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The role of mindfulness on theta inter-brain synchrony during cooperation feedback processing: An EEG-based hyperscanning study☆,☆☆,☆☆☆,☆☆☆☆,☆☆☆☆☆,☆☆☆☆☆☆

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ABSTRACT

Mindfulness appears to improve empathy and understanding in relationships, which are necessary for successful cooperation. However, the impact of mindfulness on cooperation has not been fully studied. This study used hyperscanning technique to examine the effect of mindfulness on the inter-brain synchrony of interacting individuals during the cooperative tasks. Forty-one dyads were randomly assigned to a mindfulness group or a non-mindfulness group. Dyads of the mindfulness group performed a short mindfulness exercise following a 15-minute mindfulness audio guidance. Dyads of the non-mindfulness group were instructed to rest quietly with their eyes closed. Then, simultaneously and continuously EEG was recorded from all dyads when they completed a computer-based cooperative game task. Reaction times (RTs) and success rates were used to indicate the behavioral performance, and phase locking value (PLV) was used to indicate the inter-brain synchrony. The results showed that (1) Greater theta inter-brain synchrony during the cooperative computer game tasks was observed in the mindfulness group than in the non-mindfulness group; (2) Greater theta inter-brain synchrony was observed in the successful cooperation conditions as compared to those in the failure cooperation conditions; (3) Greater theta inter-brain synchrony was observed at the frontal region as compared to those at the parietal-occipital region in the successful cooperation condition. The results expand the neural basis of the effects of mindfulness on cooperation feedback processing.

Introduction

Mindfulness is a non-judgmental attitude towards experiences and thoughts, which can be improved through constant training (Kabat--Zinn, 2015). There are two main points during mindfulness practices. First, mindfulness requires people to focus on their current experiences. Second, mindfulness requires people to accept their feelings and thoughts in a non-judgmental way (Reina & Kudesia, 2020). Farb et al. (2013) summarized the cognitive mechanisms of the impact of mindfulness practice on individuals (Farb et al., 2013), which include re-perception of the world (Carmody et al., 2009), reduction of self-attention (Fresco et al., 2007) or evaluation in a larger context

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(Garland et al., 2011).

Several studies have shown that mindfulness is beneficial for social and interpersonal skills (Bodie & Burleson, 2016). For example, Shapiro et al. (1998) found that participants' empathy was improved after mindfulness practice (Shapiro et al., 1998). The improvement of empathy is beneficial for individuals to develop healthier relationships (Block-Lerner et al., 2007). Similarly, Carson et al. (2004) found that mindfulness practices could improve the quality of a couple's relationship and maintain ongoing benefits. In addition, mindfulness facilitates the focus of the individual's attention on the content of the communication with the interacting partner (Goleman, 2006). Overall, mindfulness has a notable influence on the quality of social relationships, which may be achieved through promoting interpersonal coordination and connection, enhancing communication skills, and being aware of partners' nonverbal messages (Brown et al., 2007).

Cooperation refers to the coordinated action of two or more individuals, and it is one of the basic behaviors that construct and maintain human society. In everyday interpersonal cooperation, what often matters is sharing intangible 'resources' and recognizing the preferences of others (Lange & Doesum, 2015). Cooperative actions may be inherently beneficial to human beings, and indeed, they are often associated with empathic concern, emotional satisfaction, or reward (Vanutelli et al., 2016). Not only the act of cooperation itself, but also the results of successes and failures in social cooperation are particularly important to both of the dyads as a reflection of the social consequence and emotional reactions during interpersonal interactions (Koban & Pourtois, 2014). In the process of monitoring social context information and motivating individuals' feedback learning in a social context, the dorsal medial prefrontal cortex (dmPFC) as a top-down control system seemed to play an important role (Li et al., 2022). Multiple lines of evidence suggest that factors such as social environment, cues and stimuli, and hormone levels may all influence human cooperation (Iwamoto et al., 2020). A Higher level of mindfulness, as mentioned above, appears to improve empathy and understanding in relationships (Block-Lerner et al., 2007), which are also necessary for successful cooperation (Wang et al., 2019). Recent research has also found that mindfulness meditation may promote cooperation by upregulating human altruism (Iwamoto et al., 2020). However, the impacts of mindfulness on the neural mechanisms of cooperative feedback have not been fully studied. Therefore, the present study will examine the effects of mindfulness practices on the feedback processing of cooperative behavior and its neural basis.

Research suggested that the electrophysiological links between two conspecifics are inherent elements of social bonding and attachment (Vanutelli et al., 2016). More specifically, perceiving another person's actions, feelings, or emotions usually triggers corresponding cortical representations, a process also known as vicarious activations, and this substitution activation approximates the neural activation of another person, thus leading to coupled neural responses (Hasson et al., 2012). Hyperscanning is used to measure the brain activity of two or more people at the same time (Dikker et al., 2017), and recording the information about the functional connections between individual brains (Balconi & Fronda, 2020). The latter was known as inter-brain synchrony, which reflects the coupling between two or more participants at the neural level due to interpersonal interaction (Richard et al., 2021). Inter-brain synchrony, as a sensitive marker that could reflect dynamic interpersonal interactions, may be driven by shared attention during the interaction. Inter-brain synchrony may also reflect the understanding and empathy between individuals, which are the basis for successful cooperation (Wang et al., 2019).

The application of hyperscanning promoted the research on the cognitive neural mechanism of interpersonal information processing (Montague et al., 2002). For example, when researchers performed the Prisoner's Dilemma task using hyperscanning technology, they found that brain activation was synchronized between interacting individuals (Astolfi et al., 2010). A hyperscanning study found specific patterns of brain activation and reduced interbrain synchronization in the frontal regions after receiving negative feedback to interacting participants (Balconi et al., 2018b). In another study examining the effect of different types of feedback on the group performance when completing creative tasks, researchers found that inter-brain synchrony in the frontopolar and bilateral dorsolateral prefrontal cortex (DLPFC) significantly increased when receiving positive and negative feedback. Such increments of inter-brain synchrony in the frontal regions were associated with group creative performance (Lu et al., 2019). These findings suggested that the performance of cooperation between the interacting individuals could be predicted by the inter-brain synchrony (Liu et al., 2021). It also implied that there may be a link between frontal lobe activation and the corresponding responses to social feedback.

