used in previous studies of brain reconfiguration efficiency (Cole *et al.*, 2014; Vatansever *et al.*, 2015; Schultz and Cole, 2016; Zuo *et al.*, 2018). Third, we did not apply a temporal filter to the task-related data to explore possible influences of meaningful higher frequency information (Schultz and Cole, 2016; Cole *et al.*, 2019). The results were similar to our initial findings (Supplementary Tables S4– S6).

Predictions of marital quality and depression from whole-brain FC configuration efficiency of specific networks

Next, we investigated the efficiency effects of specific networks. Wives' reconfiguration efficiency of visual association network during relationship-specific stimuli processing predicted their own marital quality at 13 months. Wives' reconfiguration efficiency of medial frontal, frontal-parietal, default mode, motor/sensory and salience networks during the processing of

Fig. 3. Global reconfiguration efficiency during the processing of general emotional stimuli (A) predicts marital quality (B) and depression (C) ($n = 29$). Boxes represent the interquartile range (IR) between the 25th and 75th percentiles. The red line in the center of each box represents the median. The upper and lower error bars display the largest and smallest values within 1.5 times IR above the 75th percentile and below the 25th percentile, respectively. Each black dot represents one participant. T1 H_Global reconfiguration efficiency (General emotion): global reconfiguration efficiency of husbands while watching emotional movies; T1 W_Global reconfiguration efficiency (General emotion): global reconfiguration efficiency of wives while watching emotional movies; T2 H_Quality: marital quality of husbands at Time 2 (13 months after scanning); T2 W_Quality: marital quality of the wives at Time 2 (13 months after scanning); T2 H_Depression: depression of husbands at Time 2 (13 months after scanning); T2 W_ Depression: depression of wives at Time 2 (13 months after scanning). bpW: standardized beta value of regression from index of wives to index of husbands (partner effect of wives); baH: standardized beta value of regression from index of husbands to index of husbands (actor effect of husbands); baW: standardized beta value of regression from index of wives to index of wives (actor effect of wives); bpH: standardized beta value of regression from index of husbands to index of wives (partner effect of husbands). Numbers in parentheses are standard errors. Black solid lines indicate $P < 0.05$, and gray dotted lines indicate nonsignificant regressions.

general emotional stimuli predicted their depression at 13 months (Figure 4; Supplementary Tables S7 and S8).

Gender differences in efficiency effects

Because we mainly found significant efficiency effects on marital quality and depression among wives, we further examined whether there were significant gender-related differences; that is, whether actor or partner path coefficients were equal between genders. We computed the model indexes of the constrained model (equal actor or partner path coefficients between genders). Based on the criteria of model indexes (CFI $\geq$ 0.090, RMSEA (90% CI) $\leq$ 0.008, SRMR $\leq$ 0.008; where CFI refers to comparative fit index, RMSEA to root mean square error of approximation, CI to confidence interval of RMSEA and SRMR to standardized root mean square residual), and the change in CFI of the constrained model ($\triangle$CFI) < 0.010 compared with that of the free-estimating model (CFI = 1.000, RMSEA = 0.000, 90% CI = [0.000, 0.000], SRMR = 0.000) (Meade *et al.*, 2008); if the model indexes of the constrained model meet these criteria, there is no significant difference; otherwise, there is a significant difference (Meade *et al.*, 2008). Wives' global reconfiguration efficiency during the processing of relationship-specific stimuli showed

higher actor effect than husbands' on marital quality (constrained model with equal actor path between wives and husbands: $\triangle$CFI = 0.046, CFI = 0.954, RMSEA = 0.214, 90% CI = [0.000, 0.589], SRMR = 0.094). Wives' global reconfiguration efficiency during the processing of general emotional stimuli showed higher actor effects on depression (constrained model with equal actor path between wives and husbands: $\triangle$CFI = 0.235, CFI = 0.765, RMSEA = 0.240, 90% CI = [0.000, 0.609], SRMR = 0.094).

For specific networks, we found higher actor effects on the marital quality of wives' relative to husbands' efficiency in visual association network during the processing of relationship-specific information. Wives' relative to husbands' reconfiguration efficiency during the processing of general emotional stimuli showed higher actor effects in the medial frontal, frontal-parietal, default mode, motor/sensory and salience networks on depression 13 months later (Table 2).

