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ORIGINAL ARTICLE

Interpersonal Neural Synchronization during Interpersonal Touch Underlies Affiliative Pair Bonding between Romantic Couples

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Abstract

Interpersonal touch plays a key role in creating and maintaining affiliative pair bonds in romantic love. However, the neurocognitive mechanism of interpersonal touch in affiliative pair bonding remains unclear. Here, we hypothesized that interpersonal neural synchronization (INS) during interpersonal touch underlies affiliative pair bonding between romantic couples. To test this hypothesis, INS between heterosexual romantic couples and between opposite-sex friends was measured using functional near-infrared spectroscopy-based hyperscanning, while the pairs of participants touched or vocally communicated with each other. The results showed significantly greater INS between the mentalizing and sensorimotor neural systems of two members of a pair during interpersonal touch than during vocal communication between romantic couples but not between friends. Moreover, touch-induced INS was significantly correlated with the self-reported strength of romantic love. Finally, the results also showed that men's empathy positively modulated the association between touch-induced INS increase and the strength of romantic love. These findings support the idea that INS during interpersonal touch underlies affiliative pair bonding between romantic couples and suggest that empathy plays a modulatory role in the neurocognitive mechanism of interpersonal touch in affiliative pair bonding.

Key words: affiliative pair bonds, empathy, fNIRS, interpersonal neural synchronization, interpersonal touch, romantic love

Introduction

One of the earliest forms of human communication, interpersonal touch, plays a key role in creating and maintaining affiliative pair bonds in humans (Gallace and Spence 2010). For instance, previous research has shown that interpersonal touch is beneficial not only for mother–child interactions (Gallace and Spence 2010) but also for both the physical and mental health of adults in close relationships, such as romantic relationships and friendship (Debrot et al. 2013; McGlone et al. 2014; Lopez-Sola et al. 2019). Most importantly, individuals experiencing romantic love touch each other more frequently than individuals in other close relationships (Guerrero 1997), suggesting a more important role for interpersonal touch in romantic relationships compared with other close relationships. However, the neurocognitive mechanism of interpersonal touch in affiliative pair bonding between romantically involved adults is not well understood.

Previous theories have suggested that affiliative pair bonding in romantic love is associated with a biological mechanism that reorganizes the physiological and neural processes of a dyad and is marked as interpersonal synchronization (Feldman 2017). Accordingly, evidence has shown that electrodermal activity and heart and respiratory rates are synchronized between romantic couples who touch each other (Chatel-Goldman et al. 2014;

Goldstein et al. 2017; Reddan et al. 2020). More importantly, hyperscanning studies using either electroencephalogram, functional near-infrared spectroscopy (fNIRS), or functional magnetic resonance imaging have also shown significant interpersonal neural synchronization (INS), that is, covariance in brain activity, between two romantically involved individuals (Anders et al. 2011; Muller and Lindenberger 2014; Kinreich et al. 2017; Pan et al. 2017; Goldstein et al. 2018). Among these studies, social communication, such as interpersonal touch, joint play, or naturalistic communication, seems to be a prerequisite for INS. Therefore, previous studies have hypothesized that INS during social communication may underlie affiliative pair bonding (Koban et al. 2019).

Here, we specifically tested the hypothesis that INS during interpersonal touch (a form of social communication) underlies affiliative pair bonding between romantic couples. This hypothesis can be further divided into 3 parts. First, to the best of our knowledge, only one study has previously asserted that there is an association between interpersonal touch and INS, showing that hand-holding increases INS between romantic couples when they experience pain (Goldstein et al. 2018). However, this study did not include other social relationships for comparison. Thus, it remains unclear whether there is a distinctive pattern of INS specifically associated with romantic relationships or a general pattern of INS that applies to any type of social relationship during interpersonal touch. It is also unclear whether INS during interpersonal touch is associated with the strength of affiliative pair bonds (e.g., strength of romantic love between romantic couples).

Second, compared with men, previous research indicates that women usually play a more active role in romantic love, probably because women are more sensitive to affective information and social support than are men during communication (Buck et al. 1974; Walen and Lachman 2000). For instance, during a hand-holding task, women were assigned to receive painful stimuli, whereas men were the observers (Goldstein et al. 2016, 2017). Additionally, during a nonverbal communication task, women were selected as the senders, whereas men were selected as the receivers, of affective information (Anders et al. 2011). Difference in the roles of women and men during communication might lead to a distinctive pattern of INS relative to the situation where men and women have equal roles. Correspondingly, previous relevant evidence on communication has shown that when individuals have equal roles in communication, INS usually appears between temporally aligned brain activities in the two individuals (Jiang et al. 2012; Stolk et al. 2014; Zheng et al. 2018; Liu et al. 2019). In contrast, when individuals have different roles, such as the leader–follower, teacher–student, or romantic couples in communication, INS is usually identified when the brain activity of the dominant individual temporally precedes that of the other individual (Anders et al. 2011; Jiang et al. 2015; Zheng et al. 2018). According to this hypothesis, a lead–lag pattern of INS between romantic couples was expected with men's brain activity lagging behind that of women during interpersonal touch. However, previous behavioral studies failed to identify gender difference in either relational commitment (Johnson and Edwards 1991) or positive reactions (e.g., pleasantness, warmth/love, and sexual desire) (Hanzal et al. 2008) during hand-holding. Thus, it is also possible that the potentially different roles of women and men during interpersonal touch do not necessarily lead to a lead–lag pattern of INS.

Third, previous findings have suggested that empathy plays a key role in interpersonal touch. Specifically, evidence shows that when couples touch each other in the presence of tonic heat stimuli, men's empathy is negatively correlated with the pain experience of their female partners (Goldstein et al. 2016). Moreover, INS during touch is significantly correlated with the observer's empathy between romantic couples (Goldstein et al. 2018). These findings suggest that there is a link either between the toucher's empathy and the mental processes of the partner being touched or between the empathy of one partner and the INS that exists between partners. The gap in knowledge, however, regards how empathy, INS during touch, and the strength of affiliative pair bonds (e.g., strength of romantic love) are interrelated with one another.

To test the above hypotheses and address these issues, this study examined INS of hemodynamic concentration changes between heterosexual romantic couples and opposite-sex friends when they touched each other or vocally communicated with each other in a naturalistic context. Previous evidence has shown that interpersonal touch can significantly lower cortisol and heart rate responses to subsequent stress in women to a greater extent than can vocal support or the absence of support (Ditzen et al. 2007; Jakubiak and Feeney 2016); however, previously reported neural patterns during touch have rarely been compared with those of other modes of communication, making it difficult to determine whether the identified neural patterns are specific to touch or can generally be applied to any mode of communication. Therefore, herein, we compared vocal communication with interpersonal touch to identify touch-specific INS. We then compared touch-specific INS between pairs of romantic couples and friends. The associations between INS during touch and both empathy and the strength of affiliative pair bonds were additionally investigated to provide complete information on the neurocognitive mechanism of interpersonal touch in affiliative pair bonding between romantic couples.