Theta-band rhythm is associated with judgment, executive control (Cavanagh & Frank, 2014), and behavioral change (Cavanagh et al., 2010). Researchers have found that inter-brain synchrony in the theta band increases during cooperation, which appears to be associated with shared behavioral rhythms (Barraza et al., 2020; Shiraishi & Shimada, 2021; Wang et al., 2020). Furthermore, the influence of external feedback during cooperating has been widely examined, as it affects individuals' sense of efficacy, motivation and even emotional responses in a social context. For example, a hyperscanning study found that negative external feedback may induce a decline in the inter-brain synchrony in the low-frequency bands, suggesting that low frequency-bands like theta may be an important marker of social cognition and emotional engagement (Balconi et al., 2018a). Indeed, results from other studies also suggested that the frontal theta activity may be associated with strategic regulation of social information processing and emotional features in a social context (Billeke et al., 2013, 2014; Cristofori et al., 2013). Therefore, in the current study, we focused on the role of mindfulness practices in the inter-brain synchrony of theta-band between participants in the feedback processing during a cooperative task.

The purpose of the present study was to investigate the effect of mindfulness on inter-brain synchrony during interpersonal cooperation, particularly in cooperative feedback processing, using the hyperscanning technique. Previous research suggested that improved synchrony between brain regions implied enhanced emotional sharing, emotional understanding, and interpersonal coordination, which may result in better processing of the feedback in cooperative behavior (Liu et al., 2021). Since the prefrontal region is considered to be sensitive and relevant in cooperation, and is also important in monitoring social context and feedback (Li et al., 2022; Liu et al., 2016), we assume that greater theta inter-brain synchrony will be observed in the prefrontal region than in the parietal-occipital region in the processing of successful cooperation feedback. Mindfulness could be beneficial to improving interpersonal relationships and promoting social connection (Carson et al., 2004). We assume that participants in the mindfulness group will show higher inter-brain synchrony in the theta band when processing the successful feedback in cooperation than participants in the control group.

Method

Participants

Participants were recruited from a local university through flyers. Interested and eligible participants took part in the study of emotion and mindfulness. Participants could sign up with a partner or be randomly assigned a partner after signing up alone. We will use the term "dyad" to refer to each pair of the interacting participants who have formed a partnership in the cooperative task in the present study. It refers to a pair of interacting individuals. Eighty-six participants were recruited for the experiment and were randomly assigned to one of the two groups: the mindfulness group and the non-mindfulness group. Given the poor EEG data quality and technical error, 2 dyads were excluded from the study. Thus, the final sample was composed of 82 participants (41 dyads), which included 21 dyads in the mindfulness group (11 female dyads and

10 male dyads, aged from 18 to 24 years old, M_{age}=20.83, SD=1.53) and 20 dyads in the non-mindfulness group (14 female dyads and 6 male dyads, aged from 18 to 25 years old, M_{age}=20.70, SD=1.36). The sample size was in line with typical hyperscanning EEG studies (Barraza et al., 2020; Jahng et al., 2017).

None of the participants in this study had been exposed to mindfulness practice before. All participants were right-handed and had normal or corrected-to-normal vision. Participants had no history of neurological or psychiatric disorders. Informed consent was obtained from all participants. The local Institutional Review Board approved all experimental protocols for this study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Procedure

We employed a 2 (Group: mindfulness group vs. non-mindfulness group) $\times$ 2 (Condition: successful cooperation vs. failure cooperation) $\times$ 2 (Brain areas: frontal region vs. parietal-occipital region) repeated measures design. All participants were asked to fill out the demographic information and introduced to the procedures of the task before the experiment. Electroencephalograph (EEG) sensors were attached on both members of the dyads. The mindfulness groups were required to complete a 15-minute mindfulness meditation (see Supplementary 1), while non- mindfulness group was asked to rest with their eyes closed for 15 min. After mindfulness meditation or rest, all participants were asked to complete the Computer Game Task.

Computer game task

Each dyad was asked to complete an adapted version of a cooperative computer task (Cui et al., 2012). Participants were asked to press the key to control the dolphin on the screen to catch the ball together. The dyads were asked to press their keys at the same time to "catch the ball together".

Two participants sat side by side while playing the computer game task. For data quality, they were asked to minimize head and body movements and avoid verbal communication during the EEG measurements. A towel was placed over the participants' hands to avoid their observing each other's movements. The task began after the research assistant confirmed that the dyads fully understood the instruction. Before the test trial, participants were asked to complete five practice trials at the beginning of the experiment. The computer game task consisted of 50 trials in total. In each trial, two dolphins were shown on the screen. Two seconds later, a black hollow circle appeared above the dolphins for a random time of 0.6–1.5 s as a "Ready" signal. The black hollow circle was then replaced by a red and white ball as a "Go" signal. Dyads were instructed to press their response keys only after the “Go” signal had appeared. The participants sitting on the left were asked to press the numeric keyboard ‘1′ to respond, while the participants sitting on the right were asked to press the numeric keyboard ‘0′. After the dyads had reacted, a feedback screen was shown. The feedback screen was presented for 1.5 s at the last of the cooperative task (see Fig. 1).

If the difference between response times was below a threshold, the feedback screen would show that both dolphins catch the ball, and the dyads would gain a point. Conversely, if the differences between the response times were above the threshold, the feedback screen would show that neither dolphin catches the ball and both of the participants lose a point. The threshold was set to $T = 1/8$ (RT1+RT2), where RT1 and RT2 are the response times of the dyads in the cooperative task. Finally, participants' RTs and success rates (number of successful trials/ 50) will be extracted and calculated as indicators of their behavioral performance. The probability of success and failure in the cooperative task depends on the degree of cooperation of the dyads.

Mindfulness meditation

In the experiment, audio recordings guided by senior mindfulness lecturers were used in the mindfulness condition, including two parts: a breath-focused mindfulness practice and a body scanning practice (Deng et al., 2019). In the breath-focused mindfulness exercise, participants need to focus their attention on breathing according to instructions without making any judgment. In the body scanning exercise, participants need to move their consciousness from one part of the body to another to deeply experience their feelings of the body (see Supplementary 1).