Further examination of differences in efficiency effects relating to different stimuli processing

Because we found significant efficiency effects on marital quality in relationship-specific contexts and efficiency effects on depression during general emotional stimuli processing, we
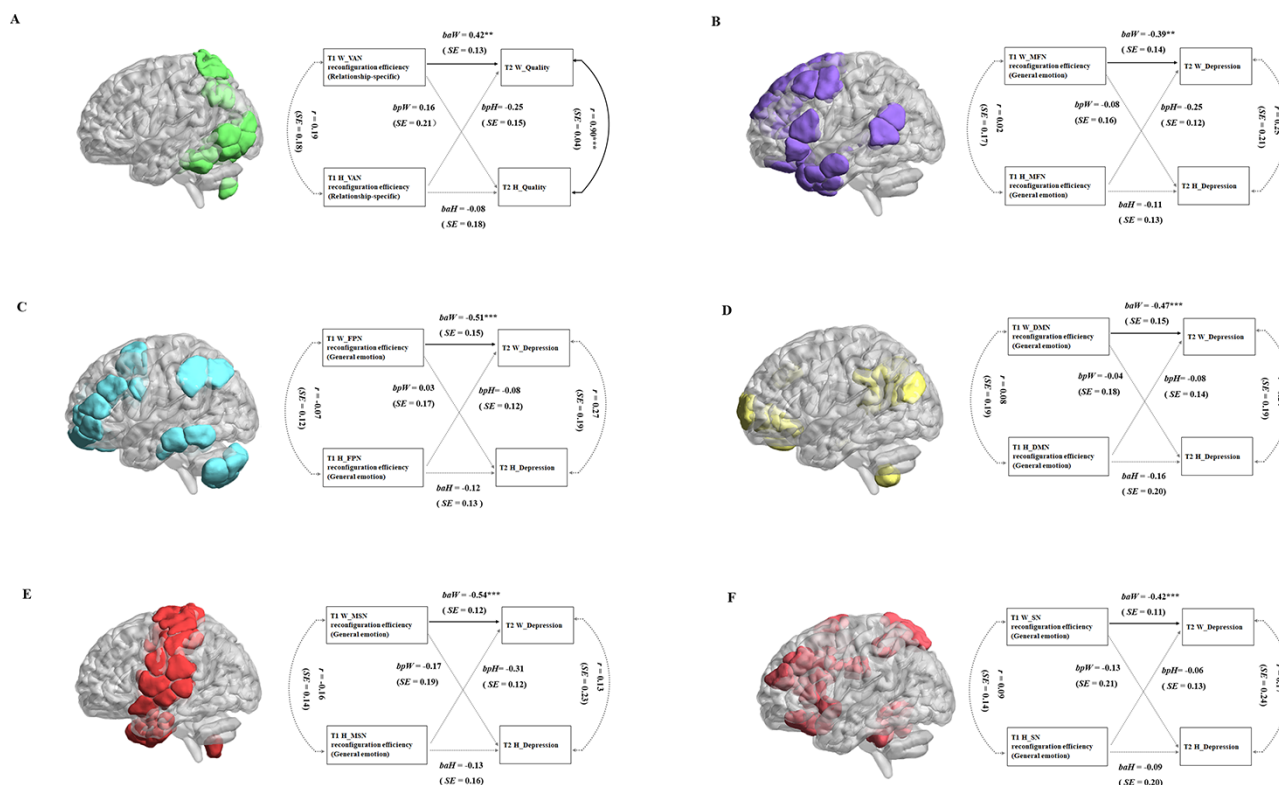
Fig. 4. Reconfiguration efficiency of visual association network during the processing of relationship-specific stimuli predicts marital quality (A); reconfiguration efficiency of medial frontal (B), frontal-parietal (C), default mode (D), motor/sensory (E) and salience networks (F) during the processing of general emotional stimuli predicts depression ($n = 29$). Boxes represent the interquartile range (IR) between the 25th and 75th percentiles. The red line in the center of each box represents the median. The upper and lower error bars display the largest and smallest values within 1.5 times IR above the 75th percentile and below the 25th percentile, respectively. Each black dot represents one participant. T1 H_VAN reconfiguration efficiency (Relationship-specific): husbands' reconfiguration efficiency of visual association network while watching relationship-specific stimuli (videos of spouse); T1 W_VAN reconfiguration efficiency (Relationship-specific): wives' reconfiguration efficiency of visual association network while watching relationship-specific stimuli (videos of spouse); T1 H_MFN reconfiguration efficiency (General emotion): husbands' reconfiguration efficiency of medial frontal network while watching emotional movies; T1 W_MFN reconfiguration efficiency (General emotion): wives' reconfiguration efficiency of medial frontal network while watching emotional movies; T1 H_FPN reconfiguration efficiency (General emotion): husbands' reconfiguration efficiency of frontal-parietal network while watching emotional movies; T1 W_FPN reconfiguration efficiency (General emotion): wives' reconfiguration efficiency of frontal-parietal network while watching emotional movies; T1 H_DMN reconfiguration efficiency (General emotion): husbands' reconfiguration efficiency of default mode network while watching emotional movies; T1 W_DMN reconfiguration efficiency (General emotion): wives' reconfiguration efficiency of default mode network while watching emotional movies; T1 H_MSN reconfiguration efficiency (General emotion): husbands' reconfiguration efficiency of motor/sensory network while watching emotional movies; T1 W_MSN reconfiguration efficiency (General emotion): wives' reconfiguration efficiency of motor/sensory network while watching emotional movies; T1 H_SN reconfiguration efficiency (General emotion): husbands' reconfiguration efficiency of salience network while watching emotional movies; T1 W_SN reconfiguration efficiency (General emotion): wives' reconfiguration efficiency of salience network while watching emotional movies; T2 H_Quality: marital quality of husbands at Time 2 (13 months after scanning); T2 W_Quality: marital quality of the wives at Time 2 (13 months after scanning); T2 H_Depression: depression of husbands at Time 2 (13 months after scanning); T2 W_ Depression: depression of wives at Time 2 (13 months after scanning). bpW: standardized beta value of regression from index of wives to index of husbands (partner effect of wives); baH: standardized beta value of regression from index of husbands to index of husbands (actor effect of husbands); baW: standardized beta value of regression from index of wives to index of wives (actor effect of wives); bpH: standardized beta value of regression from index of husbands to index of wives (partner effect of husbands). Numbers in parentheses are standard errors. Black solid lines indicate *P*<0.05, and gray dotted lines indicate nonsignificant regressions.