Additionally, previous research has primarily examined the neural mechanism of interpersonal touch from a "single-person" perspective, that is, by only examining the brain responses of participants who were continuously brushed on the forearm in a strictly controlled context (Rolls et al. 2003; McCabe et al. 2008; Lindgren et al. 2012; McGlone et al. 2012; Voos et al. 2012; Gordon et al. 2013). It is unclear, however, whether the neural mechanisms revealed in such situations are the same as those observed when the participants themselves are directly touched by a real person (Redcay and Schilbach 2019). Thus, a naturalistic context is necessary for increased ecological validity when the neurocognitive mechanism of interpersonal touch is investigated. In the present study, fNIRS was used to measure hemodynamic signals in such a naturalistic context because of its portability and tolerance for movement artifacts. Over the past decade, fNIRS hyperscanning has been successfully used to characterize various aspects of social communication, such as verbal and nonverbal communication, turn-taking, and social engagement (Jiang et al. 2012; Silbert et al. 2014; Nozawa et al. 2016; Dikker et al. 2017; Hirsch et al. 2017; Ahn et al. 2018; Dai et al. 2018); however, it has not yet been used to assess interpersonal touch.

Based on previous findings, we first hypothesized that interpersonal touch should induce greater INS than vocal communication. Moreover, there should be a distinctive pattern of INS specifically associated with romantic couples rather than a general pattern of INS associated with both romantic couples and friends during interpersonal touch (Hypothesis 1). Second, INS during interpersonal touch should correlate with the strength of

Table 1 Demographic information of the participants

	Couples	Friends
Absolute length (in months) of relationships	21.00 (15.88)	19.07 (13.06)
Relative length (in months) of relationships	9.99 (9.41)	10.85 (9.67)
Age (in years)		
Men	22.18 (2.26)	20.95 (1.86)
Women	21.45 (2.28)	20.50 (1.74)
Handedness (frequencies)		
Men	20 right-handed, 2 ambidextrous	20 right-handed, 2 left-handed
Women	22 right-handed	21 right-handed, 1 left-handed

Note: Absolute length was calculated comprising the amount of time since the pair first met, while relative length was calculated comprising the time since the pair established their relationship. Means and standard deviations (in parentheses) are provided for both relationship length and age.

romantic love (Hypothesis 2). Finally, empathy might modulate the association between increased INS during interpersonal touch and the strength of romantic love (Hypothesis 3). Our results supported each of these hypotheses.

Materials and Methods

Participants

Twenty-two pairs of heterosexual romantic couples and 22 pairs of friends of opposite sexes were recruited by advertising in universities in Beijing. No significant differences were found between romantic couples and friends with respect to age (men: $t(42) = 1.965$, $P = 0.056$, Cohen's $d = 0.590$; women: $t(42) = 1.56$, $P = 0.127$, Cohen's $d = 0.470$). Moreover, when the age of men and women was averaged within each pair, no significant difference was found between romantic couples and friends either ($t(42) = 1.874$, $P = 0.068$, Cohen's $d = 0.565$). According to self-reported data, there were no significant differences between romantic couples and friends in either the time since the individuals in the relationships first met ($t(42) = 0.438$, $P = 0.664$, Cohen's d $= 0.130$) or the time since the establishment of their relationship ($t(42) = -0.300$, $P = 0.765$, Cohen's $d = -0.090$). Detailed information about the participants is provided in Table 1.

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

Assessment of the Strength of Affiliative Pair Bonds

Before the experiment, 2 assessments were conducted to quantify the strength of the affiliative pair bonds. First, both couples and friends were required to report their frequency of daily communication on a 7-point Likert scale (1 represented no communication at all and 7 represented very frequent communication). Second, a subjective score for the strength of romantic love was recorded for romantic couples only using the Friendship-Based Love scale (FBL, 5-point scale; 1 represented the lowest level, 5 represented the highest level). This scale 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). The scale had high inter-item reliability in this study (Cronbach's $\alpha = 0.729$). We determined the strength of romantic love for each romantic couple by averaging the FBL scores between the two partners.

Assessment of Empathy

To minimize the interval between the participants' arrival in the lab and the beginning of the experiment as much as possible, empathy was measured after the experiment using the translated Interpersonal Reactivity Index (IRI) (Davis 1980). Additionally, because empathy reflects a trait of an individual across different contexts, no difference before and after communication was expected for empathy scores. Four components are included in the IRI, that is, perspective taking, fantasizing, empathic concern, and personal distress. Participants were allowed to take this assessment home and then share their results electronically. In total, 14 men and 13 women in romantic relationships and 18 men and 17 women in friendship completed the IRI scale and reported their results. The other participants failed to report their results for unknown reasons. Inter-item reliability was satisfactory after several items from each component were removed (Cronbach's α: perspective taking, 0.553; fantasizing, 0.759; empathic concern, 0.741; personal distress, 0.541). The final items used in this study are listed in Table 2. Additionally, no differences were found between men and women in the scores for these subscales, either between romantic couples or friends ($Ps > 0.05$). Finally, the perspective taking and fantasizing scores within a pair were additionally averaged to obtain an overall score for cognitive empathy (Cronbach's α: 0.711), while the scores of empathic concern and personal distress were averaged to obtain an overall score for emotional empathy (Cronbach's α: 0.773).

Tasks and Procedures

The experiment was conducted in a silent room. During the experiment, participants sat face-to-face, whereas the experimenters left the room to provide a comfortable and private environment for the participants. Moreover, the location of the chair of each participant was fixed, and the participants were required not to move their body positions as much as possible, to minimize movement artifacts (Cui et al. 2015) and potential confounding factors from postural changes (Vitorio et al. 2017). Each pair of participants was required to complete a 5-min resting-state session, a 5-min mutual gaze session, and a 5-min touch session. During the resting-state session, the participants were required to keep still with their eyes closed, relax their mind, and remain as motionless as possible (Lu et al. 2010; Jiang et al. 2012). During the mutual gaze session, participants were required to remain silent and maintain a mutual gaze. During the touch session, participants were required to hold their partner's hands (Jakubiak and Feeney 2017; Goldstein et al.

