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Neural synchronization predicts marital satisfaction

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Marital attachment plays an important role in maintaining intimate personal relationships and sustaining psychological well-being. Mate-selection theories suggest that people are more likely to marry someone with a similar personality and social status, yet evidence for the association between personality-based couple similarity measures and marital satisfaction has been inconsistent. A more direct and useful approach for understanding fundamental processes underlying marital satisfaction is to probe similarity of dynamic brain responses to maritally and socially relevant communicative cues, which may better reflect how married couples process information in real time and make sense of their mates and themselves. Here, we investigate shared neural representations based on intersubject synchronization (ISS) of brain responses during free viewing of marital life-related, and nonmarital, object-related movies. Compared to randomly selected pairs of couples, married couples showed significantly higher levels of ISS during viewing of marital movies and ISS between married couples predicted higher levels of marital satisfaction. ISS in the default mode network emerged as a strong predictor of marital satisfaction and canonical correlation analysis revealed a specific relation between ISS in this network and shared communication and egalitarian components of martial satisfaction. Our findings demonstrate that brain similarities that reflect real-time mental responses to subjective perceptions, thoughts, and feelings about interpersonal and social interactions are strong predictors of marital satisfaction, reflecting shared values and beliefs. Our study advances foundational knowledge of the neurobiological basis of human pair bonding.

marital satisfaction | fMRI | synchronization | default mode network

Humans establish intimate social and personal relationships with their partners (1), which enable them to survive, successfully mate, and raise offspring (2, 3). Marital attachment plays an important role in maintaining intimate relationships with long-lasting influences on physical and psychological well-being (4). Paralleling the centuries-old adage, "birds of a feather flock together," theories of mate selection have emphasized the role of assortative mating (5) and the tendency of two partners' characteristics to be matched on personality, social, and demographic factors (6–9). Similarity between romantic partners in domains—such as socioeconomic status, educational background, age, ethnicity, religion, physical attractiveness, intelligence, attitudes, and values—have been reported to predict higher levels of marital satisfaction and lower likelihood of separation and divorce (6–9). However, Shiota and Levenson (10) have suggested that "birds of a feather don't always fly farthest," finding that similar personalities may in fact predict more negative marital outcomes. Here we examine the neurobiological basis of marital satisfaction in humans using naturalistic ecologically relevant interpersonal communicative cues that capture shared neural representations between married couples.

Marital attributes and factors that contribute to marital satisfaction have been investigated extensively behaviorally (6–9). Studies using personality measures have shown that low levels of neuroticism and high levels of agreeableness, extraversion, and conscientiousness are associated with marital well-being (6–8). However, evidence linking personality dimensions to marital satisfaction is modest at best and long-term outcomes could even be negatively related to conscientiousness and extraversion (10). Other studies have argued that personality and emotional stability might be unreliable predictors of marital satisfaction (11, 12).

A potentially more direct and useful approach for understanding fundamental processes underlying marital satisfaction is to probe dynamic brain response to maritally and socially relevant communicative cues. Studies involving naturalistic stimuli in which intersubject synchronization (ISS) is measured while participants view movie clips, offer a potentially more representative window into perceptual and cognitive processes as they unfold over time (13). ISS assesses temporal correlations of neural responses between pairs of individuals, at each brain area or voxel, using time-series

Significance

Humans establish intimate social and personal relationships with their partners, which enable them to survive, successfully mate, and raise offspring. Here, we examine the neurobiological basis of marital satisfaction in humans using naturalistic, ecologically relevant, interpersonal communicative cues that capture shared neural representations between married couples. We show that in contrast to demographic and personality measures, which are unreliable predictors of marital satisfaction, neural synchronization of brain responses during viewing of naturalistic maritally relevant movies predicted higher levels of marital satisfaction in couples. Our findings demonstrate that brain similarities that reflect real-time mental responses to subjective perceptions, thoughts, and feelings about interpersonal and social interactions are strong predictors of marital satisfaction and advance our understanding of human marital bonding.

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data acquired during presentation of dynamic stimuli, such as movies (14). ISS has been linked to similarities in perception of visual surroundings across individuals (15, 16).

An emerging body of studies has suggested that the ongoing neural activity of two individuals become synchronized when they process shared narratives (14). Watching movies evokes highly reliable and time-locked activity in multiple brain areas along the information-processing hierarchy, including the primary and secondary auditory and visual cortex (13), as well as multisensory and language areas in the prefrontal, temporal, and parietal association cortices (14, 17). The level of neural synchronization is also dependent on the content of stimuli presented, and brain areas in the default mode network (DMN) are particularly sensitive to self- and socially relevant aspects of information processing (18, 19). Yet, the role of these brain areas in shared processing of dynamic marital interactions and their relation to successful marital bonding is poorly understood.

Recent work by Parkinson et al. (20) examined ISS during free viewing of naturalistic movies and found evidence for neural homophily: neural responses when viewing audiovisual movies were similar among friends, and decreased with increasing distance in a real-world social network. These findings led the authors to suggest that how we jointly perceive the world around us may influence interpersonal interactions and attraction. Thus, brain synchronization measures based on neural similarity in information processing that reflect dynamic mental response and subjective perceptions and feelings have the potential to more accurately and precisely capture how married couples process dynamically evolving communicative cues.

Our study had four goals. The first goal of our study was to determine whether behavior and personality measures are predictive of marital satisfaction. Based on previous behavioral literature (6–9), we tested the hypothesis that personality measures would predict marital satisfaction. We recruited 96 participants (48 married couples) and asked them to complete a battery of questionnaires. Behavioral measures included marital satisfaction, adult attachment, and the Big Five Personality Inventory.

Our second goal was to determine whether married couples have higher synchronization of neural responses compared to randomly selected male–female pairs. We scanned all 96 participants using fMRI while they viewed marital and object-related movies clips. Marital movie clips involved social interaction between married couples and their family members. They consisted of real-world situations involving sex, children's education, attitudes about relatives, conflict resolution, economic disputes, discussion of values, and egalitarian roles. Object-related movie clips consisted of documentaries on topics such as food, scenery, and architecture, using stimuli encountered in everyday life (21). Such stimuli have been shown to evoke highly reliable, time-locked, and naturalistic patterns of response-time courses across multiple brain areas (22). Daily living with one's mate requires active engagement and interactions (23), which may lead to shared neural representations related to how couples process information and make sense of their mates and themselves. We tested the hypothesis that married couples had more synchronized neural activity than random pairs of couples. Comparing synchronization of neural responses between marital- vs. object-related movies allowed us to further probe the specificity of our findings with respect to interpersonal social communicative cues.

Our third goal was to determine whether synchronization of neural responses was predictive of couple's marital satisfaction. We tested the hypothesis that brain-wide neural synchronization would predict marital satisfaction and this effect would be specific to movies with social content involving depictions of marriage, sex, and relationships, instead of general environmental scenes involving science, food, scenery, and architecture. We computed ISS between married couples and used both dimensional and categorical analyses to examine whether the ISS between married couples was associated with marital satisfaction. We hypothesized that ISS would be positively related to marital satisfaction: that is, highly satisfied married couples would show more similar neural responses than less satisfied married couples.

In addition to brain-wide neural synchronization, we also specifically examined the role of the DMN in marital satisfaction. The DMN is a large-scale brain network implicated in processing internal mental representations and stimulus-independent thoughts (13). Its core nodes—most notably the medial prefrontal cortex, precuneus, posterior cingulate cortex, and temporoparietal junction—are reliably engaged during experimental tasks involving theory of mind and judgement about others (24). The DMN has also been linked to sharing of thoughts, feelings, or beliefs with others, including beliefs about the world outside of one's own social relationships or interactions (25). Such a role for the DMN is consistent with task-based manipulations, which have highlighted a key role of this network in social cognition (24, 26). Building on these findings, we examined whether ISS in the DMN was related to specific components of marital satisfaction, including personality, communication, conflict resolution, and egalitarian roles in marriage. We tested the hypothesis that the DMN, and other brain areas that were known to dynamically interact with it, including the salience and frontoparietal networks, were associated with marital satisfaction. We predicted that the ISS between married couples would emerge as a strong predictor of marital satisfaction, and further hypothesized that ISS in the DMN would be highly correlated with the shared communication component of marital satisfaction.

Our findings demonstrate that shared neural representations predict marital satisfaction and provide insights into the neurobiological basis of human marital bonding.

