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# Interpersonal coordination enhances brain-to-brain synchronization and influences responsibility attribution and reward allocation in social cooperation

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ABSTRACT

Fair distribution of resources matters to both individual interests and group harmony during social cooperation. Different allocation rules, including equity- and equality-based rules, have been widely discussed in reward allocation research; however, it remains unclear whether and how individuals' cooperative manner, such as interpersonal coordination, influence their subsequent responsibility attribution and reward allocation. Here, 46 dyads conducted a time estimation task—either synergistically (the coordination group) or solely (the control group)—while their brain activities were measured using a functional near-infrared spectroscopy hyperscanning approach. Dyads in the coordination group showed higher behavioral synchrony and higher interpersonal brain synchronization (IBS) in the dorsal lateral prefrontal cortex (DLPFC) during the time estimation task than those in the control group. They also showed a more egalitarian tendency of responsibility attribution for the task outcome. More importantly, dyads in the coordination group who had higher IBS in the dorsal medial prefrontal cortex (DMPFC) were more inclined to make egalitarian reward allocations, and this effect was mediated by responsibility attribution. Our findings elucidate the influence of interpersonal coordination on reward allocation and the critical role of the prefrontal cortex in these processes.

## 1. Introduction

The last few decades have seen a growing interest in the cognitive and neural basis of resource distribution (Feng et al., 2021; Walster et al., 1973). Justice evaluation and the sense of fairness influence immediate emotional and behavioral reactions (Sanfey et al., 2003) and also future social behaviors/inclinations (Barker et al., 2012). To date, previous literature has typically discussed different distribution rules, including equity- and equality-based distribution rules (Deutsch, 1975; Melamed, 2012). The equity-based rule argues that individual rewards should match the work effort or contribution (Adams, 1965; Homans, 1974), whereas the equality-based rule holds that people have egalitarian motives in resource distribution and tend to split rewards evenly among group members regardless of their effort or contribution (Deutsch, 1975). Previous studies have provided empirical evidence that individual work effort during the production phase plays a key role in shaping fairness evaluation during reward allocation (e.g Cappelen et al., 2014.). Moreover, early social psychologists also argued that task features influence individual work effort in small-group performance (Kerr and Bruun, 1983), leading to an open and interesting question: does the manner of cooperation—such as whether it is interpersonal coordination—modulate decisions on reward distribution?

In the present study, we explored the effect of interpersonal coordination on reward allocation based on the team's outcome. Previous studies have reported that interpersonal coordination may foster prosociality among individuals. For example, synchronized walking, singing, and tapping could increase prosocial behaviors/inclinations such as group bonding (Lumsden et al., 2014), affiliation (Hove and Risen, 2009) and helpfulness (Cirelli et al., 2014). The goal of maintaining group harmony leads to greater use of the equality principle in resource allocation (Barrett-Howard and Tyler, 1986; Fadil et al., 2005). Thus, following interpersonal coordination, individuals may tend to make prosocial decision and share rewards equally between all contributors rather than maximize their self-interest. However, interpersonal coordination might also lead to self-serving allocation. The so-called "self-serving bias" refers to the pervasive phenomenon where people tend to take credit for a positive outcome and make external attributions for negative out-

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comes (for a review, see Mezulis et al., 2004). This bias often occurs in an ambiguous interpersonal context without clear feedback for individual performance (Deffains et al., 2016; Wang et al., 2017) because of unclear personal responsibility when the link between identity and event is missing (Schlenker et al., 1994). For instance, ambiguity has been shown to increase self-serving assessments of ability (Dunning et al., 1989) and self-serving allocation (Haisley and Weber, 2010; Rodriguez-Lara and Moreno-Garrido, 2012). In a coordination task, it is relatively difficult to provide precise feedback for individual performance. Thus, the second possibility is that coordinative cooperation leads to self-serving bias and selfish reward allocation.

To better analyze the tendency for prosocial or self-serving behavior, we measured individuals' acknowledgment of responsibility after interpersonal coordination. In past studies of equity- and equality-based distribution rules, individual objective contribution (effort) was commonly manipulated and calculated to measure how much reward distributors rely on this information (Bierhoff and Rohmann, 2011; Cappelen et al., 2014). However, we proposed that the responsibility attribution, i.e. subjective rating of individual contributions, matters more especially in an ambiguous condition where feedback regarding one's contribution is unclear. Our previous study showed that subjective rating of responsibility was distinct from objective contribution and influenced certain participants' behavioral adjustment in cooperation (Li et al., 2018). Another study also demonstrated that concern about individual responsibility influences fairness during reward redistribution (Cappelen et al., 2010). Therefore, we measured responsibility attribution in the present study and predicted that it would play an important mediation role between task-related psychological activities and decision-making in resource allocation.