Dual-EEG recording and data analysis

The experiment was arranged in an electrically shielded and dimly

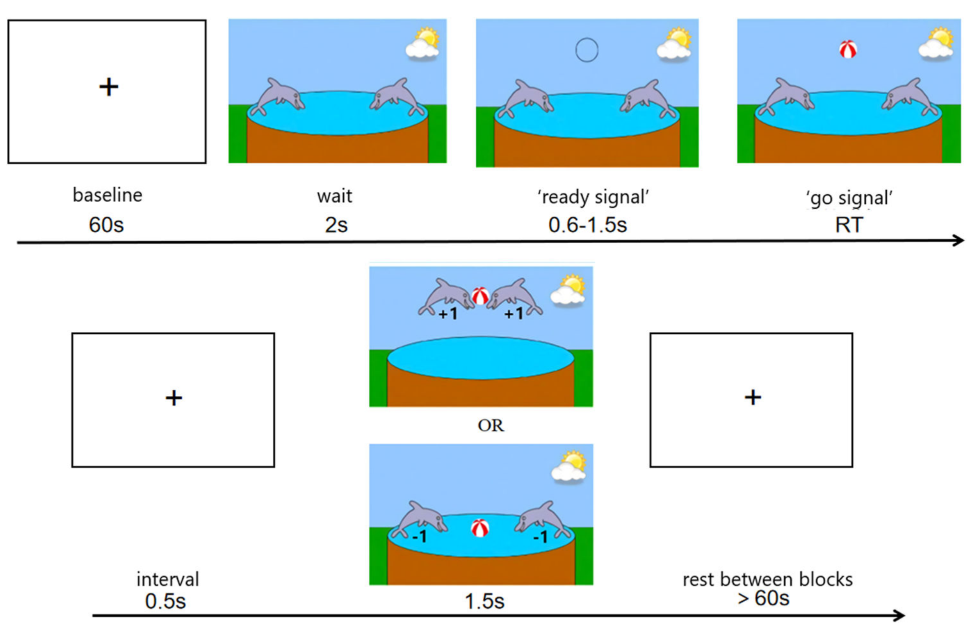


Fig. 1. Cooperative computer game task.

light room, where dyads sat comfortably side by side. Brain electrical activity during cooperative computer game task was recorded simultaneously and continuously using two 32-channel portable EEG systems (BrainAmp, Brainproducts GmbH, Germany) with a sampling frequency of 500 Hz. EEG data were collected with electrode impedances below 5 k ohms. EEG signals were referenced offline to the averaged mastoid (TP9 and TP10) and band-pass filtered in the range of 1 to 40 Hz. Ocular artifacts were removed from the EEG using ICA component rejection by using EEGLAB. Using manual inspection to remove strong eye movements or other movement artifacts. Trials marked as artifacts were excluded from subsequent analysis. The final mean number of valid trials was 23.54 for the successful cooperation condition, 22.00 for the failure cooperation condition. Onsets were set as the points where feedbacks of the cooperative computer game were displayed. The artifact-free EEG signal from each trial was segmented from 1000 ms before to 1500 ms after the onset. EEG data were transformed by Short Time Fourier Transform (STFT). To examine the inter-brain synchrony during cooperation, we focused on the theta frequency band (4–7 Hz), which are associated with judgment, executive control and behavioral change (Cavanagh et al., 2010). Dan Glauser and Scherer (2008) indicated theta band activation may be a promising focus for investigations concerning subjective feeling emergence (Dan Glauser & Scherer, 2008). In addition, theta inter-brain synchrony was associated with the social interaction and the behavioral performance of the dyads (Barraza et al., 2020).

To compute brain-to-brain synchrony between dyads in the processing of the successful and the failure feedbacks during cooperation, we employed a phase synchrony measure known as phase locking value (PLV). PLV has been developed to measure whether the signals from the two interacting participants are phase locked across time and reflected the inter-trial variance of the phase difference between participants (Burgess, 2013). In line with previous hyperscanning research (Barraza et al., 2020; Mu et al., 2016), the inter-brain PLV at a given time t and frequency f was calculated as the absolute value of the sum of the phase φ differences of two electrodes (j, k) from two individuals of a dyad across N epochs. The frequency resolution was set to 1 Hz, and the window size was set to 0.2 s in Matlab. The average PLV between the onset of the stimulus and 1.5 s in the theta frequency band (4–7 Hz) was calculated, with a baseline time of 1000 ms. Finally, we selected the inter-brain synchronous activity between −200 and −800 ms as the baseline state, performed a baseline deduction to examine the state of inter-brain synchronous activation following stimulus presentation, and we selected the time window of interest based on the temporal region in which inter-brain synchronous activation is concentrated. Inter-brain PLV was calculated at the representative electrode of the frontal regions (Fp1, Fp2, F7, F3, Fz, F4, and F8) and parietal-occipital regions (P7, P3, Pz, P4, P8, O1, Oz, and O2) (Sanger et al., 2012).

$$PLV_{j,k,t} = N^{-1}\left|\sum_{k=1}^{N} e^{i[\varphi j(f,t)-\varphi k(f,t)]}\right|$$

To demonstrate the existence of neural synchronization when peers experience different task feedback together, the surrogate data was established similar to prior interbrain research (Barraza et al., 2020; Pérez et al., 2017). The surrogate data was created with signals from different experiments, but preserving the sitting position of each participant in dyads (left or right). For example, participant A_{left} from the left in the first pair was paired with player B_{right} from the right in a random pair. By shuffling the dyads, the indexes of the theta interbrain synchrony that would be expected by chance were obtained. Using Mann-Whitney test, we compared the real and surrogate data to assess the control distribution of the experimental effect. The interbrain synchrony of the real data was significantly different from that of the surrogate data ($ps < .05$). The interbrain synchrony of the real data was then used in a series of subsequent statistical analyses.

