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Original Article

Interpersonal conflict increases interpersonal neural synchronization in romantic couples

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Previous studies on dual-brain social interaction have shown different patterns of interpersonal neural synchronization (INS) between conflictual and supportive interactions, but the role of emotion in the dual-brain mechanisms of such interactions is not well understood. Furthermore, little is known about how the dual-brain mechanisms are affected by relationship type (e.g., romantic relationship vs. friendship) and interaction mode (e.g., verbal vs. nonverbal). To elaborate on these issues, this study used functional near-infrared spectroscopy to collect hemodynamic signals from romantic couples and cross-sex friends while they were discussing conflictual, neutral, or supportive topics. For the couples but not the friends, INS between the sensorimotor cortex of both participants was greater when discussing the conflictual topic than when discussing the supportive topic. INS was positively correlated with the arousal level but not the valence level of communication contents. INS was also positively correlated with interpersonal physiological synchronization based on galvanic skin response, a physiological measure of arousal. Furthermore, the differences in INS between the conflictual and supportive topics were closely associated with verbal rather than nonverbal behaviors. Together, these findings suggest that it is the arousal level induced by verbal interactions during interpersonal conflicts that increases romantic couples' INS.

Key words: arousal; functional near-infrared spectroscopy; interpersonal conflict; interpersonal neural synchronization; romantic relationship.

Introduction

Human beings are social animals involved in complex social interactions. Extensive social psychological research has examined their social and cognitive mechanisms (Snyder and Stukas 1999; Colman 2003; Dunlap et al. 2013; Hamilton 2015). With the advent of the hyperscanning technique (Montague et al. 2002), cognitive neuroscientists have begun to investigate the dual-brain neurocognitive mechanisms involved in social interactions (Redcay and Schilbach 2019). These studies have found that interpersonal neural synchronization (INS) is a key measure of the quality of social interactions (Jiang et al. 2021). For example, INS is increased when interacting individuals are behaviorally synchronized (e.g., key pressing, playing) (Cui et al. 2012; Sanger et al. 2012), when quality of interactions is improved (e.g., selective attention to the target speaker, mutual understanding, emergence of shared concepts or knowledge) (Jiang et al. 2012; Stolk et al. 2013; Dai et al. 2018; Zheng et al. 2018), or when social affiliation is built (e.g., between teachers and students or between leaders and followers) (Jiang et al. 2015; Zheng et al. 2020). Most of these studies, however, have involved interactions that are typically emotionally neutral and hence have not examined the role of emotion in the dual-brain mechanisms involved in naturalistic social interactions.

Thus far, seven hyperscanning or pseudo-hyperscanning studies have used emotion-eliciting situations. On the one hand, previous findings suggest that emotional valence, particularly positive emotion, can increase the strength of INS. Specifically, two early studies found that naturalistic communication was associated with higher EEG gamma-band synchrony during the moments with positive emotion than during the emotionally neutral moments (Kinreich et al. 2017; Fachner et al. 2019). Three recent studies compared positive and negative emotions, showing that compared to negative emotion, positive emotion was associated with greater INS of the alpha-band EEG signal in the temporoparietal junction (TPJ), or greater theta and beta-band EEG signal and greater INS of the hemodynamic activity in the left frontal cortex (Balconi and Fronda 2020; Santamaria et al. 2020; Balconi et al. 2021). On the other hand, however, other findings indicate that negative valence of emotion can also increase INS, and emotional arousal also plays a role in the neural response to social interaction. For example,

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one study showed that negative emotion (induced by emotional stimuli of higher arousal but lower valence) led to higher intensity of drumming response, which was further associated with greater local hemodynamic activity in the TPJ of the receiver of a communication signal (Rojiani et al. 2018). More importantly, another study showed that the alignment of the listener's brain activity with that of the speaker in the primary sensorimotor cortex (SMC) was more closely associated with the synchrony of arousal levels between the listener and the speaker, whereas the neural alignment involving the left premotor cortex and bilateral TPJ was more closely associated with the synchrony of their valence levels (Smirnov et al. 2019). Taken together, these results seem inconsistent across studies regarding the role of emotion in INS. One possible reason is that previous hyperscanning studies on naturalistic social interactions did not simultaneously consider different aspects of emotion (e.g., valence, arousal) together with other important factors such as the type of relationships (e.g., strangers, friends, romantic partners) and the mode of social interaction (verbal, nonverbal).

The type of relationship between the interacting dyads is an important factor, because relationship type may impact how individuals interact with one another in a top-down manner, as articulated by a recent framework of neural mechanisms involved in social interaction (Jiang et al. 2021). Although most previous hyperscanning studies relied on interactions between strangers, recent hyperscanning studies on romantic couples have found greater INS when expressing emotions (Anders et al. 2011), kissing the partner's hand (Muller and Lindenberger 2014), mutual gazing (Kinreich et al. 2017), or touching (Goldstein et al. 2018) as compared to situations without such interactions. More importantly, compared to friends or strangers, romantic couples showed greater INS either when partners were touching each other (Long et al. 2021) or when they were cooperating on a key-pressing task (Pan et al. 2017). However, it is not well understood how relationship type would modulate the role of emotion in INS.

In terms of the mode of social interactions, a major distinction is between verbal and nonverbal behaviors. Verbal behaviors are more precise in communicating intention, whereas nonverbal behaviors are more vital in transmitting social and emotional information that is difficult to express in words (Levelt 1999; Field 2014). Previous hyperscanning studies on emotional interactions, however, did not differentiate verbal and nonverbal behaviors (Kinreich et al. 2017) or focused only on nonverbal behaviors (Rojiani et al. 2018; Balconi and Fronda 2020; Santamaria et al. 2020; Balconi et al. 2021) or verbal behaviors (Smirnov et al. 2019). Studies of nonverbal behaviors revealed greater INS or higher single-brain activity for positive emotion than negative emotion (Balconi and Fronda 2020; Santamaria et al. 2020; Balconi et al. 2021), whereas the study on verbal behaviors revealed different patterns of INS for emotional valence and arousal (Smirnov et al. 2019). Thus, it remains unknown how the mode of interaction (i.e., verbal vs. nonverbal behaviors) would modulate the effect of emotion on INS during social interaction.

In the present study, we examined how emotion-eliciting situations (supportive, conflictual, and neutral) would be associated with INS between romantic couples as compared to opposite-sex friends, which dimension of emotion (valence vs. arousal) would be most relevant, and whether the mode of communications (verbal vs. nonverbal) and the type of relationship (romantic couples vs. friends) would matter.

Materials and Methods

Participants

Twenty-two pairs of romantically involved heterosexual couples and 22 pairs of close opposite-sex friends were recruited through advertising in universities in Beijing. The self-reported relationship type was confirmed using the Sternberg's Triangular Love Scale (see Supplementary Materials). According to their self-reports, there were no significant differences between couples and friends either in how long they had known each other ($t(42) = -0.438$, $P = 0.664$) or how long they have been in romantic relationship or best friendship ($t(42) = 0.300$, $P = 0.765$). Also, no significant differences were found between couples and friends in age (men, $t(42) = 1.965$, $P = 0.056$; women, $t(42) = 1.56$, $P = 0.127$). Nevertheless, these variables were controlled for all subsequent analyses to avoid potential confounding effects.

Written informed consent was received from all participants. The study protocol was approved by the Institutional Review Board of the State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University.

Assessment of the Strength of Romantic Love

Romantic couples were asked to complete the Friendship-Based Love (FBL) scale, Passionate Love Scale (PLS), and Compassionate Love Scale (CLS), which measure different aspects of love (Berscheid 2010). FBL measures "a comfortable, affectionate, trusting love for a likable partner, based on a deep sense of friendship and involving companionship and the enjoyment of common activities, mutual interests, and shared laughter" (Grote and Frieze 1994). PLS measures "intense, overwhelming, passionate, consuming, exciting and confusing" aspects of romantic relationships (Hatfield and Sprecher 1986). CLS measures "feelings, cognitions, and behaviors that are focused on caring, concern, tenderness, and an orientation toward supporting, helping, and understanding" (Sprecher and Fehr 2016). All these scales had high inter-item reliability in this study (Cronbach's $\alpha > 0.700$).