We further focused on the related neural mechanisms underlying the effect of interpersonal coordination on reward distribution. Given the interactive nature of interpersonal coordination, it is imperative to adopt the hyperscanning technique (i.e., the measurement of brain activity from two or more individuals simultaneously) (Babiloni and Astolfi, 2014; Czeszumski et al., 2020). Meanwhile, due to its mobility, relatively low cost, and suitable temporal and spatial resolution, recent hyperscanning studies have used functional near-infrared spectroscopy (fNIRS) to investigate interpersonal brain synchronization (IBS) during social coordination (Amyot et al., 2020; Ferrari, and Quaresima, 2012; Tak and Ye, 2014; Tak et al., 2016). For instance, increasing IBS has been reported in various coordinative tasks such as cooperative singing/humming (Osaka et al., 2014, 2015) and coordinated group walking (Ikeda et al., 2017). Taking advantage of the fNIRS hyperscanning technique, we measured IBS data as the neural index of how well two partners coordinated with each other during social interaction.

The brain regions of interest were the right temporal–parietal junction (rTPJ) and the prefrontal cortex, including the dorsal medial prefrontal cortex (DMPFC) cortex, the frontopolar and the dorsal lateral prefrontal cortex (DLPFC). These regions were selected due to their distinct yet complementary functions in supporting social coordination; they frequently have been investigated simultaneously (Cui et al., 2012; Gvirts and Perlmutter, 2020). Specifically, the DMPFC, frontopolar cortex and rTPJ are associated with mentalization (theory of mind), mutual social attention system, and shared self-other representations that are essential for cooperation (Cheng et al., 2015; Cui et al., 2012; Czeszumski et al., 2020; Decety and Lamm, 2007; Gvirts and Perlmutter, 2020; Liu et al., 2016). The DMPFC cortex and rTPJ have shown increased IBS during cooperation experiments compared to control conditions (Funane et al., 2011; Liu et al., 2016; Mccabe et al., 2001; Miller et al., 2019; Nozawa et al., 2016). On the other hand, the DLPFC is part of the executive function system and also plays an important role in top-down control over cognitive and emotional processes (MacDonald et al., 2000; Grossmann, 2013; Balconi and Pagani, 2015). Enhanced IBS of the DLPFC was also frequently observed in previous fNIRS-based hyperscanning studies (Cheng et al., 2015; Reindl et al., 2018).

In light of the above, we wanted to explore how individuals attribute responsibility and distribute rewards after interpersonal coordination. In the current study, participants were asked to conduct a time estimation task either synergistically (the coordination group) or solely (the control group) (Hu et al., 2017) while their brain activities were recorded using fNIRS. We first hypothesized (hypothesis 1) that interpersonal coordination elicits higher levels of behavioral coordination and IBS across the two participants in a dyad in the coordination group compared to the control group. Our second hypothesis was that interpersonal coordination would influence participants' responsibility attribution and reward allocation. Individuals might perform more prosocially and be more inclined to equalize distribution and promote attribution of shared responsibility during coordination; alternatively, interpersonal coordination might lead an individual to believe that they will put more effort into the task and, therefore, would attribute more responsibility and allocate more reward towards oneself. This hypothesis could be tested by determining participants' decision-making after cooperation (i.e., responsibility attribution and resource allocation) and its relationship with IBS. Previous studies have also found that IBS during interpersonal coordination can predict subsequent mutual helpfulness and mediate the prosocial effect of interpersonal coordination (Hu et al., 2017). Thus, we used correlation analysis, mediation analysis, and multivariate pattern analysis (MVPA) to explore the correlation between behavioral decision-making and univariate/multivariate pattern of neural synchronization.

## 2. Materials and methods

### 2.1. Participants

In total, 92 healthy college students (46 males and 46 females) were recruited as participants. They were randomly assigned as 46 same-gender dyads, with 23 dyads in the coordination group (age, mean ± standard deviation: 21.48 ± 1.91 years) and 23 dyads in the control group (21.67 ± 2.06 years). Gender and age were matched between the two groups (gender: $\chi^2 = 2.788$, $df = 1$, $p = 0.095$; age: $t[90] = -0.47$, $p = 0.64$). The two participants in a dyad did not know each other before the experiment. All participants were right-handed and had a normal or corrected-to-normal vision, and none of them reported a history of neurological or psychiatric disorders. Written informed consent was obtained from each participant before the experiment. Participants were compensated for their participation (65–75 RMB *yuan* based on their performance in the experiment). The study was approved by the Medical Ethical Committee of Shenzhen University.

### 2.2. Experimental procedure and tasks

The two participants were seated on opposite sides of a table in a silent room, separated by their computer monitor and keyboard (Fig. 1A). All participants wore headphones to block keypress sounds and to prevent verbal or nonverbal communication with each other. For each dyad, participants would first have a 3 min resting-state session for collecting baseline fNIRS data, during which they were required to relax and stay motionless. During the formal experimental task session, participants were required to perform a time estimation task and report their responsibility attribution and resource allocation (Fig. 1B). The tasks were conducted using the E-prime 3.0 software (Psychology Software Tools Inc., Pittsburgh, PA, US).