Results

Marital Satisfaction and Individual Behavioral Characteristics. A total of 96 participants (48 heterosexual married couples) who had been married for at least 1 y participated in the study. Twelve married couples were excluded due to high levels of head motion during fMRI scanning, and one couple was excluded due to a lack of respiratory and cardiac signals (see *Methods* for details). Data from the remaining 35 couples were used in further analysis. Multiple regression was used to evaluate the relationship between marital satisfaction and general demographic and behavioral measures. No significant relation was observed between marital satisfaction, as assessed using the Chinese Marital Quality Inventory (CMQI), and either age, sex, length of marriage, or personality traits (Table 1). A negative association between marital satisfaction and anxiety on the Adult Attachment Scale was detected ($\beta = -9.955$, SE = 4.227; $P_{Regress} = 0.022$). Correlation analysis confirmed that marital satisfaction was negatively correlated with anxiety ($R_{\mathrm{Pearson}} = -0.329$, $P_{\mathrm{Pearson}} = 0.005$). Results were replicated in the original sample comprising all 48 couples (*SI Appendix*, Table S1). These results suggest that demographic and personality measures are unreliable predictors of marital satisfaction and identify anxiety as a potential, and understudied, contributor to marital satisfaction.

Intersubject Neural Synchronization during Viewing of Marital and Nonmarital Movies. We first examined whether married couples showed higher levels of synchronization compared to

Table 1. Relationship between individual behavioral characteristics and marital satisfaction

	Coefficient β	SE	$P_{Regress}$	$R_{Pearson}$	$P_{Pearson}$
Sex	3.437	4.182	0.414		
Age	−0.131	0.676	0.847	0.206	0.088
Length of marriage	0.856	0.765	0.268	0.183	0.130
Personality					
Neuroticism	−0.051	0.287	0.858	**−0.260**	**0.030**
Conscientiousness	0.111	0.294	0.706	0.210	0.082
Agreeableness	−0.280	0.402	0.489	0.154	0.204
Openness	0.052	0.307	0.866	0.163	0.177
Extraversion	0.482	0.297	0.110	0.202	0.093
Adult attachment scale					
Close dependence	−0.598	4.402	0.892	0.120	0.323
Anxiety	**−9.955**	**4.227**	**0.022**	**−0.329**	**0.005**

Note: β is the regression coefficient from multiple regression analysis. $P_{Regress}$ is the P value from multiple regression analysis. $R_{Pearson}$ is the Pearson correlation coefficient from correlation between the individual behavioral characteristics and marital satisfaction. $P_{Pearson}$ is the P value from correlation between the individual behavioral characteristics and marital satisfaction. Bold font indicates the significance level at $P < 0.05$.

random pairs of study participants, and whether this was specific to marital movie clips. Random male–female pairs were generated by pairing a male with a randomly selected female who was not married to the selected male.

During fMRI scanning, each participant viewed two types of movie clips: one involving marital life-related scenes and the other involving nonmarital natural object-related scenes (Fig. 1; for movie clips, see https://zenodo.org/record/6960421#.YusvSepBxPY). Except for three participants who had previously watched 2 of the 12 movie clips, none of the other 67 participants had any prior exposure to the movie clips. A complete summary of participants' reported familiarity with the movie clips is shown in *SI Appendix*, Table S3.

For each participant, we first examined ISS in each of the 246 anatomical regions of interest (ROIs) spanning the entire brain using the Brainnetome Atlas (27). In each ROI, ISS was defined as the temporal correlation between the mean fMRI time series of the married couple, or randomly selected male and female participants, and a Fisher's r-to-z transform was applied to convert the correlation coefficient (r) value to a normally distributed variable z (28) (Fig. 1). ANOVA revealed a main effect of marriage (married couples vs. random pairs), with stronger ISS in married couples ($F = 5.29$, $P < 0.05$). A significant interaction effect was found between movie type and marriage ($F = 6.03$, $P < 0.05$). Compared with random pairs, ISS was higher in married couples during the viewing of marital movies ($t = 2.05$, $P < 0.05$; false-discovery rate [FDR]-corrected), but not in nonmarital movies ($t = 1.46$, $P = 0.15$) (Fig. 2). Similar results were observed with raw correlation values without Fisher's r-to-z transformation (*SI Appendix*, Table S2). These results demonstrate that married

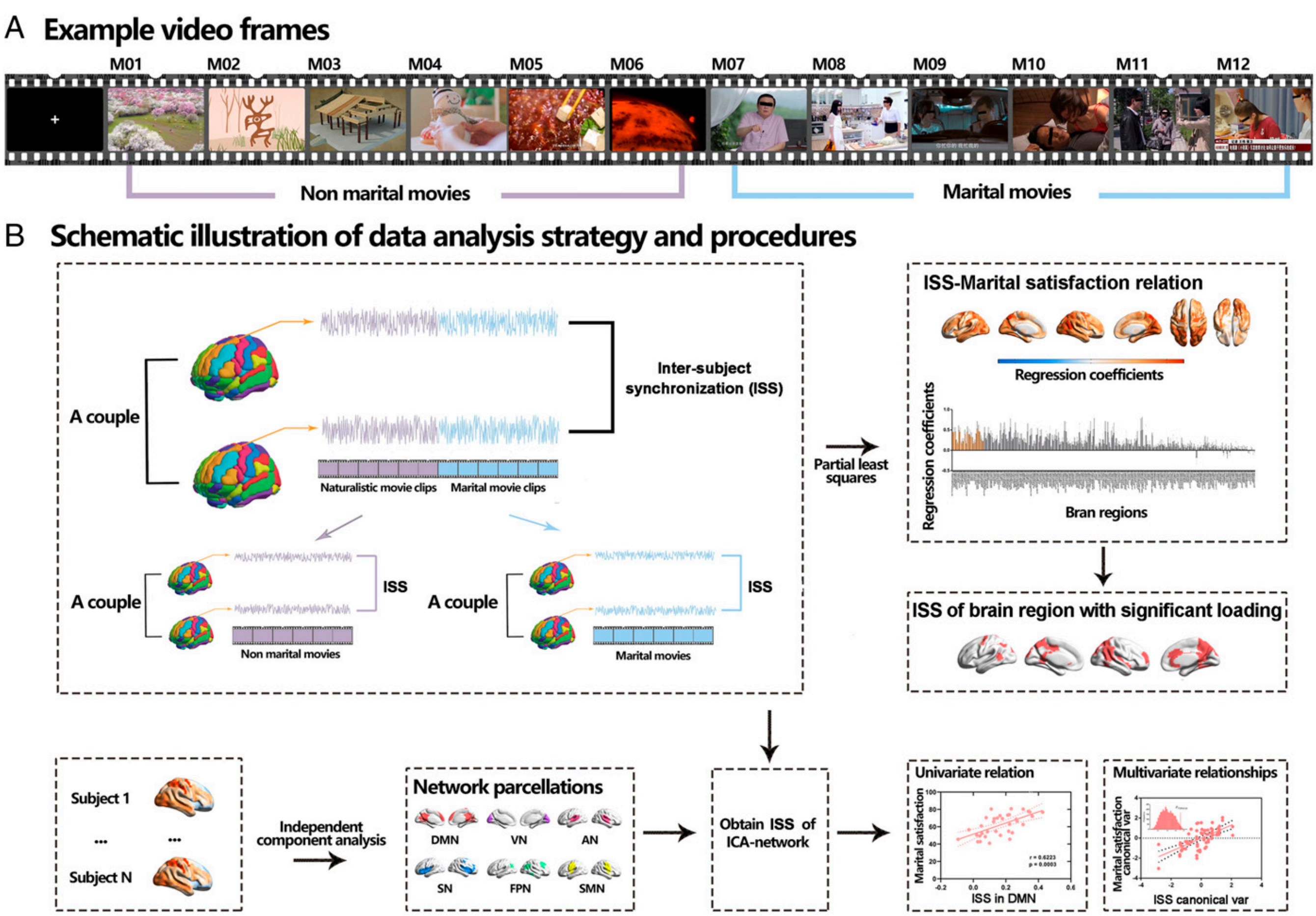

Fig. 1. Examples of movie stimuli and overview of analysis pipeline. (*A*) Example movie frames for marital and nonmarital movie clips. (*B*) Schematic illustration of data analysis strategy and procedures. First, ISS was determined by calculating the correlation of neural response time series between married or random couples. Second, PLS regression was used to determine brain regions underlying the relationship between ISS and marital satisfaction. Third, network-level measures were used to determine the relation between ISS in the DMN and marital satisfaction. Fourth, CCA was performed to determine multivariate relationships between network-level ISS and distinct components of marital satisfaction. AN, auditory network; FPN, frontoparietal network; SMN, somato-motor network; SN, salience network; VN, visual network.