Tasks and Procedures

During the experiment, participants sat face-to-face. An initial resting-state session of 5 min served as

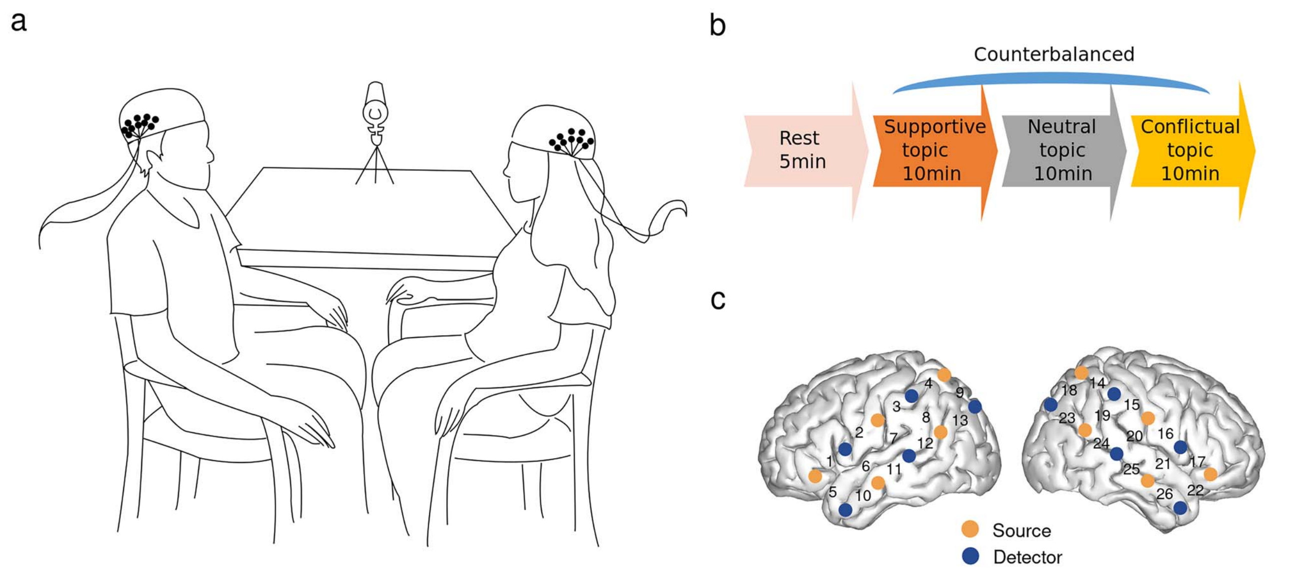

Fig. 1. The setup of the experiment. (*a*) During the experiment, the two participants sat face-to-face. Time-aligned fNIRS and GSR data, as well as video recordings of the experimental procedures, were collected for each pair of participants simultaneously. (*b*) Experimental procedures. (*c*) The optode probe set was placed on the bilateral frontal, temporal, and parietal cortices. CH11 was placed just at T3, and CH25 was placed at T4 in accordance with the international 10-20 system.

the baseline. Then, three interaction sessions were conducted. The participants were first asked to finish a 5-min mutual gaze session, and a 5-min touch session, which was reported elsewhere (Long et al. 2021). Then pairs of participants freely interacted with each other on three different topics: supportive, conflictual, or neutral (Fig. 1*a*,*b*, and Supplementary Materials). The participants were told to discuss each topic for 10 min. Then, the experimenter left the room to provide a private situation for the participants. Ten minutes later, the experimenter returned to the laboratory and interrupted their discussion. The sequence of three topics was counterbalanced across the participant pairs (see Supplementary Materials). For each interaction, two additional 15-s silence intervals were inserted both at the beginning and ending phases of the task to allow the functional near-infrared spectroscopy (fNIRS) instrument to reach a steady state. The entire experimental procedure was video recorded, with permission from participants.

Assessment of the Valence and Arousal Levels Induced by Each Topic

To assess the valence and arousal levels of the communication contents for each topic, the natural language processing (NLP) method was used to analyze the transcribed text of each participant. Specifically, for each participant's topic-related communication text, a "Jieba Chinese Text Segmentation" tool was used to segment the connected text into single words (Sun 2020). Then, sentiment words were extracted from these segmented words according to the lexicon of Chinese Valence-Arousal Words (CVAW) (Yu et al. 2016). Based on the CVAW, the valence and arousal levels of extracted words were obtained and averaged across words, generating communication content-related valence and arousal levels for each participant.

Because the scores of the valence and arousal levels for words in CVAW were annotated by five annotators based on 2009 sentences extracted from web texts, we had a concern that the contextual differences between the extracted sentences in CVAW and the communication contents in the present study may affect the validity of the assessments. Therefore, we recruited five additional raters who did not know our experiment to assess the valence and arousal levels of each participant's communication content. The levels were rated on a 5-point pictorial scale (1 = lowest level, 5 = highest level) (Bradley and Lang 1994). The inter-rater reliability was high (Cronbach's alpha ranged from 0.715 to 0.843 for different topics). Finally, in order to balance the effects of the context of communication, we combined the two sets of indices for subsequent analyses.

Galvanic Skin Response Data Acquisition and Analyses

BIOPAC MP150 with GSR100C at a sampling rate of 1000 Hz was used to collect the galvanic skin response (GSR) data. Two electrodes were placed on the left middle and ring fingers, facing the volar surface on the distal phalange. Out of the 22 pairs each of romantic couples and friends, 16 pairs of romantic couples and 15 pairs of friends yielded valid GSR data based on a visual check. The deleted cases had obvious noises, which were mainly spikes that seemed to have resulted from motion artifacts or poor contacts between the electrodes and skin, rather than a lack of phasic activity. These valid data were then preprocessed using a band-pass filter, with a low cut-off of 0.2 Hz to split the phasic component of the electrodermal activity from the tonic one and a high cutoff of 1 Hz to filter out noises and to suppress artifacts (Vecchiato et al. 2010). Next, to obtain IPS in GSR for each pair of participants, Pearson correlations were calculated between the man's and the woman's GSR signals across time for each pair of participants in each topic, and the coefficients were used to index the pair's IPS. Before group-level statistical tests, the missing data of IPS (i.e., the Pearson coefficients of dyads) for the six pairs of couples and seven pairs of friends were replaced by group means of IPS for each topic and relationship type.

Next, the relationship between IPS and arousal or valence level was examined. In order to correlate the dyadic IPS with the dyads' emotions, we averaged the pairs' scores of valence or arousal levels to create dyadic indices. Because our main aim was to examine differences between types of topics in their IPS and emotion correlates, we used difference scores by subtracting the IPS and valence and arousal levels for the supportive topic from those for the conflictual topic. Finally, Pearson correlations were calculated between the sets of difference scores.

Coding and Analyzing of Interaction Behaviors

Due to technical issues, we failed to capture, in video, a set of interactions from one couple and a set of interactions from two pairs of friends, leaving complete data for 21 pairs of couples and 20 pairs of friends. Missing behavioral data (e.g., duration of verbal and nonverbal behaviors) of each participant and INS data of each pair were replaced by group means within each topic during statistical analyses.

Verbal and nonverbal behaviors were coded based on the video recordings. For verbal behaviors, the speech of each participant during the interaction was transcribed into text. The transcription was carefully inspected character-by-character by an experimenter (Y. L.) to ensure 100% accuracy. Verbal behaviors were marked. For nonverbal behaviors (i.e., laughter, smiles, nods, and gestures), two additional coders who were not involved in the experiment were recruited. Inter-coder reliability was computed as intraclass correlation coefficients (ICC) at the time-point level for each pair of participants. The ICC ranged from 0.740 to 0.940, indicating good reliability. Finally, the overlapping portions of verbal and nonverbal behaviors for each participant were removed to obtain clean data. For time points on which coders initially did not agree with each other, the two coders would discuss to reach a consensus.