*The time estimation task*: For the coordination group, participants were required to press keys simultaneously with their partner after counting a time in their mind. Specifically, at the beginning of each trial, an integer number (range, 6–10) was displayed in the center of the screen for 500 ms as a cue, representing the target time (in seconds) for participants to estimate. A red fixation point appeared afterward to remind participants to count the time according to the target time displayed. When the participants finished counting, they pressed the response keys ("1" and "2" for the two participants, respectively). The

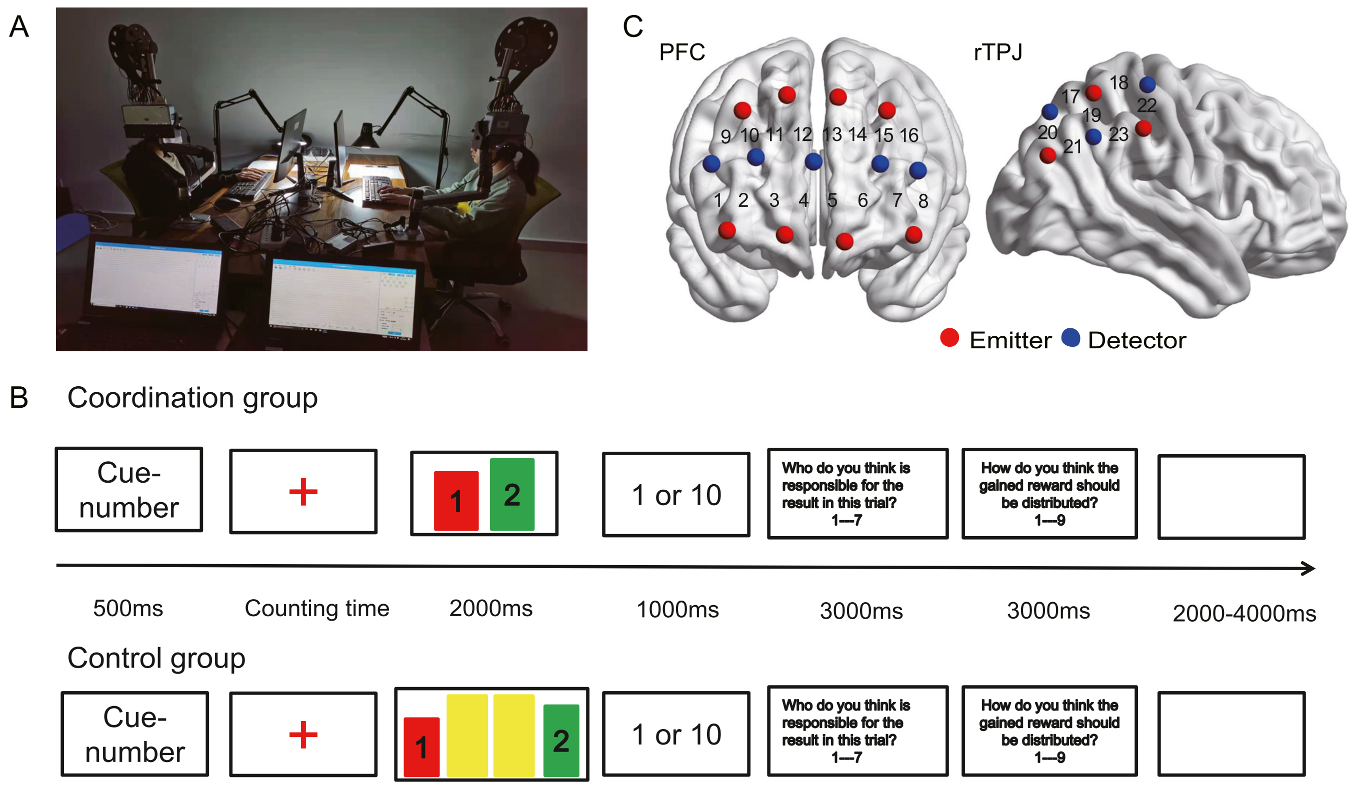


**Fig. 1.** Experimental design. (A) The fNIRS recording setup. (B) Experimental tasks and procedures. The sequence of events and time flow in a trial of the time estimation task are shown. The red and green bars in the feedback screen indicate the counting times of the two participants. The yellow bars for the control group indicate the target times generated by the computer. (C) Probe configuration. The integers on the cerebral cortex indicate the recording channels (CHs). The red dots are the emitters and blue dots are the detectors.

participants were instructed to coordinate with their partners by narrowing the difference in their counting times (i.e., reaction time, RT). In other words, the smaller difference of RTs between two participants in a dyad, the better coordination they had. If the difference in RTs was $< 700$ ms, participants gained 10 points; otherwise, they gained only 1 point. Once the responses had been entered, a feedback screen containing the two participants' counting time (i.e., their RTs, indicated by the height of two bars) was displayed for 2 s to help participants adjust their speed intuitively and synchronize with their partners. Next, the reward outcome that participants gained ("10″ or "1″) was displayed for 1 s. For the control group, although the two participants conducted the task as a team, they were required to synchronize with the computer. In each trial, the computer's counting time was set to the time indicated by the starting prompt, which was the same as for the dyads. Accordingly, four bars were presented in the first feedback screen, indicating the reaction times of the two participants and the corresponding computers. Next, the second feedback screen (reward outcome) was also displayed for 1 s.