The inter-brain PLVs were assessed using 2 (Group: mindfulness group vs. non-mindfulness group) × 2 (Condition: successful cooperation vs. failure cooperation) × 2 (Brain areas: frontal region vs. parietal-occipital region) repeated measures ANOVAs, with Condition and Brain area as within-subject variable and Group as a between-subject variable. Using SPSS 20.0 to evaluate the inter-brain PLV. The significance level was set at $p < .05$, and Greenhouse-Geisser correction was applied to p values associated with multiple-df comparisons. Partial eta squared was reported as a measure of effect size. Finally, in order to explore the potential correlations between participants' behavioral performance and inter-brain synchrony, Pearson correlation analysis was employed. The correlation analysis was conducted between the inter-brain synchrony and success rate of all participants under failure conditions and between the inter-brain synchrony and success rate under successful conditions. The significance level was set at $p < 0.05$ (two-tailed), and analyses were conducted using SPSS software (version 20.0).

To rule out the possible impact of relevant variables of the dyads' social interactions on our findings, demographic variables, the level of depression, the level of anxiety, closeness to the interacting partner, trait mindfulness and interpersonal competence were examined. Repeated measures ANOVAs were used and these relevant variables were set as the covariates. The results of the repeated measures ANOVA indicated that there were no significant main effects of demographic variables and other examined variables on the inter-brain PLV between the mindfulness and non-mindfulness groups (see Supplementary 2).

The data of this study are available from the corresponding author, upon request.

Results

Behavioral results

The results of descriptive statistics for RTs and success rates for each group of participants under different conditions were shown in Table 1.

A 2 (Group: mindfulness group vs. non-mindfulness group) × 2 (Condition: successful cooperation vs. failure cooperation) repeated measures ANOVA was conducted to examine the differences in the RTs of the cooperative computer task between the mindfulness group and control group. Results showed that the main effect of Group was not significant, $F(1, 80) = 0.05$, $p = .822$, $\eta_p^2 = 0.00$. The main effect of Condition was not significant, $F(1, 80) = 1.50$, $p = .225$, $\eta_p^2 = 0.02$. The interaction of Group × Condition was also not significant, $F(1, 80) = 0.44$, $p = .511$, $\eta_p^2 = 0.01$.

The performance of the cooperative computer task was indexed by the success rate of cooperation, which was calculated as the ratio between the number of successful trials and the total number of experiment trials. T-tests showed that there was no significant difference in cooperative successful rate between the mindfulness and non-mindfulness groups ($p = .515$).

Inter-brain synchrony

First, for interbrain synchrony in feedback epochs up to 1.5 s, we

Table 1
Behavioral Performance of Mindfulness Group and Non-mindfulness Group in Different Conditions.

Behavioral performance	Conditions	Mindfulness group ($M \pm$ SD)	Non-mindfulness group ($M \pm$ SD)
RTs	Success	319.53 ± 160.04 (ms)	318.88 ± 105.48 (ms)
	Failure	324.60 ± 99.24 (ms)	335.87 ± 72.70 (ms)
Valid trials (for EEG analysis)	Success	22.90 ± 5.48	23.10 ± 5.91
	Failure	20.81 ± 4.93	21.55 ± 5.50
Success rate	/	.49 ± 0.11	.52 ± 0.11

performed a whole-brain average and observed the temporal characteristics of interbrain synchrony in the theta band to lock in the time window of interest (see Fig. 2). Based on this, the 0–500 ms after the feedback onset was selected as the time window of interest, and the PLV values in this time window are extracted for further analysis. Four 30-by-30 connectivity matrices were plotted based on the PLV values of the theta band between the EEG channels of all the peer dyads (see Fig. 3).

The 2 (Group: mindfulness group vs. non-mindfulness group) × 2 (Condition: successful cooperation vs. failure cooperation) × 2 (Brain areas: frontal region vs. parietal-occipital region) repeated measures ANOVA on the inter-brain phase synchrony in the theta band was conducted. We found that the main effect of Condition was significant, $F(1,39)=8.23$, $p=.007$, $\eta_p^2=0.17$. Greater theta inter-brain synchrony during the cooperative computer game tasks was observed in the dyads in the successful cooperation conditions as compared to those in the failure cooperation conditions. The main effect of Group was also significant, $F(1,39)=4.63$, $p=.038$, $\eta_p^2=0.11$. Greater theta inter-brain synchrony during the cooperative computer game tasks was observed in mindfulness group as compared to those in non-mindfulness group. The main effect of Brain areas was not significant, $F(1, 39)=1.71$, $p=.198$, $\eta_p^2=0.04$.

The interaction of Group and Condition was significant (see Fig. 4), $F(1,39)=4.29$, $p=.045$, $\eta_p^2=0.10$. Post-hoc tests showed that greater theta inter-brain synchrony of the cooperative computer game tasks was observed in the mindfulness group than the non-mindfulness group in the successful cooperation conditions, $p=.005$. There was no significant difference in the theta inter-brain synchrony between the mindfulness group and the non-mindfulness group in the failure cooperation conditions, $p=.757$. For the dyads in mindfulness group, greater theta inter-brain synchrony was observed in the successful cooperation conditions as compared to those in the failure cooperation conditions, $p=.001$. For the dyads in non-mindfulness group, there was no significant difference in the theta inter-brain synchrony between the successful cooperation conditions and the failure cooperation conditions, $p=.581$.

The interaction of Brain areas and Condition was also significant (see Fig. 4), $F(1,39)=4.66$, $p=.037$, $\eta_p^2=0.11$. Post-hoc tests showed that at the frontal region, greater theta inter-brain synchrony of the game was observed in the successful cooperation conditions as compared to those in the failure cooperation conditions, $p=.002$. For the parietal-occipital region, there was no significant difference in the theta inter-brain synchrony between the successful cooperation conditions and the failure cooperation conditions, $p=.081$. Post-hoc tests also showed that greater theta inter-brain synchrony was observed at the frontal region as compared to those at the parietal-occipital region in the successful cooperation conditions, $p=.044$. However, there was no significant difference between the frontal and parietal-occipital regions in the failure cooperation conditions, $p=.614$.

The interaction of Brain areas and Group was not significant, $F(1,39)=0.11$, $p=.745$, $\eta_p^2=0.00$. The interaction of Brain areas × Condition× Group was also not significant, $F(1,39)=1.95$, $p=.171$, $\eta_p^2=0.05$.