Based on the video coding, we obtained the durations of verbal and nonverbal behaviors. Then, relationship × topic × gender × mode (verbal, nonverbal) mixed-model Analyses of Covariance (ANCOVAs) were conducted on the duration of verbal and nonverbal behaviors.

Next, to further test the behavioral pattern of interactions, interactions were separated into those initiated by women and those initiated by men. There was no such case that both the woman and the man initiated a conversation at the same time. Conversation initiation and response were considered as different behaviors (Ninio and Snow 1996). Relationship × topic × gender mixed-model ANCOVAs were performed on the durations of men-initiated verbal behaviors and women-initiated verbal behaviors.

Finally, the time intervals between the time point when women initiated verbal behaviors and the time point when men responded to women's verbal behaviors were calculated. A quadratic equation was used to fit the curve of the response interval. Additionally, relationship × topic ANCOVAs on men's verbal response intervals in women-initiated interactions were conducted.

fNIRS Data Acquisition

An optical topography system (LABNIRS, Shimadzu Corporation, Japan) was used to collect fNIRS data. Two sets of customized optode probes were placed bilaterally to cover frontal, temporal, and parietal cortices. Each probe set consisted of 13 measurement channels (five emitters and five detectors, CH). CH11 was placed just at T3, and CH25 was placed at T4 in accordance with the international 10-20 system. The probe sets were examined to ensure the consistency of the positions among participants. To confirm the anatomical position of each optode, magnetic resonance imaging was obtained using a SIEMENS TRIO 3-Tesla scanner from a typical participant with a high-resolution T1-weighted magnetization-prepared rapid gradient-echo sequence (time repetition = 2530 ms; time echo = 3.39 ms; flip angle = 7°; slice thickness = 1.3 mm; voxel size = 1.3 × 1 × 1.3 mm). SPM8 (Statistical Parametric Mapping, Wellcome Department of Cognitive Neurology, London, UK) was used to normalize the image to standard Montreal Neurological Institute coordinate space. An Automated Anatomical Labeling template (Tzourio-Mazoyer et al. 2002) was used to determine the corresponding brain areas below the optodes (Fig. 1c).

The absorption of near-infrared light at three wavelengths (780, 805, and 830 nm) was measured at a sampling rate of 55.6 Hz. Based on the modified Beer–Lambert law, the changes in the oxyhemoglobin (HbO) and deoxyhemoglobin concentrations (HbR) were obtained for each channel. Because previous studies showed that HbO was the most sensitive indicator of changes in the regional cerebral blood flow and had the highest signal-to-noise ratio in fNIRS measurements (Hoshi 2007), this study mainly focused on the changes in the HbO concentration.

fNIRS Data Analysis

Preprocessing

During preprocessing, the first and last 15-s data in each task were removed to obtain data within the period of steady state. Then, the data were downsampled to 11 Hz to reduce the computing times. Functions in Homer3 (Huppert et al. 2009) were used to preprocess the data. Specifically, a discrete wavelet transformation filter was conducted to detect and correct motion artifacts (Molavi and Dumont 2012). Next, principal component analysis was used to remove global physiological noises such as the skin blood flow (Zhang et al. 2005). The threshold of variance to be removed was set at a conservative level of 80%. Finally, following previous studies (Tong et al. 2011), data above 0.8 Hz were excluded to avoid aliasing of high-frequency physiological noise such as cardiac activity (~0.8 to 2.5 Hz); data below 0.01 Hz were excluded to remove very low-frequency fluctuations; and finally, data within 0.15–0.3 Hz were also excluded to avoid the effect of respiratory activity (~0.15 to 0.3 Hz).

Pair-Level Analysis

To assess INS between the two fNIRS time series (one for each participant) within a pair, a MATLAB function "wcoherence" was used to perform wavelet transform coherence (Grinsted et al. 2004) as a function of frequency and time (Torrence and Compo 1998). The result was a 2D matrix of the coherence values, where the column and row corresponded to a specific frequency and time point, respectively. All possible CH combinations between the two participants of a pair were examined (i.e., 26 × 26 = 676 in total). In addition, previous studies have indicated that INS usually involves a time lag, probably due to the social prediction of the upcoming information or a delayed shared representation (Jiang et al. 2021). To incorporate this effect, the coherence value was calculated by shifting the time course of men forward or backward relative to that of women from 2 to 12 s (step = 2 s) as well as when no time lag was added (i.e., the two series were temporally aligned). Finally, the coherence values were converted into Fisher z-values and time-averaged across the task period. These procedures were conducted for all tasks.

Next, the coherence value from the resting state was subtracted from that of interaction tasks, resulting in an index of INS increase. The following statistical tests were conducted on INS increase.

Group-Level Statistics

To determine the CH combination(s) and frequency band of interest that were associated with the effects of topic type and relationship type, relationship × topic ANCOVAs were performed on INS increase across all CH combinations for each time lag (ranging from 0 to ±12 s, Fig. 2, Step 1). A cluster-based permutation approach was conducted to correct for multiple comparisons (Maris and Oostenveld 2007; Liu et al. 2019; Zheng et al. 2020; Long et al. 2021). First, for each time lag, participants were randomly selected to form new pairs (i.e., pairs of participants who had been in the same communication topic and the same group but had not interacted with each other), and the new pairs' INS increase was computed. Second, the INS increases were analyzed using relationship × topic ANCOVAs to identify nominally significant ($P < 0.05$) results. Third, clusters of significant INS increases in each time series were identified and the longest cluster was then averaged and reanalyzed using ANCOVA to generate a single *F*-value. The clusters were formed along with the frequency but not the CH combinations to avoid potential confounding of global physiological noise. Fourth, this procedure was repeated 1000 times to generate a distribution of cluster-based *F*-values. Finally, for each time lag, the original pairs' *F*-values were compared with the distribution of 1000 permutations and their *P* values were determined (cluster-based threshold, $P < 0.05$). Clusters that survived the threshold were selected as the CH combination(s) and frequency bands of interest, and INS increases at the specific CH combination(s) within the frequency bands were averaged for further analyses. The uncorrected *P*-values that survived the correction were reported.

The Association between INS Increase and Emotion

To examine the valence and arousal levels of each topic, a linear mixed model analysis was conducted on scores of the valence and arousal levels (based on the averaged scores from the NLP method and the independent raters' ratings) in the couples and the friends separately. In the model, the effects of gender, topic, and gender × topic were treated as fixed effects, the pair identity of each participant was treated as a random effect, while age, acquaintance length, and relationship length were treated as covariates.

To confirm the association between INS increase and emotion, the topic differences (the conflictual topic minus the supportive topic) in INS were correlated with those in IPS and in valence or arousal levels.

Interaction Mode and Emotion-Related INS Increase

To investigate the role of interaction mode (verbal vs. nonverbal behavior) in INS increase, the first step was to mark the time points corresponding with behaviors of interest (i.e., verbal/nonverbal behaviors, men/women-initiated interaction, and men's verbal responses during women-initiated interaction). Second, the time courses of INS at the significant CH combinations and time lags were downsampled to 1 Hz to obtain point-to-frame correspondence between the signal's time course and video recordings. Third, the INS data were adjusted for the delay-to-peak effect in the fNIRS signal (about 5 s). Fourth, we selected random lengths of INS during resting state to match durations of verbal and nonverbal behaviors. Fifth, the INS data corresponding to verbal and nonverbal behaviors and resting-state were separately time-averaged, while the durations of resting-state and each behavior were regressed out to obtain the residuals of INS increase to exclude the potential impact of duration on the behavior-related INS. Sixth, the residuals of INS of resting state were subtracted from those of specific interaction behavior, resulting in the behaviorally relevant INS increase, which was used for the following analyses. Finally, relationship × topic × mode (verbal and