*Responsibility attribution and resource allocation:* After each trial of the time estimation task ended, participants from both the coordination group and the control group were asked two questions: "Who do you think is responsible for the outcome?" ("1″ for completely the participant and "7″ for completely their partner); and "How do you think the gained reward should be distributed?" ("1″ for completely distributed to the participant and "9″ for completely distributed to their partner) (Yang et al., 2020). Different scales were used for the two questions to avoid participants' tendency to simply give the same response to both questions. Participants had up to 3 s to answer each question. If they did not respond within that time, they lost the opportunity to choose a trial assignment of their liking as a bonus at the end of the experiment. A random time of 2–4 s was set as the inter-trial interval (Fig. 1B).

The formal experiment task included a total of 4 blocks with 31 trials in each block and a 30 s rest period between blocks. Before the formal experiment, the participants finished 9 practice trials to make sure they understood the rules. During the task, participants were not allowed to communicate with facial expressions or gestures. They could only adjust their time estimation according to the information displayed on the feedback screens. To avoid the social expectation effect, the participants were informed that their evaluations of responsibility attribution and resource allocation were not disclosed to their partners. To enhance participants' involvement in the experiment, the reward outcome and the allocation decision were set to influence the bonus they received after the experiment. Participants were also required to complete questionnaires immediately after they arrived at the laboratory to measure individual personality traits and emotional states, as these can potentially affect coordination and social decision-making (Dang, 2017). No significant difference was found between the coordination and control group (see supplementary materials for more details).

### 2.3. fNIRS data acquisition

We used two of the same NirSmart portable near-infrared brain functional imaging systems (NirSmart, hcmedx, China) to simultaneously collect brain activities for the two participants in each dyad. Based on our hypotheses, two optode probes were used in the present study. One optode probe was placed on the PFC (Fig. 1C), with 8 emitters and 5 detectors forming 16 recording channels. The other optode probe was placed on the right TPJ (rTPJ), with 3 emitters and 3 detectors forming 7 recording channels. The emitter and detector were placed according to the 10–20 system, with Fz and C6 as references. The distance between emitters and detectors was approximately 3 cm. The changes in blood oxygenation at two wavelengths (760 and 850 nm) were measured with a 10 Hz sampling rate.

### 2.4. Data analysis

#### 2.4.1. Manipulation check: coordination performance

Two behavioral indexes were used for each dyad to evaluate interpersonal coordination. We first calculated the absolute difference in RTs between the two participants ($RT_{\text{pp-diff}}$). In Eq. (1), $RT_1$ and $RT_2$ represent the RT of participants 1 and 2, respectively.

$$RT_{pp-diff} = |RT_1 - RT_2| \tag{1}$$

We also calculated the average of the absolute RT differences between the two participants and the target time for the dyad to estimate (6–10 s) randomly generated by the computer ($RT_{\text{pc-diff}}$). In Eq. (2), $RT_{p1}$ and $RT_{p2}$ represent RTs of participants 1 and 2, respectively, and $RT_C$ is the target time estimate by the dyads.

$$RT_{pp-diff} = \left(\left|RT_{p1} - RT_c\right| + \left|RT_{p2} - RT_c\right|\right)/2 \tag{2}$$

These two behavioral indexes were first calculated for each trial and then averaged across all trials for each participant. Independent sample $t$-tests were then used to examine whether there was a remarkable difference between the coordination and control groups. In addition, we also compared the raw RT scores between the two groups to exclude their potential influence on IBS data.

#### 2.4.2. Responsibility attribution and reward allocation

We asked participants to provide their subjective rating of responsibility attribution on a straightforward scale, i.e. "1″ for attributing responsibility to oneself and "7″ for attributing responsibility to the partner. To evaluate how coordination influences collectiveness and subsequent behaviors, we normalized the responsibility attribution by transforming it to a continuum scale ranging from shared responsibility/equal distribution to individual responsibility/independent distribution (Loehr, 2018). Specifically, we subtracted 4 from the original rating scores and converted the scale from the original 1–7 to -3–3. Next, the absolute value was considered so that "0″ corresponded to "we were equally responsible for the result," and larger values meant one individual (participants 1 or 2) contributed more to the outcome.