Table 2 Items from the IRI used in this study

Fantasy scale
1. When I am reading an interesting story or novel, I imagine how I would feel if the events in the story were happening to me
2. I really get involved with the feelings of the characters in a novel
3. I am usually objective when I watch a movie or play, and I do not often get completely caught up in it (–)
4. After seeing a play or movie, I have felt as though I were one of the characters
5. I daydream and fantasize, with some regularity, about things that might happen to me
6. Becoming extremely involved in a good book or movie is somewhat rare for me (–)
7. When I watch a good movie, I can very easily put myself in the place of a leading character
Perspective-taking scale
1. Before criticizing somebody, I try to imagine how I would feel if I were in their place
2. I sometimes try to understand my friends better by imagining how things look from their perspective
3. I believe that there are two sides to every question and try to look at them both
5. I try to look at everybody's side of a disagreement before I make a decision
6. When I'm upset at someone, I usually try to "put myself in their shoes" for a while
Empathic concern scale
1. When I see someone being taken advantage of, I feel kind of protective toward them
2. When I see someone being treated unfairly, I sometimes do not feel very much pity for them (–)
3. I often have tender, concerned feelings for people less fortunate than me
4. I would describe myself as a pretty soft-hearted person
5. Sometimes I do not feel sorry for other people when they are having problems (–)
6. Other people's misfortunes do not usually disturb me a great deal (–)
7. I am often quite touched by things that I see happen
Personal distress scale
1. In emergency situations, I feel apprehensive and ill at ease
2. I am usually pretty effective in dealing with emergencies (–)
3. Being in a tense emotional situation scares me
4. When I see someone get hurt, I tend to remain calm (–)
5. I tend to lose control during emergencies

Note: (–) indicates reverse coded items. Items were rated from 1 to 5, with 1 = "Does not describe me well" and 5 = "Describes me very well." Note that several items from each component have been removed to increase inter-item reliability.

2018). They were also required to remain silent and maintain a mutual gaze (Fig. 1*a*). The rest, gaze, and touch sequence were fixed.

Next, participants vocally communicated with each other in 3 different contexts: supportive, conflict, and neutral. During vocal communication, participants were required to freely communicate with each other by focusing on a topic for 10 min. The period of this task was longer than that of the touch task because during the pilot experiment, participants reported that a period longer than 5 min was better for communicating an interesting topic. The topic used in the vocal communication task was selected based on assessment of the level of support or conflict among participant pairs, regarding several alternative topics with a 7-point Likert scale (1 represented the lowest level of support and 7 represented the highest level of support) (Fletcher and Thomas 2000). The sequence of three vocal communications was counterbalanced across the participant pairs.

In this study, we only focused on the resting-state, gaze, and touch tasks, as well as the vocal communication task in the supportive context. The results for the other vocal communication tasks are reported elsewhere. Because previous evidence has suggested that visual contact may modulate interpersonal touch (Keizer et al. 2019), we used the mutual gaze task as a control task to exclude potential modulating effect of visual contact on touch. This process also ensured that the touch task was more naturalistic than simply closing one's eyes. Moreover, we compared the vocal communication task in the supportive context with the touch task because touch expresses more supportive information than negative or neutral information (Ditzen et al. 2007), making the touch task more comparable to the supportive vocal communication task with respect to emotional valence.

Additionally, two 15-s intervals were included at the beginning and end of each task session to ensure that the fNIRS system reached a steady state. The entire experimental procedure was video recorded with permission from the participants.

fNIRS Data Acquisition

A LABNIRS system (Shimadzu Corporation) was used to collect the fNIRS data. Four sets of customized optode probes (5 emitters and 5 detectors, 13 measurement channels) were used. Two sets were used for men, and the other 2 sets were used for women. For each participant, 2 sets of optode probes covered the frontal, temporal, and parietal cortices of the left and right hemispheres, respectively. The international 10–20 system was used to roughly localize the anatomical structures below the measurement channels (CHs). Specifically, T3 and T4 in the left and right temporal cortices corresponded to the positions of

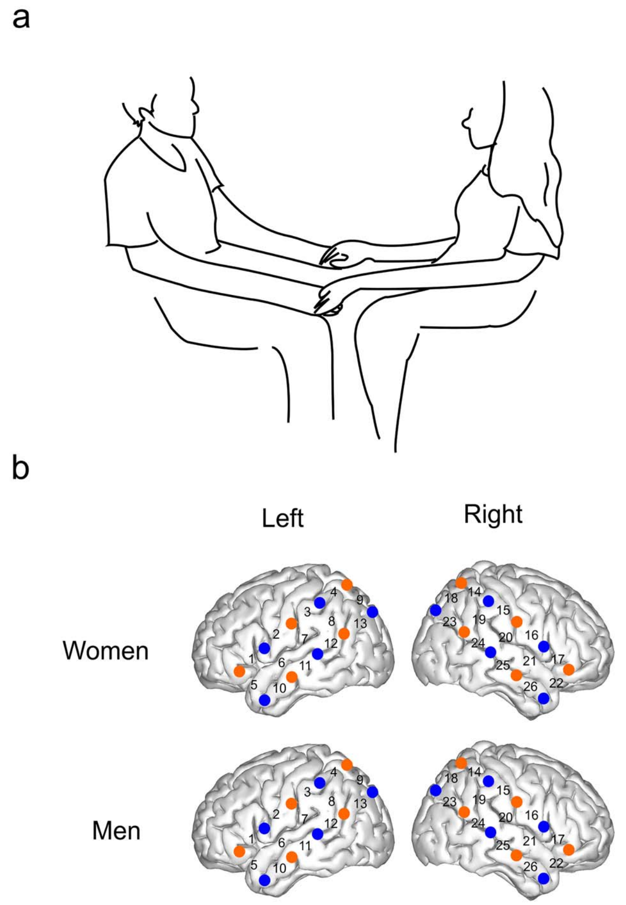

Figure 1. Schematic of the experimental design. (*a*) During the interpersonal touch task, participants were required to hold their partner's hands. They were also required to remain silent and maintain a mutual gaze. (*b*) The optode probe set was placed on the bilateral frontal, temporal, and parietal cortices. Channels 11 and 25 were placed at T3 and T4, respectively, in accordance with the international 10–20 system. The positions of the channels were further confirmed and adjusted based on the MRI scan of a typical participant.

CH11 and CH25, respectively. The probe sets were examined to ensure that the positions were consistent among participants.

Additionally, a SIEMENS TRIO 3-Tesla scanner was used to collect an anatomical image from a typical participant; a high-resolution T1-weighted magnetization-prepared rapid gradient echo sequence was used (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) was used to normalize the image to a standard Montreal Neurological Institute coordinate space (Ashburner and Friston 2005). An automated anatomical labeling template (Tzourio-Mazoyer et al. 2002) was used to determine the corresponding anatomical structures below the CHs (Fig. 1*b*).

The optical density of near-infrared light at 3 wavelengths (780, 805, and 830 nm) was measured with a sampling rate of 55.6 Hz. Then, the oxyhemoglobin, deoxyhemoglobin, and total hemoglobin concentration changes (HbO, HbR, and HbT, respectively) were assessed based on the modified Beer–Lambert law. In this study, only HbO concentration changes were used because they have the highest sensitivity to changes in regional cerebral blood flow and signal-to-noise ratio (Hoshi 2007).

fNIRS Data Analysis

Preprocessing

During preprocessing, the first and last 15 s of data in each task were removed to exclude data when the fNIRS system was not stable. Then, data from both the baseline and the task conditions were downsampled to 11 Hz to reduce the computational time. Functions in Homer3 (Huppert et al. 2009) were used to preprocess the data. Specifically, a discrete wavelet transformation filter was used to detect and correct motion artifacts (Molavi and Dumont 2012). Next, principal component analysis was used to remove global physiological noise, such as that due to skin blood flow (Zhang et al. 2005). The threshold of variance to be removed was set as 80% at a lenient level. Finally, filtering procedures were conducted after, rather than before, the calculation of INS (see below). This process was selected because there were no a priori expectations about the frequency range of interest in a study with a naturalistic design (Jiang et al. 2012), and a full frequency range is good for calculating INS (Cui et al. 2012).