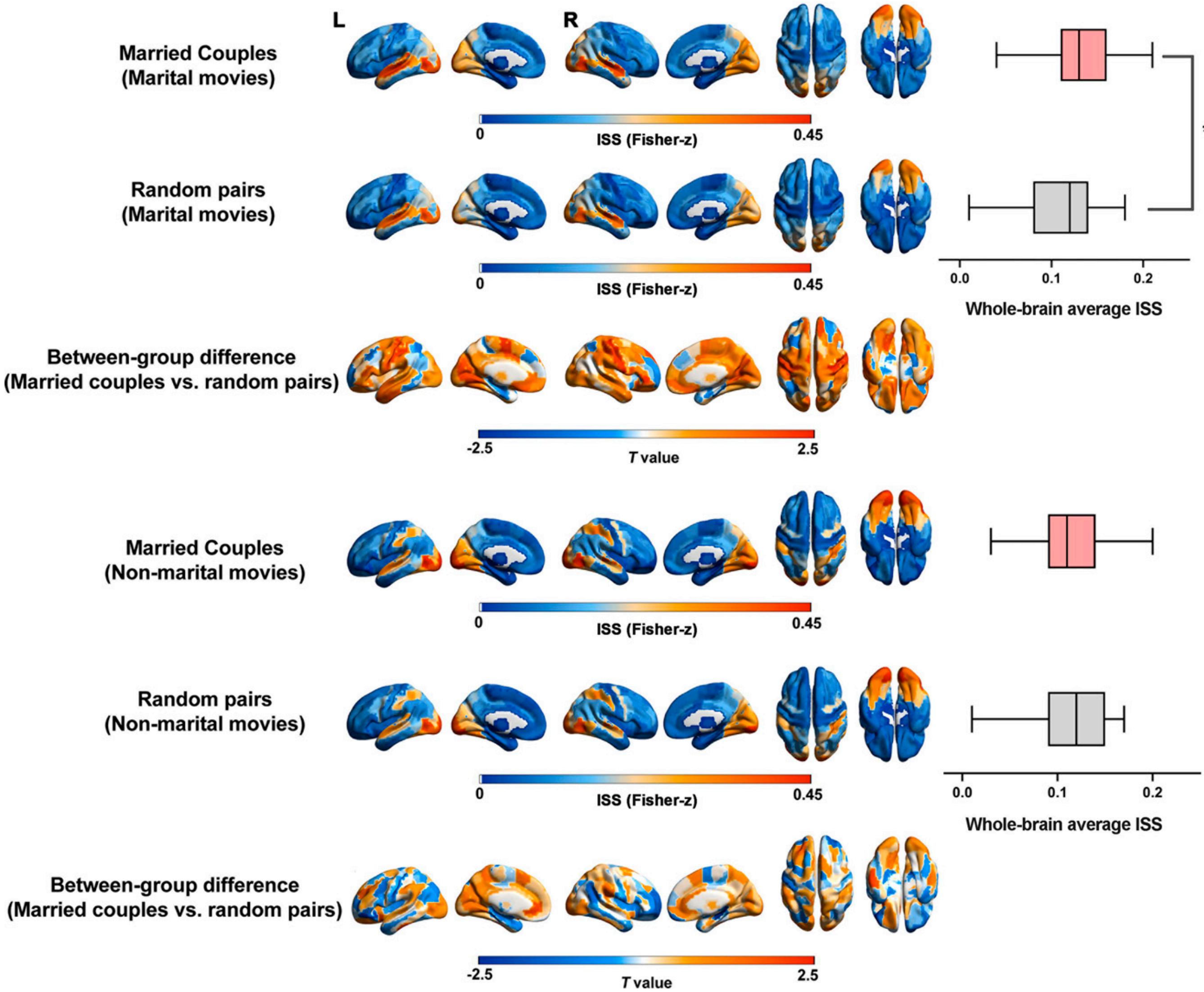

Fig. 2. Married couples showed higher ISS than random noncouple pairs at the whole-brain level. ISS maps across brain regions during viewing of marital and nonmarital movie clips are shown, *Left*. Group differences in whole-brain average ISS during viewing marital and nonmarital movie clips are shown, *Right*. *$P < 0.05$, FDR-corrected.

couples show higher levels of brain-wide neural synchronization compared to random pairs of study participants, and furthermore demonstrate that this differentiation is specific to marital movies.

Intersubject Neural Synchronization and Marital Satisfaction. Next, we examined whether ISS at the whole-brain level was related to individual differences in marital satisfaction. We averaged ISS across all 246 ROIs to obtain a whole-brain ISS measure in married couples and investigated its relationship with marital satisfaction. We found that whole-brain ISS was significantly correlated with marital satisfaction during viewing of marital movie clips ($r = 0.32$, $P < 0.05$), but not during viewing of nonmarital movie clips ($r = 0.15$, $P = 0.39$) (Fig. 3*A*). A direct comparison revealed a significant difference in synchronization between the two movie types ($F = 3.48$, $P = 0.046$). These results demonstrate that increased marital satisfaction is associated with higher levels of neural synchronization during viewing of marital movies in married couples.

We then determined whether ISS patterns during viewing marital movies across the 246 ROIs could predict marital satisfaction. We applied multivariate linear support vector regression (SVR) to predict marital satisfaction, with ISS across the 246 brain regions acting as predictors (see detailed methods in *SI Appendix*). We found that ISS between married couples reliably predicted marital satisfaction scores, and a significant correlation was detected between the estimated and observed marital satisfaction ($r = 0.39$, $P < 0.05$, permutation testing, fourfold cross-validation) (Fig. 3*B*).

To better visualize these findings, we further conducted a categorical analysis using median split on CMQI scores and compared ISS between high and low marital-satisfaction groups (*Methods*). Compared with couples with low marital satisfaction, married couples with high marital satisfaction showed higher ISS during the viewing of marital movies ($t = 2.87$, $P = 0.007$, FDR-corrected) (Fig. 3 *C* and *D*).

Contribution of Individual Brain Areas to the Relation between Intersubject Neural Synchronization and Marital Satisfaction. Next, we sought to identify brain regions driving the relationship between ISS and marital satisfaction. We used partial least-squares (PLS) regression to determine the relationship between marital satisfaction and ISS in 246 ROIs during the viewing of marital movies. The first component (PLS-1) was defined as the spatial map that captured the greatest fraction of total ISS