Scores for reward distribution were processed similarly to those for responsibility attribution. We subtracted 5 from the original scores and used the absolute values such that the final scores ranged from 0 to 4. Therefore, the smaller the value on the new scale, the higher the shared responsibility, and the more equal the monetary reward distribution. Larger values indicated a greater individual responsibility and weaker shared money distribution.

#### 2.4.3. IBS data analysis

Hemoglobin data, including oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) signals, were automatically exported by the recording systems. Our data analysis focused on the HbO time series as the HbO signal is more sensitive to changes in cerebral blood flow than the HbR signal (Cui et al., 2011; Cheng et al., 2019; Fronda and Balconi, 2020). During data preprocessing, we first discarded the initial and final 30 s of the 3 min resting-state session and used the resting-state session as the baseline for the task session (Chen et al., 2020; Tang et al., 2016). Wavelet filtering (0.02–0.5 Hz) and correlation-based signal improvement techniques were used to remove motion artifacts and improve the signal quality (Cui et al., 2010). Finally, principal component analysis was used to remove the global components (Long et al., 2020).

After data preprocessing, we used the wavelet transform coherence (WTC) function to examine the correlation between the two signals on both time and frequency for each dyad (Grinsted et al., 2004). We then used a data-driven approach to define the frequency of interest and channel of interest and a cluster-based permutation test to confirm the IBS effect. To this end, the following steps were carried out:

First, we discarded the frequency band that is generally associated with noise and used the remaining frequency bands (0.015 Hz –1 Hz) for the data analyses (Lu et al., 2021; Zhu et al., 2021).

Second, we used a data-driven approach to define the frequency of interest. To do so, we first averaged the IBS data across all trials and all channels for task phase and rest phase separately, and compared the task IBS and rest IBS across each frequency (0.015 Hz ~ 1 Hz, 73 frequencies) using one-sample $t$-tests, which yielded 73 $p$ values. Note that the input data of each $t$-test included both coordination and control groups to avoid bias (Mayseless et al., 2019). The false discovery rate (FDR) method was then used to control for multiple comparison problems (Benjamini and Hochberg, 1995). The frequency bands that showed larger IBS values in task phase than in rest phase and were retained after FDR correction were considered as frequencies of interest.

Third, we used the same data-driven approach to define the channel of interest. We first averaged the IBS data across all trials and all frequency bands for task phase and rest phase separately, and compared the task IBS and rest IBS across each channel using one-sample $t$-tests, which yielded 23 $p$ values. The input data of each $t$-test also included both coordination and control groups. The channel clusters (≥2) that showed larger IBS values in the task phase than in the rest phase and were retained after FDR corrections were considered as channels of interest. The second and third steps were independent and their order could be exchanged.

Fourth, based on the frequency of interest and channel of interest, we separated the IBS data from the two groups and conducted an independent $t$-test for group comparisons.

Fifth, to confirm whether the IBS measured in the coordination group is a real experimental effect, we ran permutation tests by selecting one participant from an experimental dyad and randomly matching another unrelated participant to calculate the IBS between them. A one-sample $t$-test was then conducted to compare task-related IBS and rest-related IBS on the random 23 dyads (23 was set to match the number of real dyads). This random permutation test was repeated 1000 times. Finally, we compared the observed cluster statistics ($t$-value) with the results of 1000 permutations (Mayseless et al., 2019; Zhu et al., 2021). The permutation tests were conducted in the coordination group and control group separately with the aim of controlling task differences when randomly pairing participants across two groups.

#### 2.4.4. IBS-behavior relationship

To explore the IBS-behavior correlations, we also conducted a data-driven approach to detect a significant correlation between behavioral data and IBS in any frequency and any channel and corrected the two-tailed $p$-values for controlling typeIerrors by the FDR method. We only reported significant correlation results within the range of frequency bands that showed significant differences between the two groups for consistency across different analyses. When we observed different patterns of correlation between behavioral scores and IBS data, we further tested whether there was a significant difference between these correlations in the two groups with the *cocor* tool (Diedenhofen and Musch, 2015).

Furthermore, we conducted a mediation analysis in the two groups to test whether responsibility attribution mediated the IBS and reward allocation. The IBS, responsibility attribution, and reward allocation were submitted to the *PROCESS* toolbox (Hayes, 2013) as the independent variable, mediating variable, and dependent variable, respectively, according to our hypothesis.

To decode the participants' rating of responsibility and reward allocation from IBS, we used an MVPA for all channels and periods at the single-trial level using *The Decision Decoding Toolbox* (Bode et al., 2019). More details of the MVPA method can be found in the supplementary materials.