Pair-Level Analysis

To assess INS between the two fNIRS time series of a given pair, the "wcoherence" function in MATLAB 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, of which the columns and rows corresponded to specific frequencies and time points, respectively. All possible CH combinations between two participants in a pair were examined (i.e., 26 ×26 = 676 in total). The coherence values were then converted into Fisher z-values and were time-averaged across the task period.

Next, previous studies have indicated that INS usually involves a time lag, probably due to the upcoming information being predicted dynamically (Stephens et al. 2010; Liu et al. 2017; Dai et al. 2018). To incorporate this effect and to test the potential lead–lag pattern of INS between women and men, the coherence value was calculated by shifting the time course of men forward or backward relative to that of women from 1 to 12 s (step = 2 s). This procedure was conducted for all tasks.

Finally, the coherence values from the mutual gaze task were subtracted from those of the touch and vocal communication tasks, resulting in an index of task-induced INS change, that is, the INS increase. This procedure was conducted for romantic couples and friends separately. All following statistical tests were conducted on the INS increase.

Determining the Frequency Ranges of Interest

In this study, the frequency ranges of interest were not predefined as done in studies with strictly controlled designs (Cui et al. 2012). Rather, it was obtained from the actual data as done in previous studies that also employed naturalistic communication tasks (Jiang et al. 2012; Dai et al. 2018). Specifically, the frequency ranges of interest were determined by conducting statistical tests on the INS increase across the full frequency range (0.01–0.7 Hz, see below) when the brain activities of men and women were temporally aligned. We then conducted other statistical tests on the INS increase within the selected frequency ranges when there was a time lag between men's and women's brain activities.

To do this, first, in accordance with previous studies (Tong et al. 2011), data values above 0.7 Hz and those below 0.01 Hz were excluded to prevent aliasing of high-frequency physiological noise, such as that of cardiac activity (~0.8 to 2.5 Hz) and very low-frequency fluctuations. Moreover, data within 0.15–0.3 Hz were also removed to exclude the effect of respiratory activity. Second, a relationship-by-mode mixed-model analysis of covariance (ANCOVA) was conducted for each CH combination when data from men and women were temporally aligned, while the age of men and women, as well as the time since the individuals in the relationships first met and the time since the establishment of their relationship, was entered as covariates. In this study, because we expected to detect a larger INS increase during the touch task than during the vocal communication task between romantic couples but not between friends, the frequency range of interest was determined based on the interaction effect between relationship and communication mode only. Third, the frequency range of interest was defined as a cluster based on the ANCOVA results. For each cluster, the position of the frequency was determined by a statistically strict threshold at the $P < 0.0005$ level, whereas the width was determined by a relatively loose threshold at the $P < 0.005$ level (Zheng et al. 2018; Liu et al. 2019). The cluster was also corrected for multiple comparisons using a cluster-based permutation approach ($P < 0.05$) (Maris and Oostenveld 2007; Zheng et al. 2020). Based on this rationale, 2 frequency ranges of interest, that is, 0.07–0.08 Hz and 0.04–0.05 Hz, were obtained. Finally, coherence values within each selected frequency range were averaged.

Group-Level Statistics

To adjust for the potential confounding effects of the age of men and women, as well as the time since the individuals in the relationships first met and the time since the establishment of their relationship, these variables were controlled in all subsequent statistical tests.

Touch-Specific INS Increase. Relationship-by-mode mixed-model ANCOVAs were conducted on the INS increase of all CH combinations of all the time lags within each of the 2 frequency ranges. The results were corrected using the false discovery rate (FDR) method for all CHs and all the time lags at the $P < 0.05$ level. The FDR procedure used here implemented the Benjamini–Hochberg method (Benjamini et al. 2006).

Validation of the Touch-Specific INS Increase via Permutation-Based Random Pairing. To investigate whether the identified INS increase was specific to interpersonal touch, a validation approach of the permutation test was applied. To that end, participants in relationships were randomly assigned to form new pairs who did not actually touch or communicate with each other and then INS increase was recalculated. Relationship-by-mode mixed-model ANCOVAs were performed on the INS increase. This permutation test was conducted 1000 times to yield a distribution (F value) of all CHs, which was then compared with the original data. The results were corrected using the FDR method ($P < 0.05$).

Validation of the Touch-Specific INS Increase by Matching the Task Duration. To exclude the possibility that differences in the length of task periods might have confounded the results, the touch task was additionally compared with the vocal communication task when matching their durations (i.e., using the first half of the vocal communication task, 4.5 min). Relationship (couples or friends)-by-mode (touch, vocal communication) mixed-model ANCOVAs were performed again (FDR correction, $P < 0.05$).

Predicting the Relationship Type Based on the Touch-Specific INS Increase. To further confirm the findings revealed by the univariate method, a multivariate method, Fisher Linear Discriminant Analysis (FLDA), was conducted. First, the difference of INS increase between interpersonal touch and vocal communication at all CH combinations was calculated. Next, the age of men and women, as well as the time since the individuals in the relationships first met and the time since the establishment of their relationship, was regressed out from the INS difference using a linear regression procedure. Finally, the residuals were used as the classification features, while relationship type was used as the class label. A step-wise method with a leave-one-out cross-validation approach was employed.

Correlation between INS Increases and the Strength of Romantic Love. Linear regression procedures were conducted to test whether INS increases during interpersonal touch or during vocal communication (i.e., touch or vocal communication task minus mutual gaze task, which are hereby termed touch-induced INS increase and vocal-induced INS increase) correlated with the strength of romantic love across romantic couples. Then, a linear mixed model was used to compare the correlations between the two communication modes in the romantic group. In addition, the same analyses were conducted on the communication frequency between romantic couples and between friends.

Relationships among Empathy, INS Increase, and the Strength of Romantic Love. A modulation model was built and tested using PROCESS (version 3.5) (Hayes 2018) within SPSS 24 (https://www.ibm.com). Specifically, based on previous findings that empathy is likely associated with both INS increase during interpersonal touch and the strength of romantic love, we hypothesized that empathy might modulate the association between touch-induced INS increase and the strength of romantic love. The data were mean-cantered, and the model was estimated using a bootstrap sampling method (5000 times, $P < 0.05$, 95% confidence interval).

Results

Touch-Specific INS Increase Was Larger between Romantic Couples Than between Friends

The ANCOVA results showed a significant interaction effect between relationship and communication mode at 0.07–0.08 Hz at the anterior temporal lobe (ATL, CH22) of women and the temporoparietal junction (TPJ, CH18) of men. The interaction effect was found when men's brain activity lagged behind that of women by 2–4 s (CH22–18, $ATL_{women} \rightarrow TPJ_{men}$, Fig. 2*a*). Additionally, the interaction effect reached a peak at a time lag of 2 s ($F(1, 38) = 33.709$, $P < 0.001$) (Fig. 2*b*,*c*).