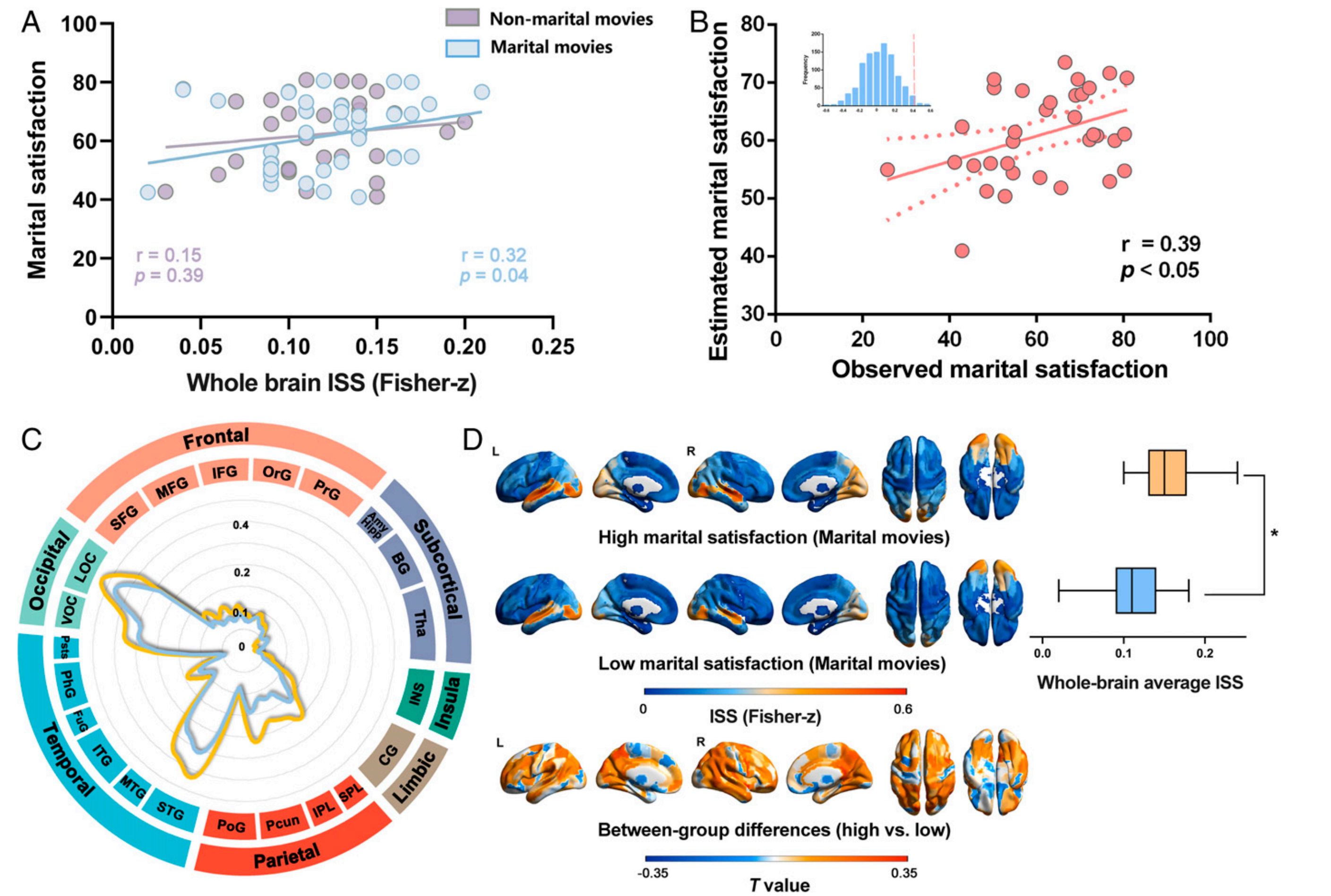

Fig. 3. Marital satisfaction is correlated with whole-brain ISS in married couples. (*A*) Correlation between average ISS across the whole brain, and marital satisfaction during viewing of marital and nonmarital movie clips. (*B*) Whole-brain ISS during viewing of marital movie clips predicts marital satisfaction. (*C*) ISS during viewing marital movie clips in each brain area in couples with high (CMQI scores > 60, orange line) compared to low (CMQI scores < 60, blue line) marital satisfaction. Abbreviations of brain regions are shown in *SI Appendix*, Table S5. (*D*) ISS during viewing of marital movie clips in couples with high and low marital satisfaction, surface rendering shown for visualization. Group differences in average ISS across the whole brain during viewing of marital movie clips are shown on the right. *$P < 0.05$, FDR-corrected.

($P_{permutation} < 0.001$). After bootstrapping (*Methods*), FDR corrections were used to correct for multiple comparisons across brain regions.

We found that ISS in multiple brain regions contributed to marital satisfaction during viewing of marital movies ($P < 0.005$; two-tailed, FDR-corrected). These regions included most prominently the precuneus, posterior cingulate, superior occipital gyrus, superior temporal gyrus, and angular gyrus (Fig. 4 and Table 2). SVR with cross-validation confirmed a significant contribution of these brain regions to prediction of marital satisfaction (*SI Appendix*, Fig. S1). There were no brain regions in which ISS was significantly correlated with marital satisfaction during the viewing of nonmarital movie clips. These results identify distributed brain areas in which neural synchronization during viewing of marital movie clips that contributes most significantly to marital satisfaction.

Relation between ISS in the DMN and Marital Satisfaction. Next, we examined the hypotheses that ISS in the DMN would be enhanced in married couples compared to random pairs, and that ISS in married couples would be associated with marital satisfaction. We used independent component analysis to identify the DMN in addition to five other cognitive control and sensory and motor networks (Fig. 5*A*). Compared with random pairs, married couples showed higher ISS in the DMN ($t = 3.54$, $P < 0.001$), as well as the salience network ($t = 2.51$, $P < 0.05$) and visual network ($t = 2.63$, $P < 0.05$), during viewing marital movie clips (Fig. 5*B* and *SI Appendix*, Table S2). No such differences were found during viewing of nonmarital movie clips.

We then examined the relationship between ISS in each network during viewing marital movie clips and marital satisfaction. Our results revealed that ISS in the DMN was significantly correlated with marital satisfaction ($r = 0.6212$, $P = 0.0004$, FDR-corrected). No such relation was detected in any of the other networks ($P > 0.05$, FDR-corrected) (Fig. 5 *C*–*H*). In addition, no correlation was observed in the case of nonmarital movies (*SI Appendix*, Fig. S2). Additionally, compared with the low marital-satisfaction group, the high marital-satisfaction group showed significantly higher ISS in the DMN ($t = 4.00$, $P < 0.001$) during viewing of marital movies (*SI Appendix*, Fig. S3 and Table S2).

Relationship between DMN Neural Similarity and Subcomponents of Marital Satisfaction. Next, we sought to determine whether ISS in the DMN was associated with distinct dimensional components of marital satisfaction. We performed canonical correlation analysis (CCA) to delineate multivariate relationships between ISS in the core networks and subdomains of marital

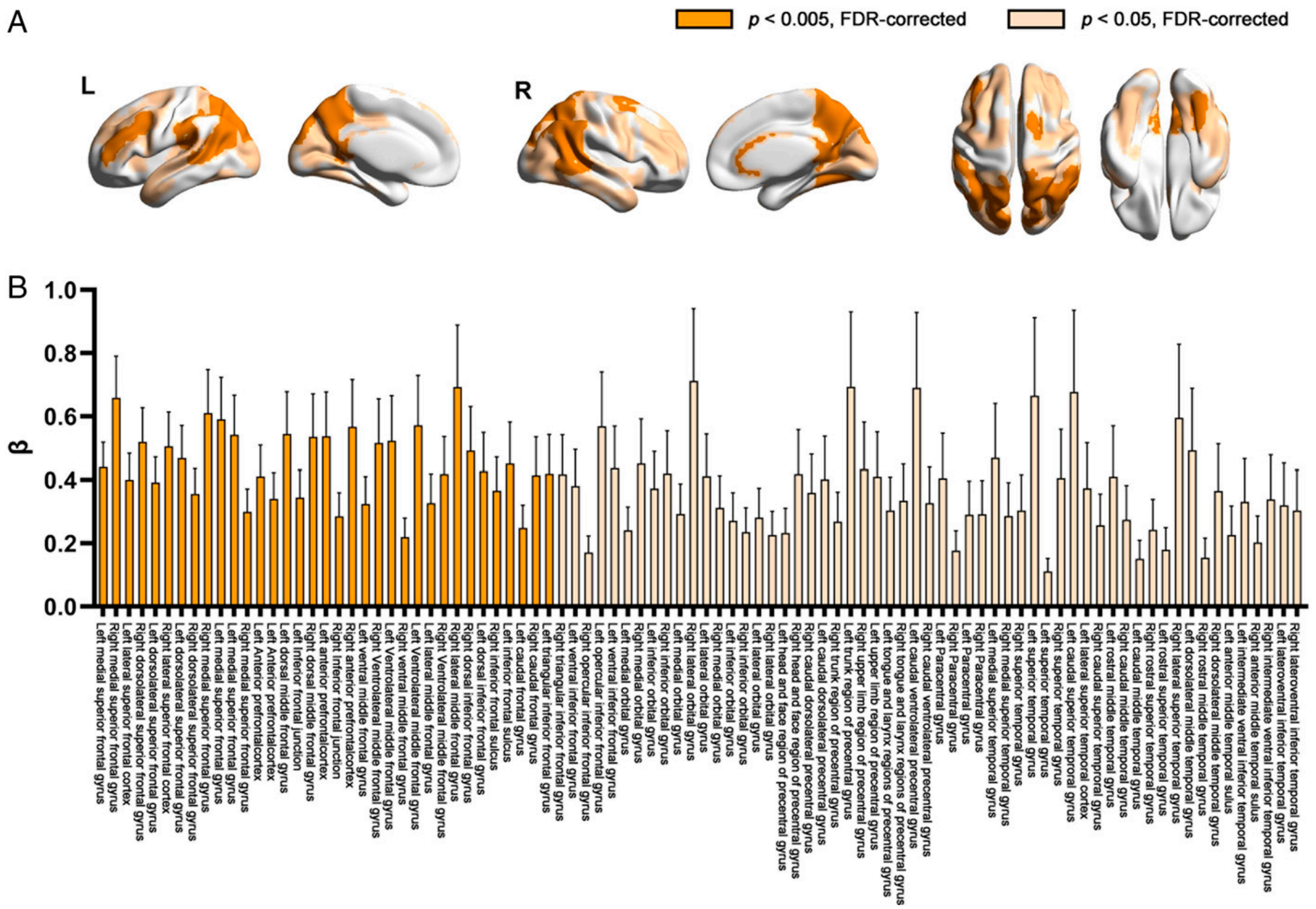

Fig. 4. Brain areas in which marital satisfaction was correlated with ISS during viewing of marital movies. (*A*) Brain areas that contributed significantly ($P < 0.05$ and $P < 0.005$, FDR-corrected) to marital satisfaction, based on PLS regression analysis. (*B*) Brain areas in which ISS was significantly predictive of marital satisfaction. High levels of ISS were observed in posteromedial and temporoparietal cortical regions associated with the DMN. Positive regression coefficients for ISS indicate that higher ISS is associated with higher marital satisfaction. Nomenclature of brain regions and coordinates are shown in *SI Appendix*, Table S5. Error bars indicate SEs of the regression coefficients.