To examine the possible effects of mindfulness on other frequency bands, similar analysis was conducted in other EEG frequency bands. At other EEG frequencies, none of the interactions were significant (see Supplementary 3). To clarify the potential effect mindfulness may have on inter-brain synchrony in the baseline time window, we extracted the whole brain PLV values in the baseline time widow of all participants and conducted a repeated measures ANOVA with 2 (Condition: successful vs. failure) * 2 (Group: mindfulness vs. non-mindfulness) design. The results showed that neither the main effect nor the interaction was significant (see Supplementary 4). The analysis of the potential effects of the outliers presented in fig4 was conducted, and the results were also supplemented in Supplementary 4.

To test our PLV results against the potential influence of common sources and demonstrate the existence of neural synchronization between interaction pairs, the surrogate dataset was created. For all eighty-two participants, the combinations of real pairs were shuffled randomly to ensure that participants in the same position (sitting on the left or right) were assigned to someone sitting in another position who was not in the task together but took the same task. As the order of feedbacks differed across pairs, we adjusted the data and matched different conditions between random pairs as same as the procedure in the previous hyperscanning research (Jing et al., 2012). In this way, a surrogate data set with new 41-dyad random samples was created. Their

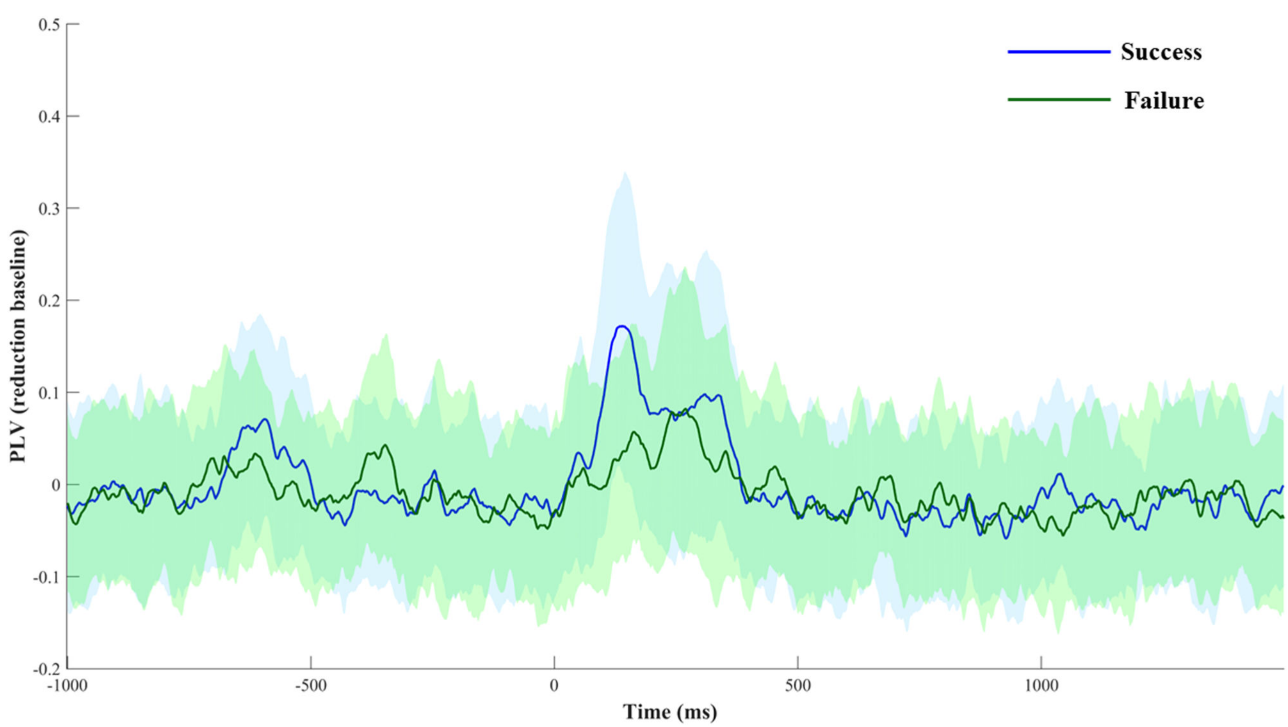


Fig. 2. Temporal distribution of whole brain activation of PLV values in theta band (baseline corrected). Shades indicated ± 1SD.