Additional pairwise comparisons of the result at the 2-s time lag revealed significantly larger INS increases during interpersonal touch than during vocal communication for romantic couples ($P < 0.001$, Fig. 2*d*). However, the opposite result was found for friends, that is, a significantly larger INS increase during vocal communication than during interpersonal touch ($P = 0.006$, Fig. 2*d*). No significantly larger INS increases were found during vocal communication than during interpersonal touch between romantic couples, nor was the opposite pattern observed between friends at

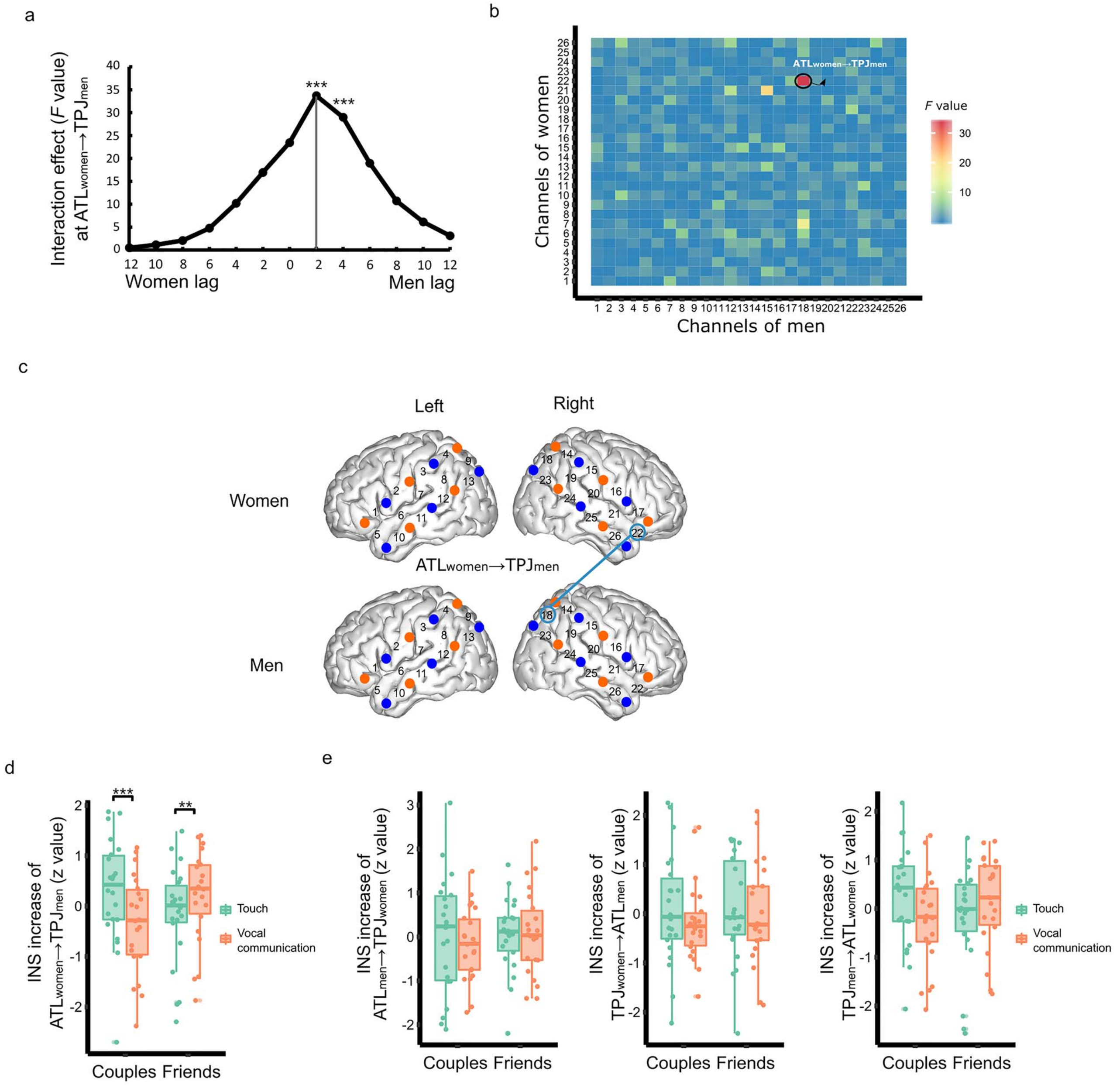

Figure 2. The relationship-by-mode mixed-model ANCOVA results. (*a*) A significant interaction effect between relationship and communication mode was observed across several time lags at the $ATL_{women} \rightarrow TPJ_{men}$ (CH22-18). (*b*) The interaction effects (*F* value) for all channel combinations when men's brain activity lagged behind that of women by 2 s. (*c*) The anatomical positions of the anterior temporal lobe (ATL) - temporoparietal junction (TPJ) (CH22-18, $ATL_{women} \rightarrow TPJ_{men}$). (*d*) Comparisons of INS increase at the $ATL_{women} \rightarrow TPJ_{men}$ and (*e*) the other three validations.

0.07–0.08 Hz ($Ps > 0.05$). No significant results were found at 0.04–0.05 Hz.

Finally, to further validate the INS pattern, we additionally tested the following three questions: first, whether there was a significant INS increase at the $ATL_{men} \rightarrow TPJ_{women}$ when women's brain activity lagged behind that of men; second, whether the INS increase at the $TPJ_{men} \rightarrow ATL_{women}$ was still significant when women's brain activity lagged behind that of men; third, whether there was a significant INS increase at the $TPJ_{women} \rightarrow ATL_{men}$ when men's brain activity lagged behind that of women. The results did not show any significant main effects of relationship or communication mode, nor were there significant interactions between communication mode and relationship in any of the 3 cases for any time lags (Fig. 2*e*, $Ps > 0.05$).

In summary, these findings confirmed the hypothesis that interpersonal touch increases INS to a greater extent than do other modes of communication between romantic couples but not between friends (Hypothesis 1).