also further examined differences in efficiency effects on marital quality and depression as related to the processing of different stimuli. There were differences in actor effects of global reconfiguration efficiency on marital quality (processing of relationship-specific information > processing of general emotional stimuli; constrained model with equal actor path between different stimuli: △CFI = 0.000, CFI = 1.000, RMSEA = 0.000, 90% CI = [0.000, 0.475], SRMR = 0.020) and on depression (processing of relationship-specific information < processing of general emotional stimuli; constrained model with equal actor path between different stimuli: △CFI = 1.000, CFI = 0.000, RMSEA = 9.201, 90% CI = [0.009, 9.508], SRMR = 0.042).

For efficiency effects in specific networks, we found higher actor effects of reconfiguration efficiency on marital quality in

visual association network and lower actor effects in medial frontal, frontal-parietal, default mode, motor/sensory and salience networks during the processing of relationship-specific information *vs* general emotional stimuli (Table 3).

Relevance of brain reconfiguration efficiency

All efficiency effects on marital quality were eliminated when task-based FC was held constant (with resting-state FC varying), and when resting-state FC was held constant (with task-based FC varying) (Supplementary Table S9). Despite some significant efficiency effects on depression, some other efficiency effects were not significant when task-based FC was held constant (with resting-state FC varying) or when resting-state FC was held constant (with task-based FC varying) (Supplementary Table S10).