satisfaction. Input to the CCA consisted of ISS in the DMN and the other five networks and nine marital satisfaction component scores (*Methods*). Permutation testing revealed a significant CCA component that represents a distinct pattern relating marital satisfaction measures to ISS in specific brain networks (FDR-corrected, $P < 0.05$) (Fig. 5*I*). Crucially, the first CCA component showed significant relations between ISS in the DMN and shared communication, financial management, and egalitarian role components of marital satisfaction (Bonferroni-corrected, $P < 0.05$) (Fig. 5*J*).

Reproducibility of Findings across Brain Parcellations. To verify reproducibility of findings across brain parcellations, we performed the same set of analyses using the automated anatomical atlas (AAL-90) parcellation (29), which has been widely used in neuroimaging research. The main findings of our study were reproduced with the AAL-90 atlas (*SI Appendix*, Figs. S4 and S5). Finally, findings were also replicated in posterior parietal and temporal cortex "Gestalt cortex" regions (30), implicated in subjective construal involving personal understanding of situations and the people and objects within them (*SI Appendix*, Fig. S6).

Discussion

We examined the neurobiological basis of successful marital bonding by probing the similarity of neural responses between married couples, and randomly selected male–female pairs. We evaluated ISS of brain responses during free viewing of marital movies that involved interpersonal and social interactions, as well as nonmarital object-related documentaries that did not involve social interactions. Our analysis revealed that married couples showed a significantly higher level of ISS than randomly selected pairs of couples. Furthermore, higher ISS between married couples was associated with greater marital satisfaction, and the level of ISS in the DMN emerged as a strong predictor of marital satisfaction. Canonical correlation analysis further revealed a specific relation between ISS in the DMN and shared communication, financial management, and egalitarian-role components of marital satisfaction. Our findings demonstrate that brain similarities that reflect real-time mental responses to subjective perceptions, thoughts, and feelings about interpersonal and social interactions are strong predictors of marital satisfaction and advance our understanding of human marital bonding.

Higher Intersubject Synchronization Is Enhanced in Married Couples and Is Associated with Higher Levels of Marital Satisfaction. Behavioral studies of marital relationships have reported that similarities in demographic attributes, individual characteristics, and interpersonal behaviors are associated with the quality of marital relationships (6–9, 31). On the other hand, theories based on disassortative mating suggest a pattern

Table 2. Brain regions in which ISS significantly predicted marital satisfaction

Region	β	SE	*t* scores	*P* value	*P* value (FDR-corrected)
Left medial superior frontal gyrus	0.4403	0.0785	5.6061	0.0000	0.0000
Right medial superior frontal gyrus	0.6586	0.1317	5.0025	0.0000	0.0001
Left dorsolateral superior frontal gyrus	0.4005	0.0836	4.7904	0.0000	0.0001
Right dorsolateral superior frontal gyrus	0.5193	0.1075	4.8303	0.0000	0.0001
Left lateral superior frontal cortex	0.3920	0.0803	4.8813	0.0000	0.0001
Right lateral superior frontal cortex	0.5057	0.1082	4.6724	0.0000	0.0001
Left dorsolateral superior frontal gyrus	0.4691	0.1019	4.6037	0.0000	0.0001
Right dorsolateral superior frontal gyrus	0.3561	0.0790	4.5095	0.0000	0.0002
Left medial superior frontal gyrus	0.6106	0.1371	4.4526	0.0000	0.0002
Right medial superior frontal gyrus	0.5907	0.1328	4.4477	0.0000	0.0002
Left medial superior frontal gyrus	0.5419	0.1250	4.3356	0.0000	0.0003
Right medial superior frontal gyrus	0.2996	0.0713	4.2012	0.0000	0.0005
Left anterior prefrontal cortex	0.4114	0.0986	4.1730	0.0000	0.0006
Left anterior prefrontal cortex	0.3405	0.0823	4.1361	0.0000	0.0006
Left dorsal middle frontal gyrus	0.5447	0.1334	4.0845	0.0000	0.0007
Right dorsal middle frontal gyrus	0.3444	0.0870	3.9608	0.0001	0.0011
Left Inferior frontal junction	0.5355	0.1354	3.9563	0.0001	0.0011
Right Inferior frontal junction	0.5375	0.1396	3.8505	0.0001	0.0015
Left anterior prefrontal cortex	0.2853	0.0739	3.8599	0.0001	0.0015
Right anterior prefrontal cortex	0.5669	0.1497	3.7871	0.0002	0.0019
Left ventral middle frontal gyrus	0.3242	0.0865	3.7463	0.0002	0.0021
Right ventral middle frontal gyrus	0.5161	0.1397	3.6928	0.0002	0.0024
Left ventrolateral middle frontal gyrus	0.5231	0.1420	3.6840	0.0002	0.0024
Right ventrolateral middle frontal gyrus	0.2199	0.0595	3.6951	0.0002	0.0024
Left ventrolateral middle frontal gyrus	0.5724	0.1575	3.6334	0.0003	0.0028
Right ventrolateral middle frontal gyrus	0.3270	0.0915	3.5749	0.0004	0.0032
Left lateral middle frontal gyrus	0.4190	0.1169	3.5846	0.0003	0.0032
Right lateral middle frontal gyrus	0.6931	0.1955	3.5446	0.0004	0.0035
Left dorsal inferior frontal gyrus	0.4918	0.1398	3.5174	0.0004	0.0036
Right dorsal inferior frontal gyrus	0.4282	0.1217	3.5171	0.0004	0.0036
Left inferior frontal sulcus	0.3660	0.1058	3.4595	0.0005	0.0042
Right inferior frontal sulcus	0.4516	0.1303	3.4660	0.0005	0.0042
Left caudal frontal gyrus	0.2487	0.0721	3.4466	0.0006	0.0042
Right caudal frontal gyrus	0.4142	0.1209	3.4272	0.0006	0.0044
Left triangular inferior frontal gyrus	0.4199	0.1230	3.4134	0.0006	0.0045

Results from PLS regression analysis. Brain regions in which the ISS was significantly predictive of marital satisfaction ($P < 0.005$, FDR-corrected, two-tailed) are shown. Nomenclature of brain regions and coordinates are shown in *SI Appendix*, Table S5.

of "opposites attract," in which individuals with dissimilar characteristics mate with one another more frequently than would be expected under random mating (32). Such conflicting findings suggest that demographic variables and personality characteristics may not be robust predictors of marital satisfaction (11, 12). Our analysis confirmed that behavior measures, including personality, are unreliable predictors of marital satisfaction.

In contrast, we found that married couples displayed higher levels of synchronized neural activity than random pairs. Moreover, this effect was specific to marital movies, revealing specificity of our findings with respect to situations involving interpersonal and social communicative cues. Dynamic intersubject synchronization of brain responses to marital movie scenes emerged as strong predictors of marital satisfaction. Multiple analyses confirmed that couples with high levels of marital satisfaction had higher ISS during viewing of marital movie scenes.

In addition to ISS measures at the whole-brain level, our analyses identified specific brain areas that were predictive of marital satisfaction. Marital movie clips evoked high ISS associated with marital satisfaction between couples in the posteromedial and temporoparietal cortex, comprising key nodes of the DMN, as hypothesized. Higher intersubject synchronization in the lateral frontoparietal cortex and language systems were also associated with marital satisfaction. In each of these brain regions, marital—compared to nonmarital—movies evoked higher levels of synchronization in neural response between married couples. This pattern of distributed brain regions suggests that marital movie scenes evoke shared sensory and cognitive processes across multiple levels of the cortical information processing hierarchy.