Validation of the Touch-Specific INS Increase via Permutation-Based Random Pairing

Compared with the distribution generated by the permutation procedure, the interaction effect between relationship and

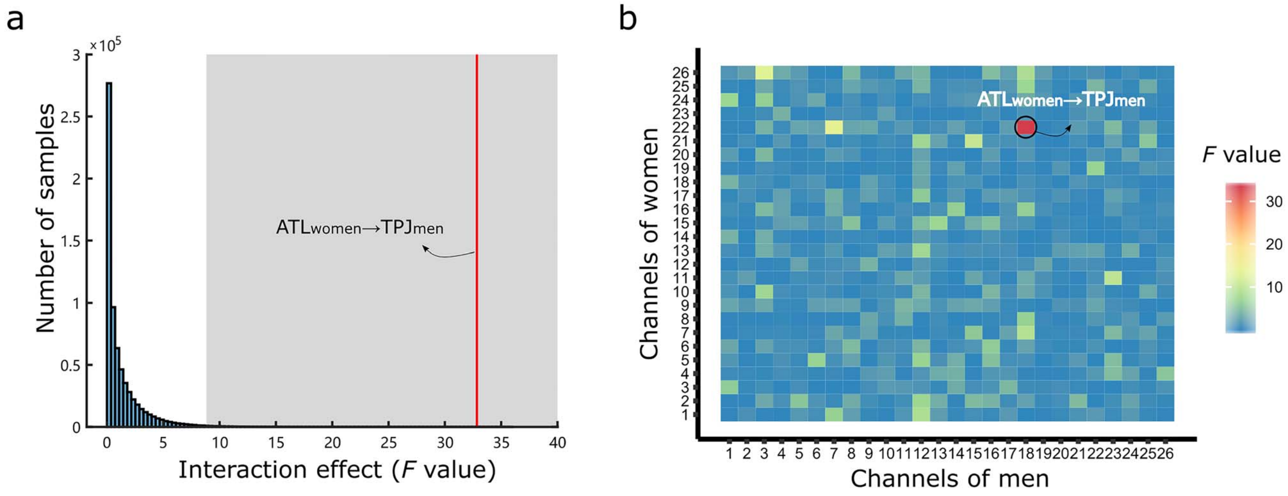

Figure 3. Validation of the results. (*a*) The results of the permutation test, showing the distribution of the interaction effect (*F* values) for all channel combinations. The effect of the anterior temporal lobe→temporoparietal junction (red line) in the original pairs was significant within the 1% area (gray color) after FDR correction ($P < 0.05$). The x-axis represents the *F* value, and the y-axis represents the number of samples. (*b*) The interaction effect (*F* values) for all channel combinations when the duration of the vocal communication task was matched to that of the interpersonal touch task.

communication mode at the $ATL_{women} \rightarrow TPJ_{men}$ (CH22-18) reached significance at the $P < 0.01$ level for the original pairs when men's brain activity lagged behind that of women by 2 s (Fig. 3*a*).

Validation of the Touch-Specific INS Increase by Matching the Task Duration

The results of relationship (couples or friends)-by-mode (touch, vocal communication) mixed-model ANCOVAs were the same as those reported above. That is, a significant interaction was found between relationship and communication mode at the $ATL_{women} \rightarrow TPJ_{men}$ (CH22-18) when men's brain activity lagged behind that of women by 2 s ($F(1, 38) = 33.463$, $P < 0.001$; Fig. 3*b*). Additional pairwise comparisons showed a significantly larger INS increase during interpersonal touch than during vocal communication for romantic couples ($P = 0.001$), but the opposite pattern was found for friends ($P < 0.001$). No other significant effects were identified ($Ps > 0.05$).

Predicting the Relationship Type Based on Touch-Specific INS Increase

The FLDA results showed that the averaged prediction accuracy reached the highest level when the men's brain activity lagged behind that of the women by 2–6 s. Specifically, 82% of the pairs of romantic couples and 86% of the pairs of friends were correctly predicted (chance level = 50%) at 2 s (Fig. 4*a*). Moreover, 3 classification features, that is, INS increase at the $ATL_{women} \rightarrow TPJ_{men}$ (CH22-18), and 2 additional CH combinations (CH13 of women and CH15 of men, $TPJ_{women} \rightarrow SMC_{men}$; CH21 of women and CH15 of men, $ATL_{women} \rightarrow SMC_{men}$) significantly contributed to the high prediction accuracy ($\chi^2 = 46.432$, $P < 0.001$, Fig. 4*b*).

Correlation between INS Increase and the Strength of Romantic Love

This correlation was assessed by averaging INS increase among the 3 CH combinations that accurately predicted the relationship type (i.e., CH22-18 at the $ATL_{women} \rightarrow TPJ_{men}$, CH13-15 at the

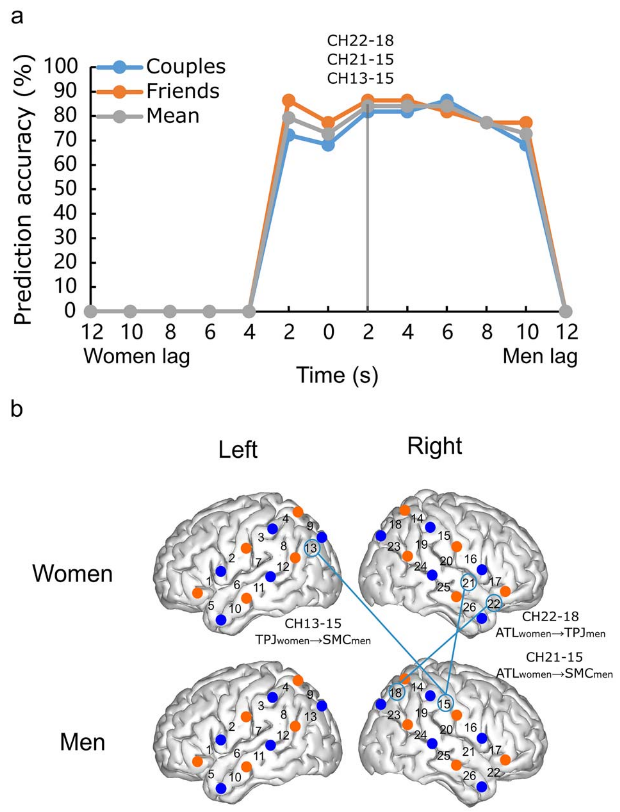

Figure 4. The FLDA results. (*a*) Prediction accuracy at each time lag, showing that accuracy reached its highest levels when men's brain activity lagged behind that of women by 2–6 s. The channel numbers next to each time lag indicate the channel combinations that significantly contributed to the prediction. (*b*) INS increase in CH22-18 at the ATL→TPJ, CH21-15 at the ATL→SMC, and CH13-15 at the TPJ→SMC made significant contributions to predictions at the 2-s time lag.