## 3. Results

### 3.1. Manipulation check: behavioral coordination

An independent $t$-test indicated that the difference in RTs between two participants ($RT_{\text{pp-diff}}$) in the coordination group (565.08 ±

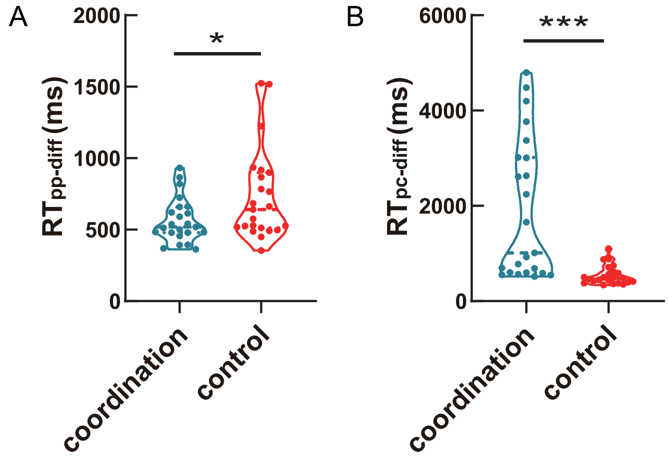


**Fig. 2.** Behavioral manipulation checks. (A) RT differences in time estimation between two participants in a dyad. (B) The average of absolute RT differences between each participant and the target time for the coordination and control groups. Error bars indicate the standard error of the mean $^{*}p < 0.05$, $^{***}p < 0.001$.

32.34 ms) was significantly smaller than that in the control group (734.54 ± 66.95; $t$ [44] = -2.28, $p$ = 0.03, Cohen's $d$ = -0.67) (Fig. 2A). Additionally, the absolute difference in RTs between the two participants and the target time generated by the computer ($RT_{pc\text{-}diff}$) in the coordination group (1906.51 ± 308.21 ms) was significantly larger than that in the control group (541.76 ± 41.51 ms; $t$ [44] = 4.39, $p < 0.001$, Cohen's $d$ = 1.29) (Fig. 2B). The results presented here included all participants and indicate the validity of our manipulation. Additionally, there was no significant difference between the raw RT of the coordination group (mean=7776.29 ms, SEM=484.64 ms) and the control group (mean=7859.11 ms, SEM=50.52 ms), $t$ (44) = −0.17, $p$ = 0.87. The large standard error was observed in the raw RT data between the coordination group (484.64 ms) and control group (50.52 ms), suggesting that different dyads in the coordination group had large variations on deviation from the target time as set by the program because they were required to maintain synchronization within partners in this task.

### 3.2. Behavioral data: responsibility attribution and reward allocation

We first performed an independent-samples $t$-test to examine the differences in transformed responsibility attribution scores between the two groups. The scores in the coordination group (0.53 ± 0.10) were lower than those in the control group (0.95 ± 0.11; $t$ [44] = -2.90, $p$ = 0.006, Cohen's $d$ = -0.87), indicating that participants in the coordination group were more likely to attribute their results to shared responsibility than those in the control group (Fig. 3A). Similarly, analysis of reward allocation showed lower scores in the coordination group (0.87 ± 0.20) than in the control group (1.10 ± 0.17; $t$ [44] = -0.88, $p$ = 0.38), but the difference was not significant (Fig. 3B).

We compared the proportion of receiving good feedback (10 points) in total trials (success rate) between the two groups and found that there was no significant difference between the coordination group (0.76 ± 0.02) and control group (0.76 ± 0.04; $t$ [44] = 0.02, $p$ = 0.987), suggesting the two groups received comparable reward feedback (Fig. 3C).

### 3.3. Interpersonal brain synchronization during interpersonal coordination

Based on the data-driven IBS analysis, a frequency band (0.1–0.2 Hz) was selected as the frequency of interest and channel clusters (one consisted of CH1, CH2, CH3, and CH4 and the other contained CH9, CH10, and CH11) were defined as the channel of interest (Fig. 4A). The independent-samples $t$-tests revealed the averaged IBS of CH9-CH11 was higher in the coordination group (0.04 ± 0.01) than in the control group (0.01 ± 0.01; $t$ [44] = 2.53, $p$ = 0.015, Cohen's $d$ = 0.76, Fig. 4B). On the contrary, the averaged IBS at CH1-CH4 cluster was not significantly different between two groups ($t$ [44] = -0.56, $p$ = 0.58). Importantly, within the CH9-CH11 cluster, the IBS effect in the coordination group ($t$ [22] = 5.57) was survived after permutation test which randomly paired participants ($p$ = 0.001) while this effect ($t$ [22] = 1.49) was not significant in the control group ($p$ = 0.46), (Fig. 4C). The task coherence was visualized using the BrainNet Viewer toolbox (Xia et al., 2013).