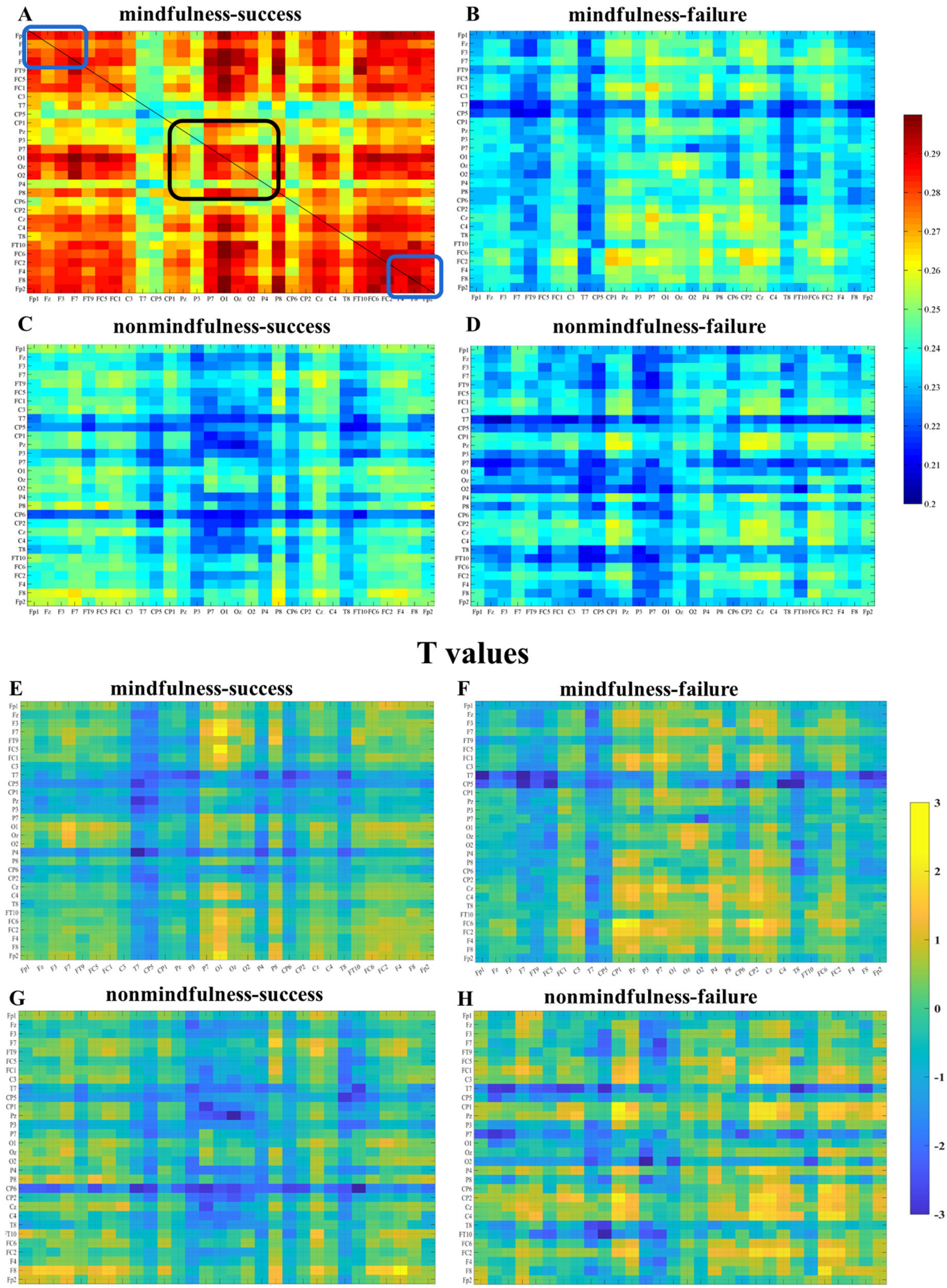
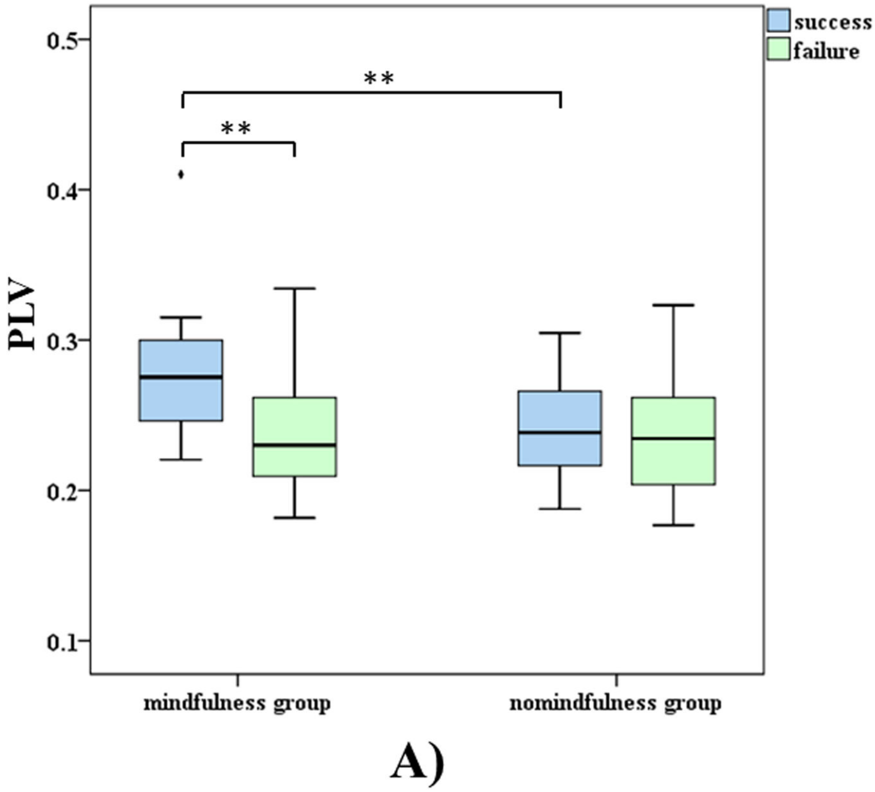


Fig. 3. Inter-brain PLVs matrices of all electrode channels between peer dyads and the corresponding t-values (one-sample *t*-test by taking group-mean values) matrices in mindfulness group-cooperation success condition (A) and (E), mindfulness group-cooperation failure condition (B) and (F), non-mindfulness group-cooperation success condition (C) and (G), and non-mindfulness group-cooperation failure condition (D) and (H). The horizontal and vertical coordinates of the matrix indicated the 30 scalp electrode channels for the left and right individuals of dyads. The regions marked in the blue boxes are the frontal regions and the black box are the parietal-occipital regions in (A).