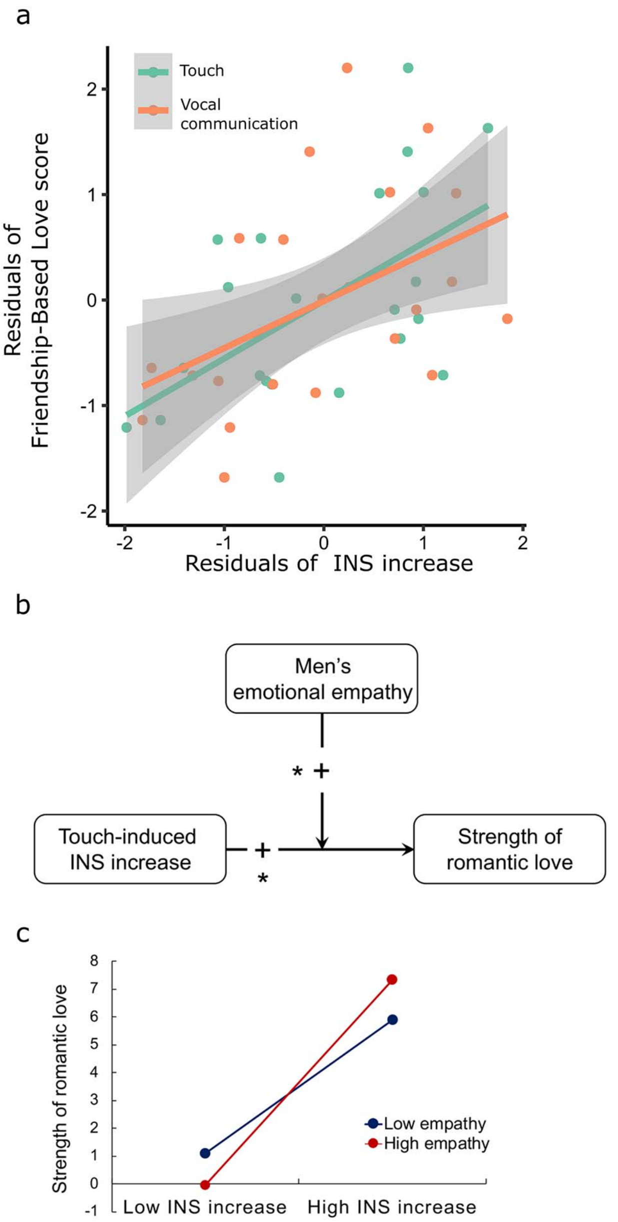

Figure 5. Relationships among empathy, INS increase, and the strength of romantic love. (*a*) The correlation results. Touch-induced INS increase was significantly correlated with the strength of romantic love (i.e., FBL scores) after controlling for the age of men and women, time since the individuals in the relationships first met, and time since the establishment of their relationship (green color). No significant correlation was observed for vocal-induced INS increase (orange color). The gray area indicates the 95% confidence interval. (*b*) The modulation model. It shows that the correlation between touch-induced INS increase and the strength of romantic love was modulated by men's emotional empathy. "+" indicates a positive effect. Asterisk indicates significance at the $P < 0.05$ level. (*c*) The modulation pattern. The higher men's emotional empathy, the stronger the INS increase during interpersonal touch can strengthen the romantic love.

$TPJ_{women} \rightarrow SMC_{men}$, and CH21-15 at the $ATL_{women} \rightarrow SMC_{men}$). The results showed a significant partial correlation between touch-induced INS increase and the strength of romantic love between romantic couples ($r_p = 0.542$, $P = 0.020$, Fig. 5*a*) after controlling for the age of men and women, time since the individuals in the relationships first met, and time since the establishment of their relationship. No significant correlation was found between vocal-induced INS increase and the strength of romantic love ($r_p = 0.442$, $P = 0.066$, Fig. 5*a*).

A direct comparison between the correlation during interpersonal touch and during vocal communication showed that the correlation between touch-induced INS increase and the strength of romantic love was significantly higher than that between vocal-induced INS increase and the strength of romantic love ($F(1, 6.715) = 6.498$, $P = 0.040$), which supported the second hypothesis (Hypothesis 2).

No significant results were observed for the communication frequency between either romantic couples or friends ($Ps > 0.05$).

Relationships among Empathy, INS Increase, and the Strength of Romantic Love

This analysis was conducted on touch-induced INS increase only because the above results showed that only touch-induced INS increases were significantly correlated with the strength of romantic love. The results showed a significant modulation effect (R^2 change = 0.032, F change (1, 14) = 6.415, $P = 0.024$), that is, men's emotional empathy positively modulated the facilitative effect of touch-induced INS increase on the strength of romantic love (Fig. 5*b*,*c*). No significant effect was observed for men's cognitive empathy, nor was there significant effect for either emotional or cognitive empathy of women ($P > 0.05$). These findings support a modulatory role for empathy in the neurocognitive mechanism of interpersonal touch in affiliative pair bonding (Hypothesis 3).

Discussion

This study examined the neurocognitive mechanism of interpersonal touch between adults by testing the hypothesis that INS during interpersonal touch underlies affiliative pair bonding between romantic couples. The results supported the hypothesis by showing that INS increase was larger during interpersonal touch than during vocal communication between romantic couples but not between friends. Moreover, touch-induced INS increase was positively correlated with the strength of romantic love. Finally, the association between touch-induced INS increase and the strength of romantic love was positively modulated by the level of men's emotional empathy. These findings are discussed in sequence below.

First, our results showed that INS increase was larger during interpersonal touch than during vocal communication between romantic couples. Previous research has indicated that while vocal communication is more effective in precisely transmitting complex information, such as social intention (Levelt 1999), touch is more powerful with respect to vitality and immediacy (Field 2014). However, although various neural patterns for interpersonal touch have been previously identified, it is unclear whether these neural patterns are specific to interpersonal touch or generally apply to any mode of communication. The present findings suggest that interpersonal touch differs from other modes of communication, such as vocal communication, not only in behavioral performance but also in neural pattern.

Second, a larger touch-specific INS increase was found between romantic couples only. Previous evidence on the association between INS and romantic love is inconclusive because, as far as we know, most of the previous studies did not compare romantic relationships with other social relationships when measuring INS (Anders et al. 2011; Muller and Lindenberger 2014; Kinreich et al. 2017; Goldstein et al. 2018). One exception is a study that compared romantic couples with friends and strangers during a button-press cooperation task, showing higher INS in the right superior frontal cortex between romantic couples than between friends (Pan et al. 2017). The present study extended this evidence by comparing INS during interpersonal touch between heterosexual romantic couples and opposite-sex close friends. The results additionally suggest that the larger INS increase at the $ATL_{women} \rightarrow TPJ_{men}$ during interpersonal touch compared with during vocal communication is distinct for romantic relationships and does not apply generally to any type of social relationship, such as friendship. This conclusion is also consistent with the human attachment theory that romantic relationships are distinct relative to other social relationships among adults because they might be fundamentally associated with mother–infant relationship and share similar biological and physiological mechanisms with mother–infant relationship (Feldman 2016, 2017).

There is another possibility, however. The hand-holding task used in this study is not a typical mode of communication between opposite-sex friends, which might lead to the opposite effect of INS increase between friends. Most importantly, in this study, we did not measure the subjective feeling about the role of interpersonal touch in each relationship. Therefore, it remains to be determined whether touch-specific INS differences between romantic relationships and friendship were associated with the self-reported feeling of touch, unnaturalness of the task, or both. Future studies should employ an interpersonal touch task that is more comparable between romantic couples and friends. Moreover, it is expected that in a touch task that is more typical for friends than hand-holding, a distinctive pattern of INS increase should also be identified between friends but not between romantic couples.