### 3.4. Association of the IBS with responsibility attribution and reward allocation

In the coordination group, a data-driven correlation test showed that averaged IBS of frequencies (0.11–0.16 Hz) at CH13 and CH14 in the DMPFC was negatively correlated with responsibility attribution ($r$ [44] = -0.53, $p < 0.001$), but no significant correlations were found in the control group (Fig. 5A). Similarly, averaged IBS was negatively correlated with reward allocation ($r$ [44] = -0.65, $p < 0.001$), but no significant correlations were found in the control group (Fig. 5B). These results still hold when excluded out the outliers in the upper left corner of Fig. 5A&B. We further tested whether there was a significant difference between the correlations in the two groups through the *cocor* tool (Diedenhofen and Musch, 2015). The results indicated that the correlation between IBS and responsibility attribution was different in the coordination group than in the control group ($z$ = -2.95, $p$ = 0.003; two-tailed) and the reward allocation was different in the coordination group than in the control group ($z$ = -3.47, $p < 0.001$; two-tailed). In addition, the responsibility attribution score significantly correlated with reward allocation ($r$ [46] = 0.689, $p < 0.001$). All of the above-mentioned correlation analyses were conducted on data of each participant to explore individual differences and all of the results were corrected by FDR. Correlation results in other channels were reported in the supplementary materials (Fig. S3).

In addition, we conducted a mediation analysis in the two groups to test whether responsibility attribution mediated the IBS and reward allocation. The mean IBS across 0.11–0.16 Hz and collapsed between CH13 and CH14, responsibility attribution, and reward allocation were submitted to the *PROCESS* toolbox (Hayes, 2013) as the independent variable, mediating variable, and dependent variable, respectively. This analysis in the coordination group indicated that the significant total mediating effect was -9.36 (95% CI: [-12.63, -6.10]), (Fig. 5C). Notably, the mediation analyses with other mediating directions did not reach significance ($ps > 0.35$).

Further, the MVPA found that both responsibility attribution and reward allocation scores could be decoded from IBS data of each dyad, and the decoding accuracy of allocation scores from IBS in the lower frequency was different between the two groups ($p < 0.05$, Fig. S1).

## 4. Discussion

In the current study, we employed the fNIRS-based hyperscanning technique to investigate IBS during interpersonal coordination and its influence on subsequent responsibility attribution and reward allocation in social cooperation. In line with our previous studies (Hu et al., 2017), behavioral results and analysis of task-related IBS in the DLPFC confirmed that participants exhibited interpersonal coordination and higher IBS in the coordination group than in the control group. The results also showed that coordinating dyads were more likely to attribute responsibility to the collective than dyads in the control group. Although no between-group difference was found in reward allocation, the influence of coordination on money distribution was evident in individual differences in the coordination group. Specifically, participants with higher IBS in the DMPFC showed more egalitarian reward allocation in the

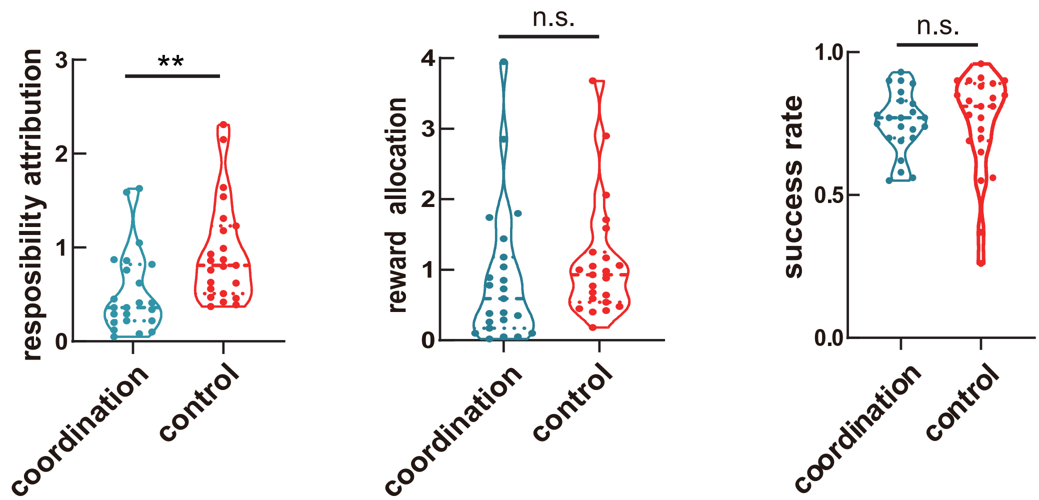


**Fig. 3.** Behavioral scoring. (A) Responsibility attribution scores in the two groups. (B) Reward allocation scores in the two groups. (C) Proportion of good feedback received in total trials (success rate) in the two groups $^{**}p < 0.01$, n.s. denotes not significant.