High levels of ISS observed between couples across distributed brain regions suggest that marital satisfaction is more directly related to similarities in latent cognitive, emotional, and mental states rather than overt behavioral measures, such as personality. The rich, engaging, and dynamic nature of socially relevant movies scenes aligns well with mental processes engaged during day-to-day partner interactions, including communication, sex, attitudes toward relatives, conflict resolution, managing financial disputes, and discussion of shared values (13). Moreover, in contrast to self-reported personality measures, ISS responses during natural viewing of movies confers the benefit of concurrent measurement of the brain activity associated with aspects of mental processing, which might be difficult to explicitly report (33). ISS thus captures a married couple's joint mental processes as they unfold over time and enable quasireal-time

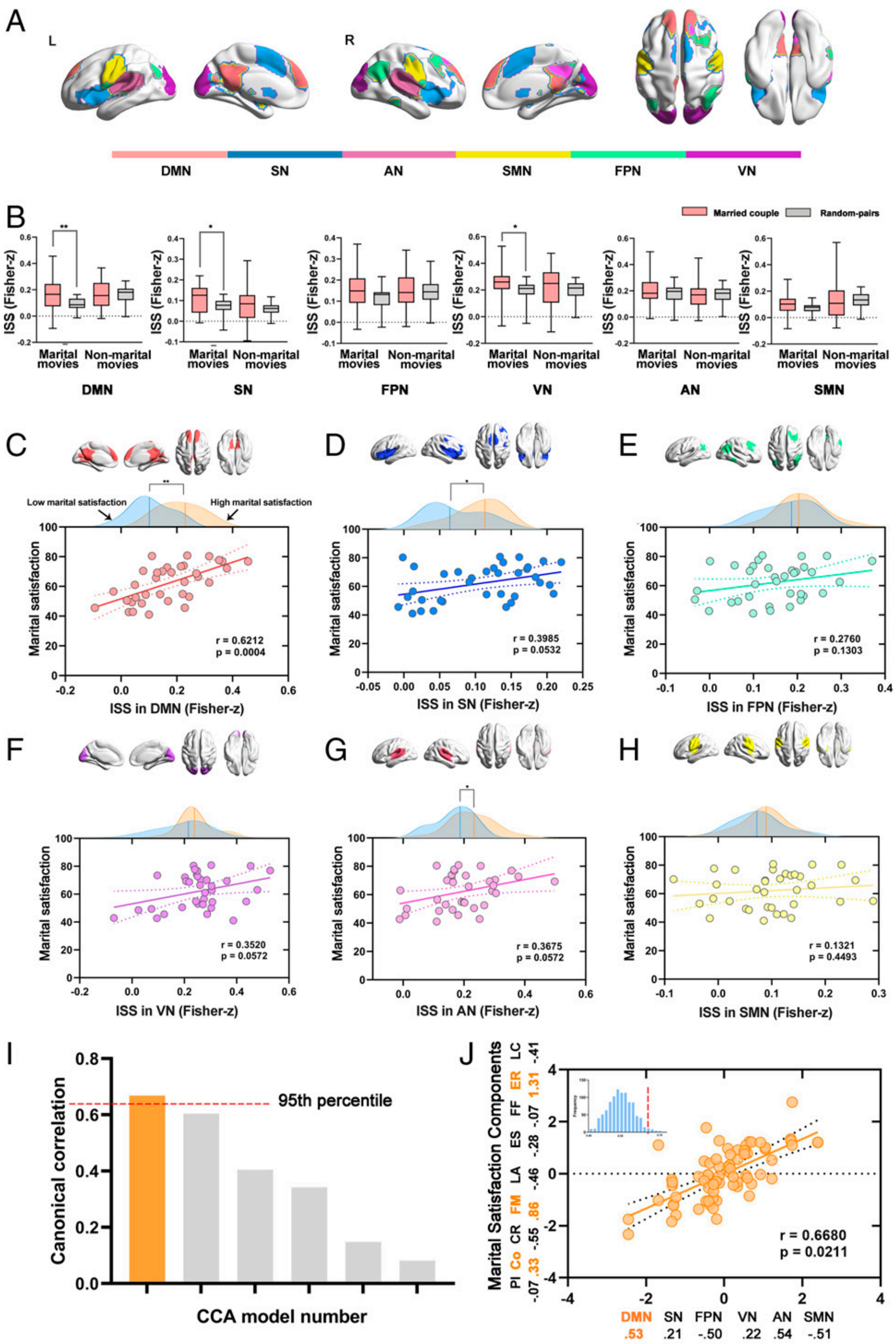

Fig. 5. Relationship between marital satisfaction and network-level ISS. (*A*) Six brain networks, each shown in a different color. (*B*) Group differences in ISS between married couples and random pairs during viewing of marital and nonmarital movie clips. Married couples showed higher ISS compared to random pairs. **P* < 0.05, ***P* < 0.001, FDR-corrected. (*C*–*H*) Relation between network-level ISS during viewing of marital movies and marital satisfaction. Distribution of ISSs in couples with high and low marital satisfaction and group differences are shown on the *Upper* part of the frame. Orange indicates high marital satisfaction, and blue indicates low marital satisfaction. (*I*) Canonical correlations showing modes against the null distribution of the permuted canonical correlations estimated via permutation testing (FDR-corrected, $P < 0.05$). (*J*) Canonical correlation between ISS and marital satisfaction component scores. CCA weights associated with ISS in networks are shown on the *x* axis, and weights associated with marital satisfaction component scores are on the *y* axis (for details, see *Methods*). Variables showing significant contribution to the CCA mode are marked in yellow (Bonferroni-corrected, $P < 0.05$). Co, communication; CR, conflict resolution; ES, emotion and sex; ER, egalitarian roles; FF, family and friends; FM, financial management; LA, leisure activities; LC, life concept; PI, personality issues.

measurements of shared neural processes. Compared with behavioral assays, the fidelity of neural responses assessed by ISS is less likely to be influenced by a couple's attempt to present themselves in a socially desirable manner, which has the potential to distort experimental findings (34). Thus, neural similarity of brain responses may afford more "objective" insights into the similarity of a couple's mental processes as they experience and react to the world around them.

Intersubject Synchronization in the DMN Is Enhanced in Married Couples and Is Associated with Marital Satisfaction. Based on previous findings implicating the DMN in internal mental representations and stimulus-independent thoughts, and its role in anticipation and prediction of communicative cues (13), we next sought to determine whether ISS at the network level is enhanced in married couples. We used a standard brain network parcellation and probed ISS in the DMN in married couples, compared to random pairs, and examined network-level ISS in relation to marital satisfaction. We found that compared with randomly selected pairs of couples, married couples showed a significantly higher network-level ISS in the DMN during viewing of marital movie clips. Furthermore, higher ISS in the DMN between married couples was associated with greater marital satisfaction.

Our analysis further revealed multiple dimensions of marital satisfaction associated with the DMN. Canonical correlation analysis identified a significant relation between the DMN synchronization and shared communication, financial management and egalitarian roles, which constitute key elements of components of marital satisfaction. Efficient and meaningful communication helps couples to share emotional and cognitive information and is an essential component of a happy marriage (35–37). Marital relations also involve a financial partnership, in which couples work together to address financial issues, including income, debt, and assets (38). This requires couples to be open to compromises about management, planning, and use of money (39). Finally, egalitarian roles and shared household responsibilities are now increasingly viewed as essential to martial satisfaction (40). This contrasts with traditional views of marriage, in which women were viewed as responsible for only household matters, such as childcare and domestic work, and were generally submissive to their spouse (41). All three components of marital satisfaction were associated with enhanced shared neural representations in the DMN.

The DMN is consistently activated across tasks that require the integration of self-referential information in the context of interactions with others (42, 43). The DMN is also involved in forming mental representations of others, including their intentions, identity, and affiliation (44). Recent work has also shown that the neural synchronization in the DMN is related to social network proximity, based on assessments of whether individuals are friends, friends-of-friends, or farther removed in social ties (25). Our findings converge on and extend these findings and suggest that DMN synchronization mirrors marital satisfaction based on similar mental representations, reflecting shared values and beliefs, as well as a similar "style" of perceiving the world in situations involving social interactions (45).