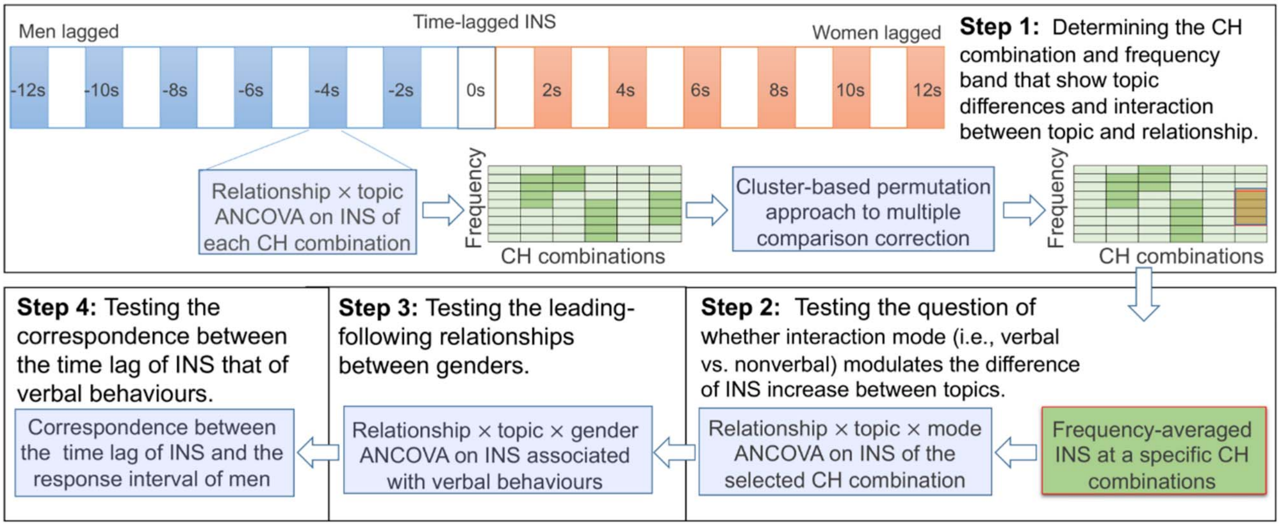

Fig. 2. The overall procedure of data analyses on INS increase.

nonverbal) ANCOVAs on selected CH combinations were performed to investigate whether couples and friends showed different INS increases for verbal and nonverbal behaviors (Fig. 2, Step 2).

A Leading-Following Relationship between Genders in Both INS and Interaction Behaviors

To test whether INS increase identified above was associated with a particular leading-following pattern, INS increase that corresponded to women-initiated verbal behaviors (time lag = 4 s) and that corresponded to men-initiated verbal behaviors (time lag = 4 s) were extracted and averaged across time points within each type of verbal behaviors. Then, a relationship × topic × gender mixed-model ANCOVA was conducted on the extracted INS increase, while the durations of women-initiated and men-initiated verbal behaviors were regressed out (Fig. 2, Step 3).

Next, to see the correspondence between the time lag of INS and that of men's verbal response, we marked individuals' verbal responses during their partner-initiated interaction. Then, INS increase that corresponded to different time intervals of the partner's response (ranging from 1 to 8 s) were extracted and separately averaged. The averaged INS increase for the supportive topic was subtracted from that for the conflictual topic. Finally, one-way ANCOVA was conducted to compare romantic couples and friends in terms of their topic difference in INS increase (Fig. 2, Step 4).

The Association between INS Increase and the Strength of Romantic Love

To examine the relationship between INS increase and the strength of romantic love, the difference between the conflictual and supportive topics in INS increase was correlated with the strength of romantic love of both men and women among couples, as measured by the FBL scale, PLS, and CLS (Berscheid 2010).

Code Availability

All analyses were performed using Matlab R2019b, with standard functions and toolboxes. All codes are available upon request.

Data Availability

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

Results

Interpersonal Conflict Was Associated with Greater INS Increase than Was Interpersonal Support in Romantic Couples

The results of the Step 1 analysis (Fig. 2) showed a significant interaction between relationship and topic at the SMC (CH20) of both women and men when the brain activity of men lagged behind that of women by 2–8 s ($SMC_{women} \rightarrow SMC_{men}$, Fig. 3*a*,*b*). The effect was found within the frequency range of 0.04–0.09 Hz and peaked when the brain activity of men lagged behind that of women by 4 s ($F(2, 76) = 13.147$, $P < 0.001$, $\eta^2 = 0.257$,Fig. 3*c*,*e*). No significant interaction between relationship and topic was found at this frequency range of any other CH combinations, nor were there significant interaction effects at any other frequency ranges of any other CH combinations ($Ps > 0.05$). Hereafter, the INS increase of the $SMC_{women} \rightarrow SMC_{men}$ at the women-led 4-s time lag was averaged within 0.04–0.09 Hz and used as an index of INS increase for all subsequent analyses. The results of main effects for relationship and topic were reported in the Supplementary Materials.

Further pair-wise comparisons on the relationship × topic interaction on women-led time-lag INS at the $SMC_{women} \rightarrow SMC_{men}$ showed that romantic couples had a greater INS increase when discussing the conflictual topic than the supportive topic (Mean Difference (MD) =