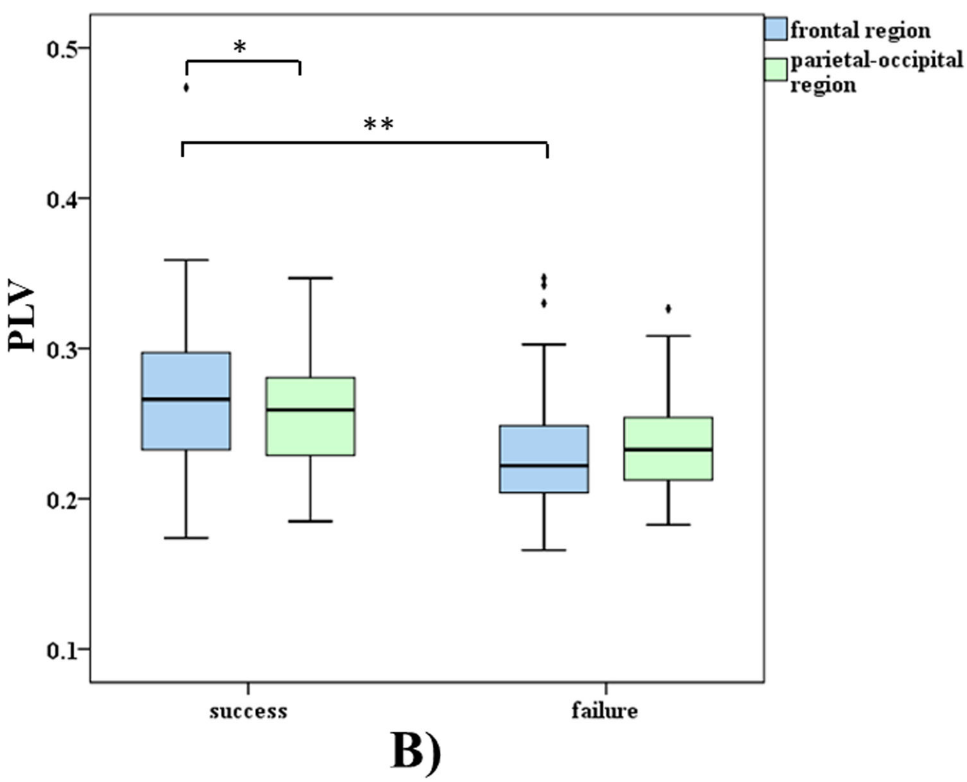


Fig. 4. A) The average of Theta band interbrain synchrony (PLV) at frontal region and parietal-occipital region between mindfulness group and non-mindfulness group in different conditions; B) Theta band interbrain synchrony (PLV) between different conditions at frontal region and parietal-occipital region. Center line indicates the median; box outlines show 25th and 75th percentiles, and whiskers indicate 1.5× the interquartile range.

inter-brain synchrony in the theta band was calculated using the same method, resulting in PLV values for at random levels. The Mann-Whitney U test was performed for differences between inter-brain synchrony calculated from the real data and the surrogate data. The results showed that there was a significant difference in the distribution of the inter-brain synchrony in the real interacting dyads and the random pairs (p = .008).

Correlation between inter-brain synchrony and behavioral performance

To examine the relationship between inter-brain synchrony and the performance in the cooperative task, correlation analyses were conducted between the success rate of cooperation and the theta inter-brain synchrony during the task in different conditions between the mindfulness and non-mindfulness groups (see Table 2). In the condition of failure, a significant positive correlation was found between the success rate of cooperation and theta inter-brain PLV in both the mindfulness group (r w= 0.48, p = .027) and the non-mindfulness group (r w= 0.48, p = .032). In the condition of success, a significant negative correlation was found between the success rate of cooperation and theta inter-brain PLV only in the non-mindfulness group ($r = -0.60$, p = .005), but not the mindfulness group ($r = -0.28$, p = .212).

Discussion

In social contexts, when individual performance affects the benefits of collaborators, activations of many brain regions are involved in the process of the outcome evaluation or performance monitoring (Koban & Pourtois, 2014). When the results of the cooperation affect the benefits of others, it's also important to examine the neural basis of feedback in the context of social interaction. Previous studies have found that mindfulness practice can improve individuals' social understanding, empathy, and interpersonal coordination (Block-Lerner et al., 2007), which can promote cooperative performance between interacting individuals (Wang et al., 2019). However, there is little neuroscientific evidence exploring the relationship between mindfulness and cooperative interaction in naturalistic settings. In this study, we used hyperscanning technique to investigate the neurophysiological mechanism of the effect of mindfulness on brain synchrony between interacting individuals in a cooperative game task, focusing on the processing of cooperative feedback.

Inter-brain synchrony can reflect the level of behavior and interpersonal synchrony (Cui et al., 2012). The neural aspect of interpersonal and behavioral synchrony is suggested to be the temporal coordination of concurrent brain activations between interacting individuals (Balconi & Fronda, 2020a). The study found that greater theta inter-brain synchrony was observed in the mindfulness group than in the non-mindfulness group in the processing of the successful and the failure feedbacks during cooperation. Previous research suggested that the theta band is associated with social empathy and cognitive control (Balconi et al., 2015; Billeke et al., 2013). The increased inter-brain synchrony may reflect a better social understanding and empathy among interacting individuals (Cui et al., 2012). This result was in line with the findings from prior research that mindfulness practices benefit

Table 2
Correlation between the success rate of cooperation and the interbrain synchrony in different groups under different conditions.

Variables	1	2	3	4	5
1. Success rate					
2. PLV- mindfulness successful	−0.28				
3. PLV- mindfulness failure	.48*	.32			
4. PLV- non-mindfulness successful	−0.60	.28	.33		
5. PLV- non-mindfulness failure	.48*	−0.16	.11	.04	

Note: *p<.05, **p<.01.

individuals in the interpersonal domains by promoting social coordination and connection (Carson et al., 2004). Previous research indicated that mindfulness enables individuals to focus their attention on current emotions and feelings and to deal with them in an accepting manner (Reina & Kudesia, 2020). In addition, research has shown that accepting attitudes toward emotions and feelings have benefits for individual empathy, including the ability to consider problems from the perspective of others and understand their emotional reactions (Davis, 1983). In this case, mindfulness might result in the improvement of individuals' empathy and understanding during interactions (Wang et al., 2019), leading to more consistent neural coordination with peers when processing information.

The present study found that greater theta inter-brain synchrony was observed after receiving positive feedback in the successful condition than in the failure condition, especially in the mindfulness group. As to successful cooperation, previous studies indicated that the processing of positive feedback in social interaction is closely related to interpersonal trust and interpersonal intimacy (Duan et al., 2020; Flores et al., 2018). Positive feedback in social interactions also contributes to people's self-enhancement (Hepper et al., 2011). Although there are relatively few studies examining positive feedback-induced inter-brain synchrony, researchers have actually found that experimentally induced positive external feedback was able to induce a corresponding increased prefrontal cortex (PFC) responsiveness in participant dyads, even accompanied by better cognitive performance (Balconi & Vanutelli, 2017). We can then speculate that the positive feedback derived from successful cooperation may elicit higher frontal lobe activation in individuals and partners, triggering positive empathy and thus higher inter-brain synchronization. The results of this study provided neuroscientific evidence illuminating the mechanism that accounts for the improving interpersonal and neural synchronization of mindfulness practices in human cooperative behavior.