Table 2. Model indexes of the constrained models with equal efficiency effects between genders of specific networks

		Prediction for marital quality					Prediction for depression				
		ΔCFI	CFI	RMSEA	90% CI	SRMR	ΔCFI	CFI	RMSEA	90% CI	SRMR
Relationship-specific	Visual association	0.101	0.899	0.331	0.055 0.685	0.128	–	–	–	– –	–
Generalized emotion	Medial frontal	–	–	–	– –	–	0.021	0.979	0.067	0.000 0.503	0.054
	Frontal-parietal	–	–	–	– –	–	0.146	0.854	0.203	0.000 0.580	0.079
	Default mode	–	–	–	– –	–	0.192	0.808	0.177	0.000 0.562	0.073
	Motor/sensory	–	–	–	– –	–	0.147	0.853	0.216	0.000 0.590	0.089
	Salience	–	–	–	– –	–	0.000	1.000	0.000	0.000 0.474	0.060

CFI: comparative fit index; RMSEA: root mean square error of approximation; CI: confidence interval of RMSEA; SRMR: standardized root mean square residual;. ΔCFI: change in CFI of the constrained model (equal actor path coefficients between genders) compared with those of the free-estimating model.

Table 3. Model indexes of the constrained models with equal efficiency effects between stimuli types of specific networks

	Prediction for marital quality					Prediction for depression				
	ΔCFI	CFI	RMSEA	90% CI	SRMR	ΔCFI	CFI	RMSEA	90% CI	SRMR
Medial frontal	–	–	–	– –	–	0.055	0.945	0.125	0.000 0.529	0.015
Frontal-parietal	–	–	–	– –	–	0.116	0.884	0.216	0.000 0.590	0.026
Default mode	–	–	–	– –	–	0.104	0.896	0.198	0.000 0.577	0.025
Motor/sensory	–	–	–	– –	–	1.000	0.000	1.160	0.870 1.418	0.056
Visual association	0.014	0.986	0.150	0.000 0.544	0.031	–	–	–	– –	–
Salience	–	–	–	– –	–	1.000	0.000	0.633	0.354 0.965	0.039

CFI: comparative fit index; RMSEA: root mean square error of approximation; CI: confidence interval of RMSEA; SRMR: standardized root mean square residual; ΔCFI: change in CFI of the constrained model (equal actor path coefficients between stimuli types) compared with those of the free-estimating model.

These results suggest that both covariance of resting-state and task-based FC contribute to efficiency effects and highlight the importance of considering brain reconfiguration.

Discussion

This is the first study to investigate the relationships between socio-behavioral outcome measures (marital quality, depression) and brain reconfiguration during social information processing. The current study found efficiency effects that wives' functional reconfiguration efficiency during the processing of relationship-specific stimuli predicted their own higher marital quality 13 months later. Wives' brain reconfiguration efficiency during the processing of general emotional stimuli predicted their lower depression after 13 months.

Efficiency effects on social outcomes during social cognition

Social cognition refers to cognitive abilities involved in the processing and interpretation of socio-emotional information in oneself and others (Newman, 2001). The current findings of efficiency effects on social outcomes during social cognition are consistent with positive correlates of brain reconfiguration efficiency during neurocognitive tasks (such as working memory, verbal comprehension, and reasoning) with respect to better performance and higher intelligence (Vatansever *et al.*, 2015; Schultz and Cole, 2016; Zuo *et al.*, 2018). This also resonates with our consideration that complex cognitive functions involving the processing of information from multiple domains depend on interactions across multiple brain networks (Hasson *et al.*, 2004; Smith *et al.*, 2009; Heinzle *et al.*, 2012; Shirer *et al.*, 2012; Nummenmaa *et al.*, 2012b; Abrams *et al.*, 2013). Correspondingly, the social information–processing model considers multiple processes, including the encoding and interpretation of socially relevant stimuli, the generation and selection of appropriate emotional or behavioral reactions and behavioral enactment (Crick and Dodge, 1994; Possel *et al.*, 2006; Luebbe *et al.*, 2010). Thus, for people who require less effort/energy to update from resting to task-optimal states when facing their spouse's behaviors or emotional stimuli, they may process and interpret these events in a manner leading to better understanding and emotional responses, which, in turn, could benefit marital and psychological well-being.

Our findings suggest that efficiency effects in neurocognition may generalize to social cognition. A potential explanation is that social cognition is distinct from but possibly related to neurocognitive (or 'nonsocial cognition') (Brunet-Gouet and Decety, 2006; Pinkham *et al.*, 2008). Neurocognitive factors could provide the foundation for dealing with complex and dynamic social stimuli and have a moderate effect on social functioning. Social cognition may mediate the relationship between neurocognitive and social functioning and account for additional independent variance in real-life social functioning (Couture *et al.*, 2006; Bell *et al.*, 2009; Schmidt *et al.*, 2011).