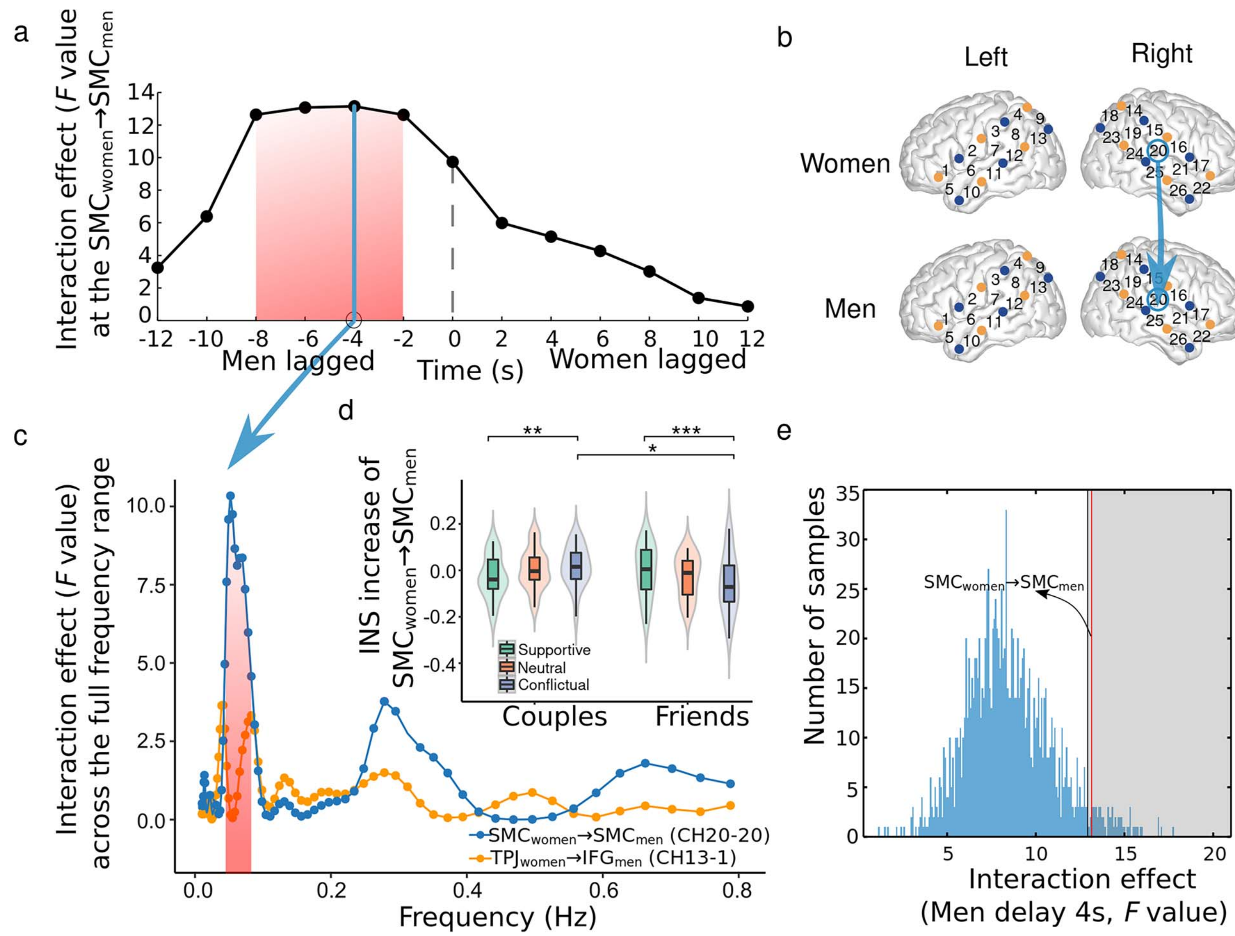

Fig. 3. The relationship × topic mixed-model ANCOVA results. (*a*) Significant interaction effects were found at the $SMC_{women} \rightarrow SMC_{men}$ when men's brain activity lagged behind that of women by 2–8 s. (*b*) The anatomical positions of the $SMC_{women} \rightarrow SMC_{men}$. (*c*) The *F* value of the interaction effect at the $SMC_{women} \rightarrow SMC_{men}$ across the frequency range (0.01–0.8 Hz) when men's brain activity lagged behind that of women by 4 s (blue). The frequency range of 0.04–0.09 Hz was highlighted. A control CH combination at the TPJ_{women}-IFC_{men} (CH13-1) is shown as a comparison (yellow). (*d*) INS increase at the $SMC_{women} \rightarrow SMC_{men}$ with a time-lag of 4 s (men lagged) for couples and friends. (*e*) The results of the permutation test. The effect of the $SMC_{women} \rightarrow SMC_{men}$ (red line) in the original pairs was significant at the 5% chance level (gray color). The *x*-axis represents the *F* value, and the *y*-axis represents the number of samples.

0.050, Standard Error (SE) = 0.014, $P = 0.001$), whereas the friends had a significantly greater INS increase when discussing the supportive topic than the conflictual topic (MD = 0.059, SE = 0.014, $P < 0.001$). No significant difference was found either between the conflictual topic and the neutral topic or between the supportive topic and the neutral topic, either in romantic couples or in friends ($Ps > 0.05$). Analyzed by topic, the INS increase was significantly greater among romantic couples than among friends when discussing the conflictual topic (MD = 0.076, SE = 0.036, $P = 0.040$), but it did not differ between romantic couples and friends when discussing either the neutral or the supportive topic ($Ps > 0.05$). These results suggest that the topic type impacts the pattern of INS, but the size of the effect depends on relationship type.

To further validate the direction of the time lag, a paired two-sample *t*-test was conducted between the topic difference in INS when men's brain activity lagged behind that of women by 4 s and the topic difference when women's brain activity lagged behind that of men by 4 s in couples. The results showed a larger topic difference in INS when men's brain activity lagged behind that of women by 4 s than when women's brain activity lagged behind that of men by 4 s (MD = 0.028, SE = 0.105, $t = 2.664$, $P = 0.015$).

The Association between INS Increase and Emotion

First, we tested potential differences between the three topics in terms of their valence and arousal levels using a linear mixed model. For the valence level, the couples did not show any significant difference among topics. The results of the friends showed a significant main effect of topic ($F(2,104.1) = 10.986$, $P < 0.001$, Fig. 4*a*), with more positive valence for the conflictual topic than for the supportive (MD = 0.538, SE = 0.118, $P < 0.001$) and neutral (MD = 0.382, SE = 0.118, $P < 0.001$) topics, but no difference was found between the latter two types of topics (MD = 0.156, SE = 0.118, $P = 0.189$). No other significant effects were found ($Ps > 0.05$).

For the arousal level, the couples showed a significant main effect of topic ($F(2,104.8) = 5.176$, $P = 0.007$, Fig. 4*b*),

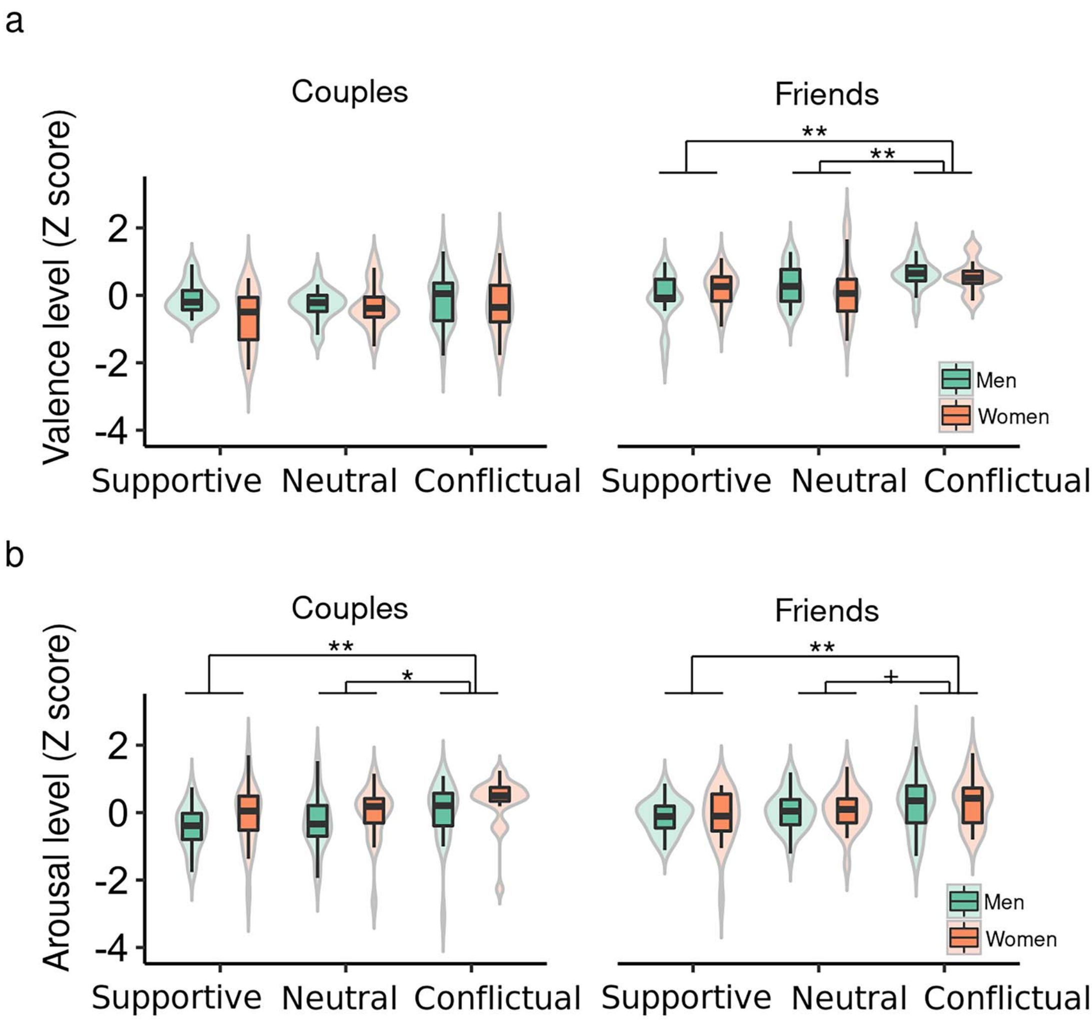

Fig. 4. Valence and arousal levels by the type of topics. (*a*) Valence. No topic differences in the valence level were found for the couples. Friends showed more positive valence for the conflictual topic than for the supportive and neutral topics. (*b*) Arousal. Both couples and friends showed higher arousal levels for the conflictual topic than for the supportive and neutral topics. +, $P < 0.1$; *, $P < 0.05$; **, $P < 0.01$.

with a higher level of arousal for the conflictual topic than for the supportive (MD = 0.450, SE = 0.145, $P = 0.003$) and neutral (MD = 0.336, SE = 0.145, $P = 0.023$) topics. No significant difference was found between the neutral and supportive topics (MD = 0.113, SE = 0.145, $P = 0.438$). The main effect of gender was also significant, with a higher arousal level for women than for men ($F(1,114.0) = 4.926$, $P = 0.028$). The interaction between gender and topic was not significant ($F(2,104.8) = 0.065$, $P = 0.937$).