The present study also found that the inter-brain synchrony in the frontal lobe was greater than that in the parietal-occipital region in the processing of successful cooperation feedback. Previous studies have shown that the frontal region is related to intention comprehension during social interaction (Thornton et al., 2019). Activations of the frontal region allow individuals to predict the intentions and behaviors of others, thereby regulating current interactions during cooperation (Barraza et al., 2020). The quality of cooperative behavior can be indexed by the level of frontal region activation (Liu et al., 2016). Greater inter-brain synchrony in the frontal brain areas (e.g., DLPFC and FPC) might also reflect the increased connection between interacting individuals during cooperation (Reindl et al., 2018). Overall, the result demonstrated an overall increase of inter-brain synchrony in the frontal brain region during social interaction as in the previous literature (Costa et al., 2006).

In this study, a significant positive correlation was found between the success rate of cooperation and theta inter-brain synchrony under the failure cooperation conditions in both groups. However, the success rate of cooperation was significantly negatively correlated with the theta inter-brain synchrony under the successful cooperation conditions only in the non-mindfulness group, but not the mindfulness group. The greater inter-brain synchrony within the interacting dyads in the failure feedback conditions reflected an increased exchange of information when they failed the cooperation task. It generally presented an ability of behavioral modification and amendment when facing difficulties in the task (Dall et al., 2005). Such behavioral modification and amendment after failure might come from the biosignals between dyads. As the indicator of a higher level of mutual temporal alignment of behaviors, the higher neural coordination they presented in the task, the higher level of cooperative behavior they had in the task (Wiltermuth & Heath, 2009). In this case, it is not hard to understanding the positive correlation between the inter-brain synchrony in the failure cooperation conditions and the performance in the cooperative task in both groups.

On the contrary, in the successful condition, the significant negative correlation between the success rate of cooperation and the inter-brain synchrony was found only in the non-mindfulness group, but not the mindfulness group. For the non-mindfulness group, the successful feedback in the cooperation task may increase the emotional sharing for the success within the two partners, which was indicated by a higher level of inter-brain synchrony (Costa et al., 2006). However, the emotional exchange and rumination toward success within the two partners might sharpen the information exchange during the task, which also may hamper the performance in the cooperative behavior. In this case, it is not hard to understand the negative correlation between the inter-brain synchrony in the successful cooperation conditions and the performance in the task in non-mindfulness group. However, the negative correlation between the success rate of cooperation and the inter-brain synchrony was not significant in the mindfulness group. Since mindfulness promotes self-awareness but not emotional rumination toward success, mindfulness practice in the present study might blur the relationship between the emotional exchange and rumination and the task performance based on behavioral coordination. In this case, the negative correlation between inter-brain synchrony and task performance was not related anymore.

Finally, as demonstrated in the supplementary material, the main effects of group and feedback were found in the delta band, but no significant interaction was found. The greater delta-band interbrain synchrony in the mindfulness group may be associated with a common elevation of attention to internal processing during the performance of a mental task (Harmony et al., 1996), whereas the greater delta-band interbrain synchrony for successful feedback processing may reflect sensitivity to the assessment of positive feedback attributes (Bernat et al., 2015). However, the current findings of delta-band interbrain synchrony are still not enough to verify that it can be used as a reliable indicator of the effects of mindfulness meditation on feedback processing during interpersonal interaction.

Limitations and future direction

The present study examined the inter-brain synchrony between interacting individuals in a cooperative task. However, due to the impact of verbal communication on EEG quality, subjects were not allowed to communicate verbally during the task. Studies have found that verbal communication is crucial in social interactions (Gvirts & Perlmutter, 2020). Therefore, future studies could consider incorporating oral communication into the experimental interaction process. In the cooperative task, participants received feedback information about the success or failure of the current trial. However, due to the lack of information about who is fast and who is slow in the failure feedback, the amount of information of positive and negative feedback may be unequal, which may also affect the interbrain synchrony of the theta band. To examine this possible effect, future studies could consider designing responses that indicate how fast or slow participants respond in the cooperative task.

In performing the data analysis, we selected the time window of interbrain synchrony activation for analysis by visual inspection. However, according to the previous study (Luck & Gaspelin, 2017), simpler collapsed localizers, mass univariate analyses, or other mathematical ways to isolate latent components take advantage in the selection of the time window of interest. Therefore, using these methods to select the components of interest could be an alternative and unbiased approach to the selection of the time window of interest in the future study. Since the cooperative tasks were measured with an EEG device, the participants' signals were more susceptible to perturbation by motion artifacts. And due to the nature of dual EEG data processing, we had to exclude the trials whenever there was any one of the participants had artifacts. Therefore, it resulted in a relatively small number of valid trials. Increasing the number of valid trials to a reasonable extent and using fNIRS devices that are less subject to motion interference are worthy of consideration for future research.

Moreover, all of the participants in the present study had no prior experience in the mindfulness practices. Future studies should examine how people differ in the level of mindfulness influence their performance in a cooperative task at behavioral and neural levels. Furthermore, the findings were based on a short time mindfulness induction rather than the typical 8-weeks mindfulness training. To examine a longer and lasting effect of mindfulness practice, future research should explore the impact of mindfulness on cooperative behavior with a longer duration.

Prior research showed that theta band activity may be affected by the novelty of stimuli (Cavanagh et al., 2012; Lee et al., 2014). Although there is no direct hyperscanning evidence showing that phase synchronization between brains could be induced by novel stimuli, it is worth examining how the stimuli feedback per se affects the inter-brain synchrony. Finally, the present study focused on examining the potential effects of short-term mindfulness interventions on interpersonal neural synchrony, and did not focus on the indicators of intra-brain connectivity. It would also be interesting and meaningful to look at intra-brain connectivity, such as whole-brain connectivity and local connectivity. The measurements of functional brain networks could be considered in future studies in mindfulness.

Conclusion

Notwithstanding these limitations, the findings of the current study contribute to the literature on the impact of mindfulness on cooperation and social interaction. The current findings suggest the implication of a hyperscanning approach to explore the behavioral and psychophysiological effects of mindfulness practices in real social interaction settings. As cooperative behavior is essential in social lives, examining the positive impact of mindfulness on cooperation in a broaden setting would be a new direction for the practical implication of mindfulness. Although no significant difference has been found from the behavioral data, the present study suggested a neural mechanism for the effects of mindfulness on improving interpersonal understanding and synchronization in cooperation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijchp.2023.100396.

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