Stronger efficiency effects of wives

Considering the effects of brain reconfiguration efficiency and gender-related differences, the current results suggest that wives may be more sensitive to social information and show stronger efficiency effects than husbands. Gender-related differences in cognitive complexity may serve as an explanation for this finding. Females are often better at detecting and understanding emotions (Cyranowski *et al.*, 2000; Croyle and Waltz, 2002; Burdwood and Simons, 2016) and are more likely to think about their

relationships (Zlomke *et al.*, 2010) and to be affected by interpersonal events than males (Cyranowski *et al.*, 2000; Burdwood and Simons, 2016). For example, when experiencing negative verbal stimuli, women have demonstrated greater limbic activation than men, with the limbic activation negatively correlated with ratings of pleasure (Shirao *et al.*, 2005). Therefore, in the face of interpersonal and general emotional stimuli, women may be more sensitive and feel more pressure than men. Better understanding and emotional regulation may help women cope with these stimuli, promoting their marital well-being and protecting themselves from depression. These currently speculative notions warrant additional investigation.

Although we hypothesized that a person's responses might simultaneously and independently relate to his or her own report (actor effect) as well as to that of his or her partner's (partner effect) (Kenny *et al.*, 2006), we only found the actor effect of the reconfiguration efficiency in wives, but no significant partner effects. This might be due to the actor effect being larger than the partner effect (Carr *et al.*, 2016; Maroufizadeh *et al.*, 2018; Boiman-Meshita and Littman-Ovadia, 2021). Further studies with larger samples are needed to examine partner effects and their magnitudes.

Brain reconfiguration efficiency of wives predicts their own higher marital quality during the processing of relationship-specific stimuli

Wives' global reconfiguration efficiency during the processing of relationship-specific stimuli predicted their own higher marital quality. This finding resonates with previous studies suggesting the relationship between activation efficiency and romantic relationship that activity in regions processing rewards, motivation, and cognitive control in the early stage of love were negatively correlated with relationship happiness scores after 40 months (Xu *et al.*, 2012). Efficiency effect on marital quality was also found in visual association network for visual processing, which has been found to be related to neurocognitive performance, such as working memory and reasoning (Schultz and Cole, 2016; Zuo *et al.*, 2018). The current findings suggest that wives who require less effort to update from rest to situational tasks may show better sensory processing, reasoning and understanding of their spouse's behaviors. Although currently speculative, each of these factors could be beneficial to marital well-being.

Wives' brain reconfiguration efficiency during the processing of general emotional stimuli predicts their lower depression

The efficiency effect on depression was found during the processing of general emotional stimuli. This finding is consistent with the important role of responses to emotional information on depression (Leppanen, 2006; Joormann *et al.*, 2007). Efficiency effects were also found in specific networks in wives, including salience network involved in allocating and switching attentional resources (Sridharan *et al.*, 2008; Menon and Uddin, 2010; Menon, 2011), motor/sensory network implicated in the perception and regulation of emotions (Schutter and van Honk, 2009; Nummenmaa *et al.*, 2012a, 2014), the FPN for attentional/cognitive control (Cole and Schneider, 2007; Dosenbach *et al.*, 2007), and the medial prefrontal and default mode networks implicated in social cognitive processing, such as perspective-taking (Raichle *et al.*, 2001; Walter *et al.*, 2004; Amodio and Frith, 2006; Nummenmaa *et al.*, 2012a; Nagels *et al.*, 2015). Efficiency in these networks has been previously linked to performance on working memory, language and reasoning tasks (Vatansever *et al.*, 2015; Schultz and Cole,

2016; Zuo *et al.*, 2018). Thus, effective reconfiguration of these networks, suggestive of better sensory processing, emotion perception and regulation during the processing of emotional stimuli, may be beneficial to an individual's emotional well-being and help mitigate depression.