Similar to the couples, the friends also showed a significant main effect of topic ($F(2,103.9) = 5.369$, $P = 0.006$, Fig. 4*b*), with a higher level of arousal for the conflictual topic than for the supportive topic (MD = 0.430, SE = 0.131, $P = 0.001$) and a marginally higher arousal level for the conflictual topic than for the neutral topic (MD = 0.235, SE = 0.131, $P = 0.077$). Again, no significant difference was found between the neutral and supportive topics (MD = 0.195, SE = 0.131, $P = 0.140$). No significant effects of gender and gender-by-topic interaction were found (Ps > 0.05). Together, these results indicated that interpersonal conflict induced a higher arousal level than did interpersonal support and the neutral topic both in romantic couples and friends.

Next, to test the relationship between INS and emotional valence and arousal, Pearson correlation was performed. The results showed a significant correlation between topic difference in INS and that in IPS ($r = 0.678$, $P = 0.001$, Fig. 5*a*) and a marginally significant correlation between topic difference in INS and that in arousal level ($r = 0.421$, $P = 0.051$, Fig. 5*b*). No significant correlation was found between topic difference in INS and that in valence level ($r = -0.014$, $P = 0.951$). Additionally, arousal level was marginally correlated with IPS ($r = 0.421$, $P = 0.051$, Fig. 5*c*), but valence level was not ($r = -0.215$, $P = 0.336$). These results indicated arousal, but not valence, was associated with INS.

The Mode of Interaction and INS Increase

Preliminary analyses of the durations of verbal and nonverbal behaviors are provided in the Supplementary Materials. The association between INS increase and interaction behaviors was investigated (Fig. 2, Step 2). The

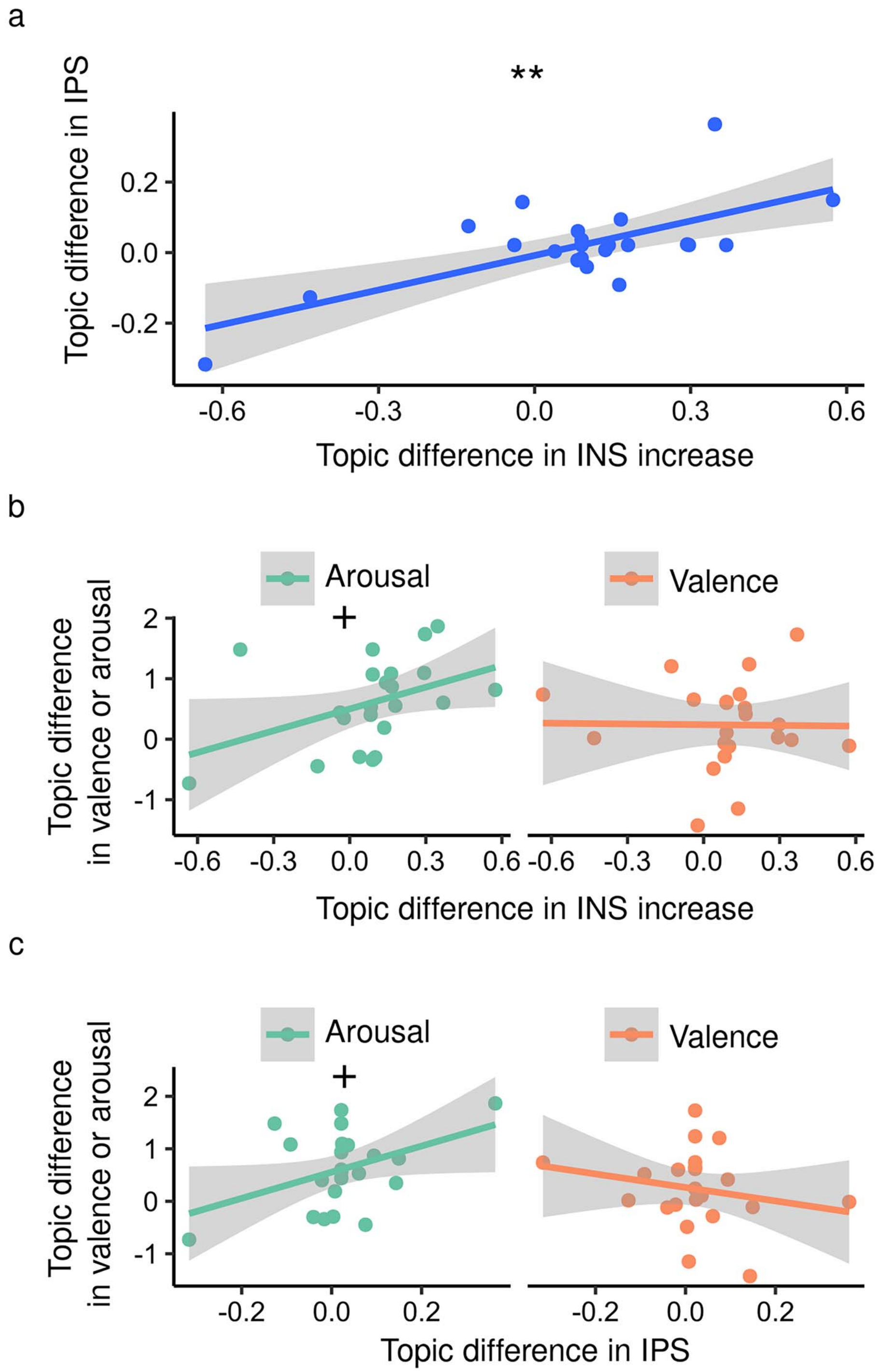

Fig. 5. Correlation results. (*a*) Correlation between topic differences in INS increase and IPS. (*b*) Correlation between topic differences in INS increase and valence and arousal levels. (*c*) Correlation between topic differences in IPS and valence and arousal levels. +, $P < 0.1$; **, $P < 0.01$.

results showed a significant main effect of relationship ($F(1, 38) = 5.297$, $P = 0.027$, $\eta^2 = 0.122$), a significant two-way interaction between relationship and topic ($F(2, 76) = 6.976$, $P = 0.002$, $\eta^2 = 0.155$), and a significant three-way interaction between mode, topic, and relationship ($F(2, 76) = 5.412$, $P = 0.006$, $\eta^2 = 0.125$). Further pair-wise comparisons on the three-way interaction showed that for verbal behaviors, romantic couples had greater INS increase when discussing the conflictual (MD = 0.024, SE = 0.01, $P = 0.024$) and neutral (MD = 0.025, SE = 0.008, $P = 0.003$) topics than when discussing the supportive topic. The opposite pattern was found for friends; that is, there was lower INS increase when discussing the conflictual topic (MD = 0.031, SE = 0.010, $P = 0.005$) and neutral topic (MD = 0.031, SE = 0.008, $P < 0.001$) than when discussing the supportive topic. During nonverbal behaviors, however, no significant differences were found among the three topics in romantic couples. For friends, discussing the conflictual topic was associated with lower INS increase than did discussing the neutral (MD = 0.068, SE = 0.024, $P = 0.008$) and supportive (MD = 0.064, SE = 0.023, $P = 0.008$) topics. These findings indicated that the emotional valence-related INS increase was more sensitive to verbal behaviors than to nonverbal behaviors for romantic couples.

The Leading-Following Pattern between Genders in Both INS and Interaction Behaviors

Results of the durations of women- and man-initiated verbal behaviors are provided in the Supplementary Materials. In Step 3 (Fig. 2), the leading-following relationship between genders was tested. The results showed a significant topic × relationship interaction ($F(2, 76) = 6.290$, $P = 0.003$, $\eta^2 = 0.142$) and a three-way interaction between gender, topic, and relationship ($F(2, 76) = 5.240$, $P = 0.007$, $\eta^2 = 0.121$). Further pair-wise comparisons on the three-way interaction showed that the verbal behaviors initiated by women induced greater INS increase when discussing the conflictual (MD = 0.048, SE = 0.016, $P = 0.005$) and the neutral (MD = 0.057, SE = 0.022, $P = 0.013$) topics than when discussing the supportive topic in romantic couples. The opposite pattern was found for friends; that is, lower INS increase was found when discussing the conflictual (MD = 0.037, SE = 0.016, $P = 0.028$) and neutral topics (MD = 0.067, SE = 0.022, $P = 0.003$) than when discussing the supportive topic. However, no significant differences were found among the three topics either for romantic couples or friends in men-initiated verbal behaviors ($Ps > 0.05$, Fig. 6*a*).