A particular strength of our study was the use of naturalistic neuroimaging paradigms involving both socially relevant marital along with nonmarital control stimuli. Additional studies with "social but nonmarital" stimuli will help to clarify whether neural synchrony is driven by marital content specifically or by social communicative cues more generally. Another crucial next step is to investigate the causal link between marital attachment and neural synchronization to better understand what may be driving this relationship. Further studies using longitudinal designs are needed to determine whether higher similarity in neural response during the early stages of mate selection predicts relationship maintenance and long-term outcomes.

Materials and Methods

Participants. A total of 48 Chinese Han couples (96 participants, right-handed, aged 35.97 $\pm$ 6.1 y; heterosexual) were recruited for inclusion in the study from local communities by flyers or internet advertisements. After quality control, 13 couples were excluded and 35 couples were finally retained for subsequent analysis. The couples had been married for at least 1 y (mean = 6.19; SD = 5.25), and marriage was the first for both spouses. Participants had no history of psychiatric or neurological disorders and were willing and eligible to participate in the fMRI study. All of them had normal or corrected normal visual acuity. Written informed consent was obtained from all the participants after fully explaining the purpose and protocols of the study. This study was approved by the Institutional Review Board of the University of Electronic Science and Technology of China and conducted in accordance with the Declaration of Helsinki.

Questionnaires. Participants completed a battery of questionnaires, including the CMQI, Adult Attachment Scale, and Big Five Personality Inventory.

CMQI was based on Olson's Evaluation and Nurturing Relationship Issues, Communication, and Happiness Marital Satisfaction Scale and surveyed 10 domains of marital quality (46), with each domain containing 9 items. Participants rated the extent to which they agreed or disagreed (on a five-point scale) with each item.

1. Personality issues (e.g., "my spouse is very forgiving or accommodating to me") assesses an individual's perception of his or her partner regarding behavioral issues and the level of satisfaction felt on those issues.
2. Communication (e.g., "talking to your spouse is a pleasure") assesses an individual's feeling and attitudes toward communication in his or her relationship. Items focus on the level of comfort felt by the partner in sharing and receiving emotional and cognitive information.
3. Conflict resolution (e.g., "we always try to find the best way to solve conflicts") assesses the partner's perception of the existence and resolution of conflict in the relationship. Items focus on the openness of partners to recognize and resolve issues and strategies used to end arguments.
4. Financial management (e.g., "my spouse and I agree on how to spend our money") assesses the attitudes and concerns about the how economic issues are managed within the relationship. Items focus on assessing spending patterns and the care with which financial decisions are made.
5. Leisure activities (e.g., "my spouse and I enjoy the same kind of social activities") assesses preferences for spending free time. Items reflect social versus personal activities, shared versus individual preferences, and expectations about spending leisure time as a couple.
6. Emotion and sex (e.g., "we often try new ways to enhance sexual pleasure") assesses the partner's feelings about the affectional and sexual relationship. Items reflect attitudes about sexual issues, sexual behavior, and sexual fidelity.
7. Children and marriage (e.g., "children seem to be a major source of conflict in our marriage") assesses attitudes and feelings about having and raising children. Items focus on decisions with regard to discipline, goals for the children, and the impact of children on the couple's relationship.
8. Family and friends (e.g., "I don't feel happy with my relatives") assesses feelings and concerns about relationships with relatives, in-laws, and friends. Items reflect expectations for and comfort with spending time with family and friends.
9. Egalitarian roles (e.g., "I hate my role in the family") assesses an individual's feelings and attitudes about various marital and family roles. Items focus on occupational, household, sex, and parental role. Higher scores indicate a preference for more egalitarian roles.
10. Life concept (e.g., "a shared attitude towards life helps our relationship develop") assesses the meaning of life in the context of the marriage (47).

Personality traits and adult attachment style were assessed using the Big Five Personality Inventory and Adults Attachment Scale. The Big Five Personality Inventory (48) is a 44-item instrument that measures extraversion, openness to experience, conscientiousness, agreeableness, and neuroticism. The Adult Attachment Scale has two subscales: comfort, depending on trust with others, and anxious concern about being abandoned or unloved. Participants were required to respond in terms of their general orientation toward close relationships (49).

Table 3 shows the demographic data and detailed questionnaire results. In accordance with the CMQI scoring rubric, the couples were divided into two groups: couples with high (CMQI total scores > 60) and couples with low marital satisfaction (CMQI total scores < 60). The marital satisfaction score of a couple was obtained by averaging the wife's and husband's marital satisfaction scores.

Table 3. Demographics and personal characteristics of study participants

	High satisfaction (n = 40)	Low satisfaction (n = 30)	t	P
Age	34.43 ± 5.63	37.5 ± 6.57	0.74	0.46
Handedness (right/left/mixed)	40/0/0	30/0/0		
Length of marriage	6.85 ± 5.36	6.27 ± 4.63	0.34	0.74
Marital quality				
Personality issues	33.54 ± 5.06	26.50 ± 4.58	5.39	<0.001
Communication	36.15 ± 3.63	24.25 ± 4.61	8.37	<0.001
Conflict resolution	33.08 ± 3.63	25.75 ± 4.65	6.21	<0.001
Financial management	38.08 ± 3.60	29.25 ± 3.50	7.25	<0.001
Leisure activities	36.92 ± 3.57	33.50 ± 3.55	6.33	<0.001
Emotion and sex	38.08 ± 4.06	31.75 ± 4.08	7.65	<0.001
Children and marriage	38.77 ± 4.08	34.25 ± 5.49	5.16	<0.001
Family and friends	35.08 ± 5.08	28.25 ± 4.14	4.68	<0.001
Equalitarian roles	41.85 ± 4.16	34.00 ± 5.64	7.30	<0.001
Life concept	39.31 ± 4.16	31.50 ± 4.29	8.07	<0.001
Total	73.89 ± 6.01	52.26 ± 9.81	9.52	<0.001
Adult attachment scale				
Anxious	3.50 ± 0.46	3.31 ± 0.44	−1.87	0.07
Close dependence	2.07 ± 0.61	2.50 ± 0.60	0.43	0.67
Personality				
Neuroticism	22.62 ± 7.68	22.25 ± 7.44	−0.33	0.74
Conscientiousness	37.69 ± 7.57	41.50 ± 6.04	−0.04	0.97
Agreeableness	36.00 ± 5.81	36.25 ± 4.93	0.92	0.36
Openness	32.15 ± 6.68	35.25 ± 6.06	−0.20	0.85
Extraversion	30.38 ± 7.29	26.00 ± 6.13	−2.36	0.02

High satisfaction: the total score of CMQI > 60; low satisfaction, the total score of CMQI < 60; n: the number of the groups; t/P: the t/P value was obtained by two-tailed, two-sample t test. Given the inclusion of childless couples (eight couples) in the sample, subscores of "children and marriage" in the Marital Quality Scale were obtained from the average of couples who had at least one child.

Difference score was the absolute value of subtracting a wife's marital satisfaction score from the husband's score. The distribution of marital satisfaction scores and other details are shown in *SI Appendix*, Fig. S7 and Table S3.

fMRI Data Acquisition. Participants were scanned using a 3T GE DISSOVERY MR750 scanner (General Electric) with an eight-channel prototype quadrature birdcage head coil. An echo-planar sequence (30-ms echo time; 2,000-ms repetition time; 3.75 × 3.75 × 3.2-mm resolution; 64 × 64 matrix size; flip angle = 90°; 240 × 240-mm^2 field of view; 43 interleaved transverse slices with no gap; 3.2-mm slice thickness) was used to acquire functional images. The functional data consisted of 708 dynamic scans, with a total functional data acquisition time of ∼23.25 min.

fMRI Paradigm. Before scanning, participants were informed that they would watch a series of movies during scanning. Stimuli and scanning were triggered synchronously to ensure time-point alignment when the experiment started. All movie series were presented to all participants in the same order to avoid inducing intersubject response variability. Before the movie sessions, participants were instructed to remain stationary and pay attention to a crosshair located at the center of the screen for 20 s. After scanning, participants were asked to report whether they had previously watched any of the movie clips used in the current experiment.

fMRI Stimuli. The fMRI stimuli consisted of 12 movie clips presented with sound over the course of the total fMRI runs, with the duration ranging from 55 to 160 s (Table 4). Each movie clip started immediately following the offset of the previous clip. We selected engaging movie clips as stimuli to avoid involving idiosyncratic thoughts unrelated to the experiment. Movie clips were based on professionally directed movies and television shows, which elicit more reliable responses within and across subjects than unedited movie footage or a series of static photographs (13, 20). We used two movie categories: nonmarital movie clips (the first 282 time points; 9.4 min) and marital movie clips (the following 416 time points; 13.86 min). Marital movie clips consisted of scenes involving interpersonal and social communication in situations involving married life, sex, and children, while nonmarital movie clips consisted of documentaries about food, objects, and architecture (Table 4).