Different patterns in efficiency effects as related to processing of different stimuli

In our study, significant efficiency effects on marital quality were only found in relationship-specific contexts, and efficiency effects on depression were only found during the processing of general emotional stimuli. Regardless of the efficiency effects on marital quality or depression, the effects of global brain and specific networks with significant results differed between the processing of relationship-specific and general emotional information. Previous studies proposed that marital quality was always associated with psychological well-being (Holt-Lunstad *et al.*, 2008; Cao *et al.*, 2017) and that women are more likely to be affected by interpersonal events was a potential explanation for higher rates of depression (Cyranowski *et al.*, 2000; Burdwood and Simons, 2016). Thus, we also investigated used the APIM approach to investigate whether husbands' and wives' marital quality mediate the association between reconfiguration efficiency during relationship-specific stimuli processing and their own (actor effects) and partner's (partner effects) depression. However, we did not find significant indirect effects from reconfiguration efficiency during the processing of relationship-specific stimuli on depression via marital quality (Supplementary Table S11). These findings suggest that efficiency effects on relationship-specific and more general outcomes may occur independently. The efficiency effects on relationship-specific outcome are higher during relationship-specific stimuli processing, while the efficiency effects on more general outcomes are higher during general emotional stimuli processing.

Both task-based and resting-state functional architecture contribute to relationships between brain reconfiguration efficiency and marital quality/depression

The effect of efficient brain reconfiguration may be due to the optimized (preconfigured) resting-state functional architecture or task-based FC modified to a lesser degree from rest. The results showed that most effects were nonsignificant when resting-state or task-based FC was held constant. These findings suggest that efficiency effects are driven by individual differences in both resting-state and task-based FC structures and highlight the importance of brain reconfiguration efficiency (Schultz and Cole, 2016).

Strengths and limitations

This study provides important insight into relationships between socio-behavioral outcome measures and brain reconfiguration during social cognition in marriage and provides a foundation for studying other kinds of relationships. First, we focused on the processing of social information and employed not only relationship-specific stimuli that previous studies have used but also general emotional stimuli. This approach provides insight into the generalizability and specificity of efficiency effects. Second, we measured both relationship-specific and more general outcomes at 13 months after scanning, which enabled us to infer predictive effects. Third, in multiple types of relationships, there are dyadic data from both partners, which are interdependent

but still differ from each other. However, previous studies only collected fMRI data from one partner. The current study utilized dyadic data and tested the actor and partner effects of brain reconfiguration efficiency and further investigated gender-related differences.

This study has practical implications. Processing of relationship-specific and general emotional stimuli is important for promoting relationship quality and preventing depression, respectively. Having insight into the brain mechanisms related prospectively to marital quality and happiness (or marital concerns and depression) may help with intervention development. Females are typically more sensitive to life events, and responding appropriately to environmental stimuli may be particularly beneficial to their marital and psychological well-being. Thus, future interventions focusing on married women might utilize an understanding of brain reconfiguration efficiency when helping married women best address relationship-related and general emotional events. If these findings generalize to other kinds of relationships, additional benefits might be conferred. Furthermore, if specific interventions were shown to effect brain reconfiguration efficiency (e.g. mindfulness mediation practices) (Brewer *et al.*, 2011), it could provide further insight into how specific health-promoting practices may operate biologically to achieve behavioral outcomes relevant to marital quality and happiness.

Study limitations warrant mention. First, couples in the present study represented a sample of heterosexual married Chinese couples in early years and without children, with high education and high marital quality, and these qualities may limit the generalizability of the findings. Future studies should enroll more types of couples to confirm and extend our results. Second, although participants had a rest after the relationship-specific task, began the task involving the processing of general emotional stimuli when they felt calm and largely showed similar emotional states at the onset of each task (except for sadness in husbands) (Supplementary Table S12), order effects may have existed. Although previous research has also studied the efficiency effects on different cognitive processes using data of the Human Connectome Project with a fixed order (Schultz and Cole, 2016; Zuo *et al.*, 2018), future studies should counterbalance task order. Third, a resting-state scan between the two fMRI tasks was not collected. Future studies should consider such a design in order to measure more precisely reconfiguration changes from resting to task-related states. Fourth, additional measures (e.g. of positive health, intelligence, and emotional regulation) were not collected and future studies should consider such measures.

Conclusion

Efficiency effects in neurocognition may generalize to social cognition. That is, the ability to modify FC pattern efficiently during social information processing is a potential hallmark of better social outcomes, especially among women in early-stage marriages. The efficiency effects on relationship-specific and more general outcomes are, respectively, higher during the processing of relationship-specific stimuli and general emotional stimuli. Future studies should examine the extent to which the findings generalize to other types of relationships.

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

Data availability statement

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

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