In Step 4 (Fig. 2), the correspondence between the time lag of INS increase and that of men's verbal response was investigated. It was expected that the time lag (men lag by 4 s) of INS increase should match men's verbal response interval (4 s, Fig. 6*b*, red dash line). A quadratic equation significantly fitted the curve of the response interval ($F(2, 8) = 7.248$, $P = 0.016$, $R^2 = 0.644$, Fig. 6*c*). The results showed that the mean interval of men's verbal response was 4.019 s (Standard Deviation (SD) = 1.10) and most responses occurred within a period of 1–8 s. Relationship × topic ANCOVAs on men's verbal response intervals in women-initiated interactions showed no significant effects ($Ps > 0.05$). The topic difference in INS was larger in romantic couples than in friends at the 5-s time lag only ($F(1, 38) = 9.884$, $P = 0.003$, $\eta^2 = 0.206$, Fig. 6*d*). Taken together, these findings indicated a correspondence between women-led time-lagged INS increase and women-led time-lagged verbal behaviors.

The Association between INS Increase and the Strength of Romantic Love

Based on the results aforementioned, this correlation analysis was conducted on INS increase during verbal behaviors initiated by women when men's response interval was 5 s. The results showed a significant positive correlation for the PLS score of women ($r = 0.457$, $P = 0.033$) but not for that of men ($r = -0.301$, $P = 0.174$). No other correlations were significant ($Ps > 0.05$). These results further suggested that emotional arousal increased the strength of social affiliation in romantic couples by enhancing the time-lagged INS during verbal behaviors.

Discussion

This study examined the neurocognitive mechanisms of social interactions when emotions were involved. The results showed that among romantic couples but not friends, a time-lagged INS increase was significantly greater when discussing the conflictual topic than when discussing the supportive topic. Moreover, the topic difference in INS increase was positively correlated with IPS and arousal level rather than valence level, indicating an important role of emotional arousal in enhancing INS. Additionally, the mode of interaction was found to modulate the effect of emotion, and this effect was stronger in women-led verbal interactions than in other three modes (i.e., men-led verbal interactions, women-led nonverbal interactions, and men-led nonverbal interactions) among romantic couples. Finally, the women-led time-lagged INS increase was positively correlated with the strength of passionate love in romantically involved women. These findings suggested that greater INS induced by interpersonal conflict was mainly associated with a high arousal level rather than the valence level of emotion, and both the relationship type and interaction mode modulated the effect of emotional arousal on INS. These results are discussed in detail below.

First, previous research in cognitive psychology has documented an impact of negative emotion on cognition when the negative emotion is relevant to and co-occurs with the cognitive process (Schindler and Straube 2020; Zinchenko et al. 2020). However, similar research in behavioral and physiological studies of social interactions has generated varying results (Grewen et al. 2005; Graber et al. 2011; Schneiderman et al. 2014; Packheiser et al. 2019; Vaever et al. 2020). There have also been several dual-brain hyperscanning or pseudo-hyperscanning studies on emotional social interactions, but their findings are also inconsistent (Kinreich et al. 2017; Rojiani et al. 2018; Fachner et al. 2019; Smirnov et al. 2019; Balconi and Fronda 2020; Santamaria et al. 2020; Balconi et al. 2021). The mixed results in these studies might result from the fact that these studies did not distinguish between valence and arousal of emotion. To resolve this debate, the present study directly assessed both valence and arousal. We showed that discussing a conflictual topic induced higher-level arousal than did discussing a supportive or a neutral topic. No significant valence difference was found between conflictual and supportive topics in romantic couples. Moreover, in romantic couples, the conflictual topic rather than the supportive topic induced greater INS, which was in turn positively correlated with the arousal level and IPS rather than the valence level. Our results suggest that greater INS

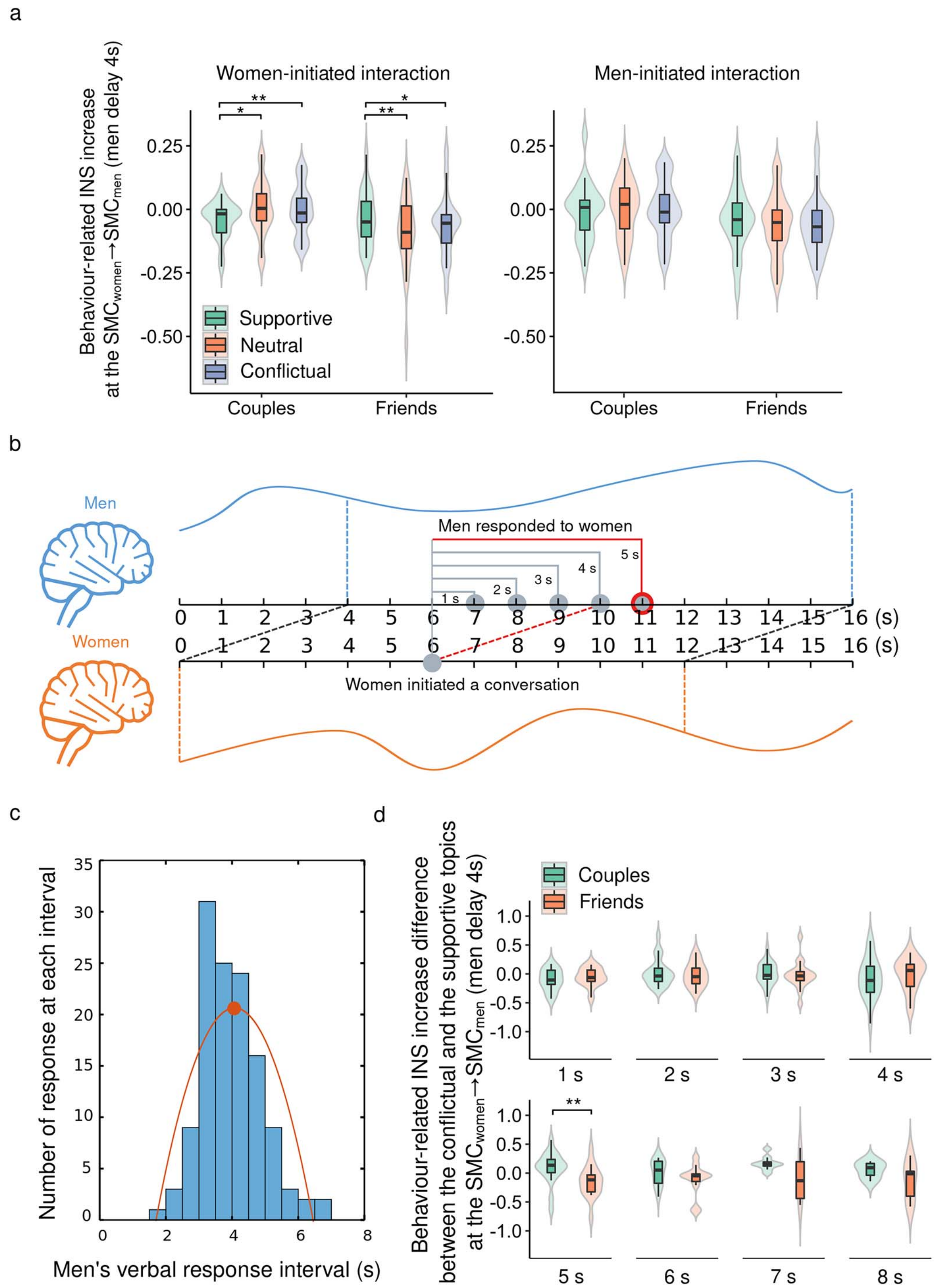

Fig. 6. Behavioral relevance of the INS increase. (*a*) Verbal interaction initiated by women induced a higher INS increase for the conflictual and neutral topics than for the supportive topic in romantic couples. The opposite pattern was found for friends. However, no significant differences were found among the three topics either for romantic couples or friends in men-initiated verbal interaction. (*b*) A schematic diagram illustrates the relationship between the time lag of INS increase and that of men's verbal response. In this example, the gray circle on the bottom line shows that the woman initiates a conversation at 6 s. Gray circles on the up line show that men respond to women 1, 2, 3, 4, or 5 s later, respectively. We expected that the time lag of INS increase (4 s) should match men's response interval (4 s, red dash line). The blue and orange brain images and lines indicate how the time-lagged INS was calculated. (*c*) A quadratic equation significantly fitted the curve of the response interval. It shows that the mean interval of men's response was 4 s. (*d*) The topic difference in INS increase was larger in romantic couples than in friends when men responded to women 5 s later.*, $P < 0.05$; **, $P < 0.01$.

induced by interpersonal conflict was mainly associated with a high arousal level rather than the valence of emotion, particularly in romantic couples.