fMRI Data Preprocessing. fMRI data were preprocessed using the toolbox of the Data Processing and Analysis of Brain Imaging (v4.3) (rfmri.org/dpabi). In each participant, the first 10 volumes were discarded due to instability of the initial MRI signal. Slice-timing correction and head-motion realignment were performed on the remaining 608 volumes, and 12 couples were excluded with high levels of head motion during scanning (i.e., the head motion of either the husband or wife exceeded 3.0-mm translation or 3° rotation). A total of 36 couples were retained following preprocessing. Brain images for these participants were then spatially normalized to a standard template for Montreal Neurological Institute and resampled to 3 × 3 × 3 mm^3. The normalized images were then linearly detrended to reduce the effects of signal drifts. Nuisance covariates (24 parameters of head motion, white matter signal, cerebrospinal fluid signal, and global signal) were regressed out from the data (50). In addition, we regressed out respiratory and cardiac signals to remove physiological noise (51, 52). One participant was excluded because of missing respiratory and cardiac data; data from 35 couples were retained for subsequent analyses. All images were smoothed with a 6 × 6 × 6-mm^3 full-width at half-maximum Gaussian kernel. Data scrubbing was used to eliminate potential motion artifacts (53). Signal outliers, whose framewise displacement (FD) > 0.5 mm with prior 1 and later 2 volumes, were fitted to the clean portion of the time series by using a third-order spline.

ISS in fMRI Time Series. fMRI time series of each participant were extracted using the Brainnetome atlas, which includes 246 anatomical ROIs (27). Couple-wise correlations of the fMRI time series were computed for each ROI (Fig. 1). In each ROI, ISS was defined as the temporal correlation between the mean fMRI time series of husband and wife, or randomly selected male and female participants, as conducted by Pearson correlation analysis (Fig. 1). Thirty-five random male–female pairs were generated by pairing a male with a randomly selected female (who was not married to the selected male), without repetition. A Fisher's r-to-z transform was applied to convert the correlation coefficient (r) values to normally distributed z scores. Convergent results from reliability analysis using correlation coefficient (r) values are reported in *SI Appendix*, Table S2.

Behavioral Analysis. Multiple linear regression was performed to evaluate the relationship between marital satisfaction and general demographic and behavioral

Table 4. Summary of movie clips shown in the fMRI study

Clips		Description	Duration (s)
Marital movie clips			
1	"Values"	Discussion about a couple who divorced because they desired different lifestyles	122
2	"Resolve conflicts"	A husband humorously resolves conflicts with his wife	123
3	"Character compatible"	Couple quarreling because of their differing personalities	110
4	"Sex and marriage"	Depicts husband who is tired of sex because of a midlife crisis	155
5	"Relatives and friends"	A couple quarreling because they were dissatisfied with each other's parents	160
6	"Child education"	Husband and wife have different views on their children's education	107
Nonmarital movie clips			
1	"Apricot blossom of Yili"	Showcases the beautiful scenery of apricot blossoms in Yili, Xinjiang, China	55
2	"Ancient Chinese characters"	Inscriptions on bones or tortoise shells of the Shang Dynasty	89
3	"Chinese ancient architecture"	Describes the beam structure and roofs of ancient Chinese buildings	83
4	"Reforming the old things"	Creative use of old socks in doll-making	120
5	"Food"	Showcases spicy food in Sichuan, China	40
6	"Scientific discoveries"	Human exploration of Mars	120

measures. Pearson correlations between each individual behavioral characteristic and marital satisfaction were used to depict the strength of relationships.

Differences in ISS between Married vs. Random Couples across Movie Types. A 2×2 ANOVA with brain-wide ISS as the dependent variable was used to determine the effects of movie type (marital movie vs. nonmarital movie), marriage (married couples vs. random pairs), and their interaction. Two-sample *t* tests were performed on the averaged ISS across the whole brain during viewing of marital and nonmarital movies between married couples and random pairs. The significance threshold was set at FDR-corrected $P < 0.05$ for multiple comparisons. Whole-brain ISS measure between married couples was obtained by averaging ISS across all 246 ROIs. Pearson correlation was used to determine the relationship between marital satisfaction and whole-brain ISS during viewing of marital and nonmarital movies. The analysis of covariance (ANCOVA) was used to compare the two correlations by testing the effect of the movie type on the ISS while controlling for the effect of marital satisfaction. Between-group differences (high marital satisfaction vs. low marital satisfaction) in the averaged ISS of neural response during viewing of marital movie clips across the whole brain were assessed by using a two-sample *t* test (two-tailed).

Relation between Region-Wise ISS and Marital Satisfaction. PLS regression was used to determine the relationship between the regional ISS of each of the 246 brain regions between couples and marital satisfaction (54). ISS of all brain regions were used as predictor variables of marital satisfaction in the PLS regression. The first component of the PLS (PLS-1) was the linear combination of ISS across regions that was most strongly correlated with marital satisfaction. Permutation testing (5,000 times) was used to test the null hypothesis that PLS-1 explained no more covariance between ISS and marital satisfaction than that expected by chance (55). Bootstrapping (bootstrap samples = 500) was used to estimate the variability of each regional ISS's weight in PLS-1. The ratio of regional ISS to its bootstrap SE was used to calculate *z* values. Confidence intervals for ISS in each brain region were calculated using *z* values. Brain regions that reliably contributed to PLS-1 were then identified after FDR correction ($P < 0.05$) for multiple comparisons.

Relationship between Marital Satisfaction and Network-Level ISS. Large-scale brain networks were identified using independent component analysis (ICA) as implemented in GIFT (Group ICA of fMRI Toolbox; icatb.sourceforge.net/) (56). fMRI data during viewing both marital and nonmarital movies from all 70 participants (35 married couples) were concatenated and entered in GIFT. "Minimum description length" criterion was used to determine a total number of 56 independent components, and spatial correlation between these components and previously computed templates of typical networks (57) was used to identify six networks of interest–default-mode network, salience network, frontoparietal network, visual network, auditory network, and somato-motor network–in our study participants. We used task–fMRI-derived ICA networks rather than a priori resting-state-fMRI–defined brain network templates to more precisely identify task-relevant brain networks in our study participants.

Between-group differences (married couples vs. random couples) in the network-level ISS were assessed for both marital and nonmarital movies using a two-sample *t* test (two-tailed). The significant threshold was set at FDR-corrected $P < 0.05$ for multiple comparisons. The relation between network-level ISS and marital satisfaction in married couples was determined using Pearson correlation. Between-group differences (high marital satisfaction vs. low marital satisfaction) in network-level ISS were assessed for marital and nonmarital movies using a two-sample *t* test two-tailed).

Relation between Network-Level ISS and Components of Marital Satisfaction. CCA (58) was used to determine the relationship between network-level ISS and nine components of marital satisfaction. Given the inclusion of childless couples in the current study, the "Children and Marriage" domain was excluded in this analysis, resulting in the retention of nine subdomains. We estimated CCA modes (components) that maximized the correlation between network-level ISS and marital satisfaction scores. For each CCA mode, permutation testing was used to test the significance of the corresponding canonical correlation by randomly shuffling the nine components of marital satisfaction across participants. CCA was rerun after each permutation, and the canonical correlation was recalculated. These procedures were repeated 1,000 times to build a null distribution of canonical correlations for comparison with the original canonical correlation. The *P* values of each CCA dimension were corrected for multiple testing across the estimated CCA modes (FDR-corrected, $P < 0.05$). To infer the contribution of the original variables to the corresponding CCA models, we computed Pearson's correlation between each original brain network variable and corresponding canonical variable, as well as Pearson's correlation between each original marital satisfaction variable and corresponding canonical variable of the marital satisfaction. The significant threshold was set at Bonferroni-corrected $P < 0.05$ for multiple comparisons (*SI Appendix*, Fig. S8).

Data, Materials, and Software Availability. Anonymized fMRI, demographic and behavioral data and code used for analyses have been deposited in a Zenodo under "Zenodo-Lilei-Neural synchronization," 10.5281/zenodo.6069677 (https://zenodo.org/record/6614433#.Ypw0BupBxPY) (59). Movie clips have been deposited in Zenodo (https://zenodo.org/record/6960421#.YusvSepBxPY).

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