Third, touch-specific INS increase reached a peak when men's brain activity lagged behind that of women by 2 s. This finding is consistent with previous reports on gender differences during communication; that is, relative to men, women are more sensitive to social support (Walen and Lachman 2000) and affective communication (Buck et al. 1974). This finding is also consistent with previous hyperscanning evidence showing that when individuals have different roles in communication, such as the teacher and the student or the leader and the follower, a lead–lag pattern of INS is expected (Jiang et al. 2015; Zheng et al. 2018). Moreover, the lead–lag pattern of INS is likely associated with a prediction process (Stephens et al. 2010; Liu et al. 2017; Dai et al. 2018; Zheng et al. 2018). Taken together, these findings seem to indicate that higher sensitivity to communication between romantic partners enables women to be better at predicting the subsequent action of men, demonstrating a women-lead time-lag pattern of INS.

Additionally, according to the early planning perspective for interpersonal communication, individuals respond earlier when the final word(s) of the question were more predictable (Corps et al. 2018). A recent computational modeling study also suggests an important role for the predictability of speech content in interpersonal communication (Friston et al. 2020). Previous hyperscanning studies have also shown that when the partner's speech content is hard to predict, for example, listening to the pre-recorded speech rather than the speech produced by a real partner (Stephens et al. 2010) or listening to the speech produced by a real partner but in a noisy situation (Dai et al. 2018), the time lag for prediction is usually 1–3 s. However, when the partner's speech content is easy to predict, for example, anticipating the knowledge state and potential responses of the students by the teacher during teaching (please note that the teacher is usually more knowledgeable than is the student and has more background information about the student than vice versa), the time lag for prediction is usually longer, such as 10 s (Zheng et al. 2018). In the present study, no verbal or nonverbal communication, other than hand-holding, was allowed, which increased the unpredictability of the mental states of the partner. Thus, it is expected that the time lag of prediction, if there was one, should be short. Our results confirmed this expectation, showing that INS increase appeared when men's brain activity lagged behind that of women by 2 s, which is similar to that reported in a low predictability situation (Stephens et al. 2010; Dai et al. 2018).

Fourth, touch-induced INS increase was found in 3 CH combinations. Specifically, significantly higher INS increases were observed during interpersonal touch than during vocal communication at the $ATL_{women} \rightarrow TPJ_{men}$. TPJ and ATL are closely associated with the mentalizing system (Saxe and Wexler 2005). Previous studies have indicated that the TPJ is selectively recruited for the attribution of mental states (Saxe and Wexler 2005), while the ATL has a key role in representing and retrieving social knowledge, including memory of people's names, biographies, and traits (Olson et al. 2013). It is likely that women are predicting the subsequent mental states of men, which are represented in the TPJ, based on the women's past experiences stored in the ATL during interpersonal touch.

While most previous hyperscanning studies have reported the involvement of only one channel combination in social communication (Jiang et al. 2012; Dai et al. 2018), other studies documented involvement of multiple channel combinations or network combinations in social communication (Goldstein et al. 2018; Zheng et al. 2018). Here, by employing the multivariate analysis, we additionally showed that similar to INS increase of the $ATL_{women} \rightarrow TPJ_{men}$, INS increases at the $ATL_{women} \rightarrow SMC_{men}$ and the $TPJ_{women} \rightarrow SMC_{men}$ also made significant contributions to the accurate prediction of relationship type. Previous evidence indicates that the perception of others' actions automatically activates the neural systems that are responsible for producing these actions in the sensorimotor cortex (SMC; Preston and De Waal 2002). This process is thought to underlie behaviors such as social facilitation (Preston and De Waal 2002; Keysers et al. 2010). Therefore, it is speculated that men are using their production-for-perception system to understand the mental states and the prediction process in the mentalizing systems of women (Pickering and Garrod 2013). This speculation suggests an interpersonal interaction between the production-for-perception system of one individual and the mentalizing system of the other individual during social communication.

Fifth, touch-induced INS increase was positively correlated with the strength of romantic love. This result is consistent with previous findings, showing that touch strengthens affiliative pair bonds by reorganizing the biological, physiological, and neural processes of romantic couples (Feldman 2016, 2017). For instance, studies have shown that women who report having received more hugs from their partners in the past have higher levels of oxytocin than those who do not have much of a history of being hugged by their partners (Light et al. 2005). Moreover, oxytocin levels positively correlate with the frequency of touch in the early stages of romantic relationships (Schneiderman et al. 2012). This finding and the above findings together support the hypothesis that INS increase during interpersonal touch underlies affiliative pair bonding between romantic couples.

Finally, our results additionally showed a modulatory effect of men's emotional empathy on the association between touch-induced INS increase and the strength of romantic love. Although men's empathy has been found to be associated with either the mental process of the female partner or the INS between men and women during touch (Goldstein et al. 2016, 2018), the specific role of empathy in touch and affiliative pair bonding has never been formally tested. The present results filled this gap of knowledge by showing a modulatory effect of men's empathy. We extended previous findings by specifically showing that it was emotional empathy modulating the relationship between touch-induced INS increase and the strength of romantic love. As discussed above, the women-lead time-lag pattern of INS increase might approximate the minimized prediction error, that is, the difference between women's prediction and men's actual input. Moreover, as previous evidence has indicated that communication input or responsiveness plays a key role in interpersonal communication (Kochanska 1997), responsiveness is closely associated with empathy. Therefore, it is likely that men's emotional empathy modulates their interaction behaviors with women by increasing their responsiveness and significantly enhances the effect of touch-induced INS increase on affiliative pair bonding between romantic couples.

A major limitation of this study is that the sequence of conditions was fixed. Apparently, a counterbalanced sequence for conditions is a better solution. However, we suspected that there might be an interaction between conditions and the sequence of conditions. For example, compared with touch, vocal communication might involve more communication cues of both verbal and nonverbal language. Additionally, vocal communication communicates information more precisely than touch. Therefore, the sequence of vocal communication-touch in a within-subject design might decrease the difference between vocal communication and interpersonal touch conditions, whereas the reverse sequence might not. In this case, as suggested previously (Winer 1971; Keppel 1992), counterbalancing conditions may not be the best solution for comprehensively addressing the sequence effect and may even exacerbate the situation. Thus, a fixed sequence is suggested if the time period between the two conditions is not very long (e.g., $<$10 or 15 min) (Sayette et al. 2010) because the danger of the sequence interaction is greater than the concern of using a fixed sequence of conditions (Baumann and Sayette 2006). In this study, the time from the onset of the touch condition to the end of the vocal communication condition was 15 min. Thus, we decided to fix the sequence of conditions. The results actually showed significantly greater INS increase in the vocal communication condition than in the touch condition between friends, suggesting that the effect of the vocal communication condition was not decreased by the touch condition. However, as this might not represent the best solution, unknown outcomes might have been introduced into our results. Thus, in future studies, a better solution should be investigated.

In summary, the present findings tested the hypothesis that INS during interpersonal touch underlies affiliative pair bonding between romantic couples. The findings confirmed this hypothesis, demonstrating that interpersonal touch induces larger INS increase than does vocal communication between romantic couples but not between friends. The results additionally showed that touch-induced INS increase positively correlated with the strength of romantic love, which was further modulated by men's emotional empathy. These findings provide new insights into the neurocognitive mechanism of interpersonal touch in affiliative pair bonding between romantic couples.

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Notes

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