Another potential explanation of the greater INS for the conflictual topic than the supportive topic is that the conflictual topic should be distressing to both individuals and hence greater interpersonal synchrony, whereas the supportive topic should presumably be distressing to only one of them and hence less interpersonal synchrony. If this were true, the two participants of each pair should have shown comparable valence or arousal levels for the conflictual topic, but different valence and arousal levels for the supportive topic. However, neither couples' nor friends' results showed such effects, that is, no significant interaction between topic and gender (here gender represents the man and woman in each pair) for either valence or arousal. Thus, this possibility can be excluded.

Second, in support of a modulating role of the interaction mode, we found greater INS induced by conflict-related arousal during verbal interactions only. Previous studies have revealed a close relationship between INS and either verbal (Dai et al. 2018; Jiang et al. 2012) or nonverbal behaviors such as gazing and smiling (Kinreich et al. 2017; Leong et al. 2017; Goldstein et al. 2018; Long et al. 2021). However, these studies did not test the role of emotion in INS. Other studies found greater INS during positive or negative social interactions (Kinreich et al. 2017; Rojiani et al. 2018; Balconi and Fronda 2020; Santamaria et al. 2020; Balconi et al. 2021), but they did not systematically test the relationship between interaction mode and emotion and did not disentangle the effects of valence and arousal either. By examining all these factors simultaneously, we showed that verbal but not nonverbal behaviors induced higher INS in the high arousal context (interpersonal conflict) than in the low arousal context (interpersonal support) for couples. These results suggest that verbal behaviors might be more efficient in expressing high arousal emotions than are nonverbal behaviors. We should hasten to add that in the present study the relevant emotion was induced by naturalistic verbal discussion rather than by nonverbal interaction alone such as facial expressions or gestures. Therefore, future studies should systematically test how interaction mode modulates the processing of emotion.

Third, the findings of this study also support a recent hierarchical model of social interaction (Jiang et al. 2021) that posits that social interactions involve a bottom-up hierarchical structure including interactive verbal and nonverbal processing, mutual understanding, and establishment of social relationships. For instance, during naturalistic speech comprehension, INS between the speaker's larynx/phonation area and the listener's left auditory temporal cortex follows a hierarchical organization, with linearly increasing lags of response in A1+, superior temporal cortex/superior temporal sulcus, and middle temporal cortex (Liu et al. 2020). On the other hand, the model also suggests that the higher levels of the interaction such as the types of social relationships may modulate the process of lower levels in a top-down manner. For instance, evidence shows that happiness expressed by an ingroup member results in lower startle responses compared to the same expression shown by an outgroup member; the opposite pattern emerges for fearful and angry expressions (Paulus et al. 2019). Additionally, evidence further shows that romantic relationship and friendship may have different patterns of interactions, which further lead to different levels of INS. Specifically, Pan et al. (2017) found that cooperation in romantic couples was associated with greater INS than that in friends. Long et al. (2021) found that, compared to friends, romantic couples preferred interpersonal touch more than verbal communication and showed greater INS during touch than during verbal communication. The latter findings seem to be contradictive to the present findings. However, Long et al. (2021) used a supportive topic only, so it remains unclear whether the findings would depend on the topic type. The present findings fill this gap by showing that when both topic and interaction mode were considered, romantic couples showed greater INS for the conflictual topic than for the supportive topic, whereas friends showed the reversed pattern, for verbal behaviors only, providing additional support for the top-down modulation hypothesis in the hierarchical model. However, as discussed earlier, the communication task employed in the present study may have affected the relationship pattern among these factors. Moreover, interpersonal touch in Long et al. (2021) may also differ from nonverbal behaviors such as manual gestures and smiling in the present study. Therefore, this issue should be further investigated in future.

Additionally, the top-down modulation of INS by relationship type was further supported by a leading-following pattern of the verbal interaction behaviors as well as the time-lag INS pattern. That is, emotional arousal-related INS was found when men's brain activity lagged behind that of women during women-initiated verbal behaviors, and the size of the neural time lag corresponded to that of the behavioral time lag that men responded to women-initiated conversation. Previously, two hypotheses have been proposed to interpret the cognitive underpinning of INS (Jiang et al. 2021). One is a shared representation of the same external stimuli, physical environments, or internal mental states/processes along the time course, which leads to similar temporal and frequency patterns of brain activities between individuals. The other is interpersonal predictive coding that is specifically associated with time-lagged INS between the brain structures of two individuals. Specifically, individuals may seek to minimize the differences between themselves and their partner in various aspects including actions, semantics/syntax, mental states or processes, and neural representations. This would lead to an increase in similarity between individuals and further demonstrate high-level interpersonal synchronization in behaviors, physiological activity, and neural activity.

In the present study, the time-lagged INS is unlikely to be associated with shared representations because most shared representations are associated with a time-aligned INS (Stolk et al. 2014; Liu et al. 2019; Zheng et al. 2020). It is also unlikely to be associated with the delayed processing of a shared representation because, as shown in a previous study, delayed processing is more likely to appear between different brain regions (Liu et al. 2020). On the contrary, time-lagged INS in the current study may reflect the minimization of the prediction error, that is, the difference between women's prediction of men's response when she initiated a verbal behavior and the actual feedback of men in response to women. Alternative tests on the time-lagged INS that corresponded to men-initiated verbal behaviors were not significant, nor were the effects when women or men initiated nonverbal behaviors.

The women-led time-lag INS was found in the SMC of women and men, which provided additional support for the predictive coding hypothesis. Previous studies have shown that the SMC is consistently involved in the embodied emotion processes, such as simulating the other person's affect, facial expression, or gesture to understand and respond to it (Prochazkova and Kret 2017). Moreover, the resonance of emotion was found to be associated with physiological activity such as the GSR (Goldstein et al. 2017; Reddan et al. 2020). Thus, in the present study, the correlation between the topic difference in INS at SMC-SMC and that in IPS indicates potential involvement of an embodied emotion process when participants were predicting and understanding their partner during social interaction. All these findings suggest that the type of relationship can modulate the time-lagged INS and the associated interpersonal predictive coding process. In the future, computational modeling methods should be applied to further test this possibility.

The results of gender-related INS are also consistent with prior research on gender differences in communication and cognition. That is, compared to men, women have higher social cognitive abilities such as that of mentalizing and empathy (Rose and Rudolph 2006; Christov-Moore et al. 2014), whereas men are more inclined to follow and be affected by women's behaviors (Moore 2010). In this case, men's behavior can be predicted by women's previous behavior, but not vice versa (Grammer et al. 2000).

In summary, the findings of this study support the proposition that emotion has a key role in increasing INS during a dual-brain social interaction context. It specifically suggests an effect of arousal induced by interpersonal conflict on social interactions among romantic couples as opposed to among friends. Importantly, we showed the effect only within verbal behaviors led by women. Finally, the present findings also support the interpersonal predictive coding hypothesis during social interactions and pave the way for computational modeling studies on this process.

Supplementary Material

Supplementary material can be found at *Cerebral Cortex* online.

Notes

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