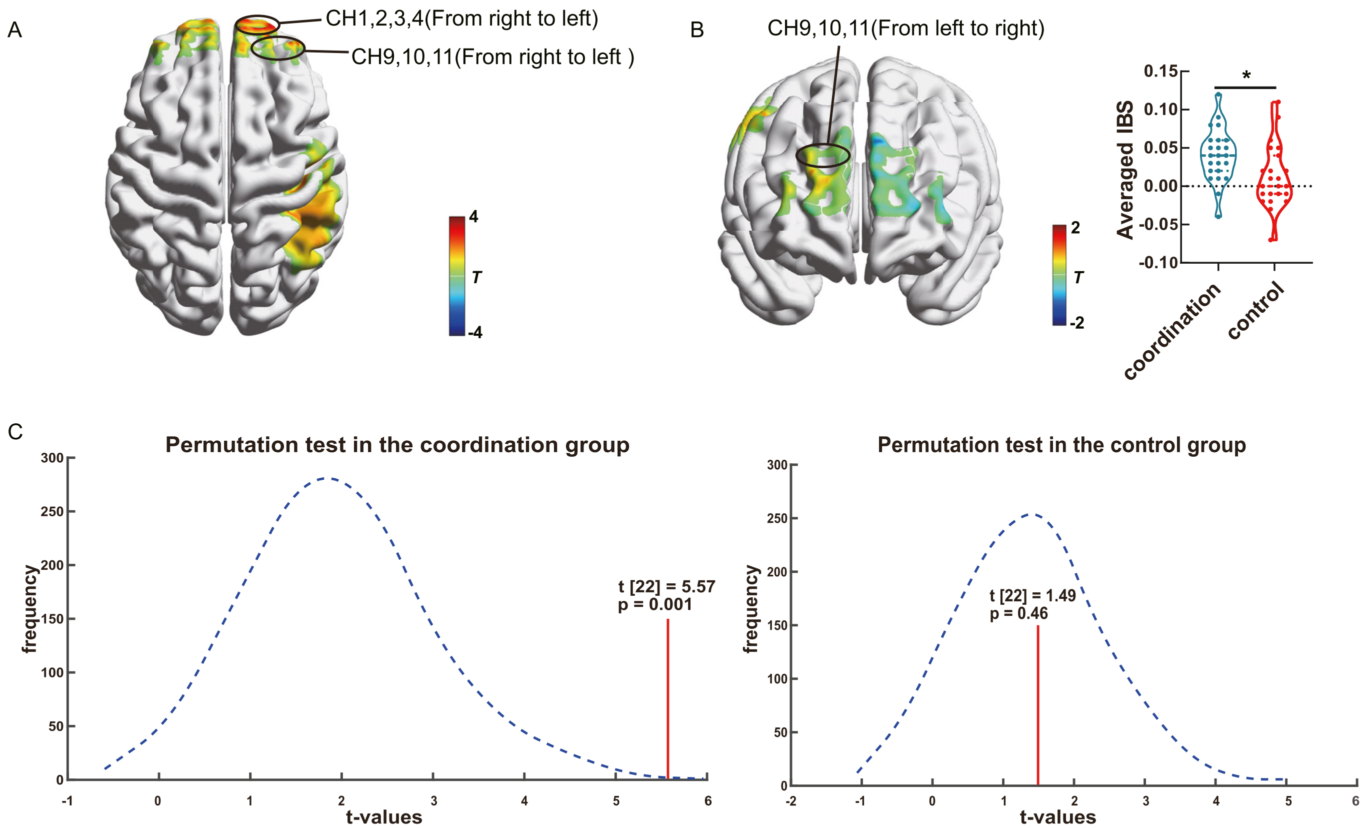


**Fig. 4.** Interpersonal brain synchronization (IBS). (A) One-sample *t*-test maps inter-brain coherence for the two groups. Task-related IBS is detectable only in the coordination groups of one cluster (CH1, CH2, CH3, CH4) and another cluster (CH9, CH10, CH11) after FDR correction. (B) The independent-samples *t*-test map of task-related IBS for group difference. The averaged task-related IBS at CH9 to CH11 (DLPFC) are significantly higher in the coordination group than in the control group. (C) The permutation tests of two groups $^{*}p < 0.05$.

coordination group, and this effect was mediated by responsibility attribution. Notably, these two groups did not differ in terms of anxiety and emotional states and empathy traits that could have influenced social behavior in the present task.

During the cooperation task, IBS in the DLPFC was higher in the coordination group than in the control group. This result was consistent with previous fNIRS hyperscanning studies that also found larger IBS in the DLPFC when participants coordinated with partners (Cheng et al., 2015; Hu et al., 2017; Reindl et al., 2018). This region has frequently associated with top-down control over cognitive and emotional processes (MacDonald et al., 2000; Grossmann, 2013; Balconi and Pagani, 2015; Miller and Cohen, 2001; Sela et al., 2012; Jeurissen et al., 2014). Moreover, the DLPFC is used for cognitive control depending on the task on hand (Miller and Cohen, 2001; Sela et al., 2012; Jeurissen et al.,

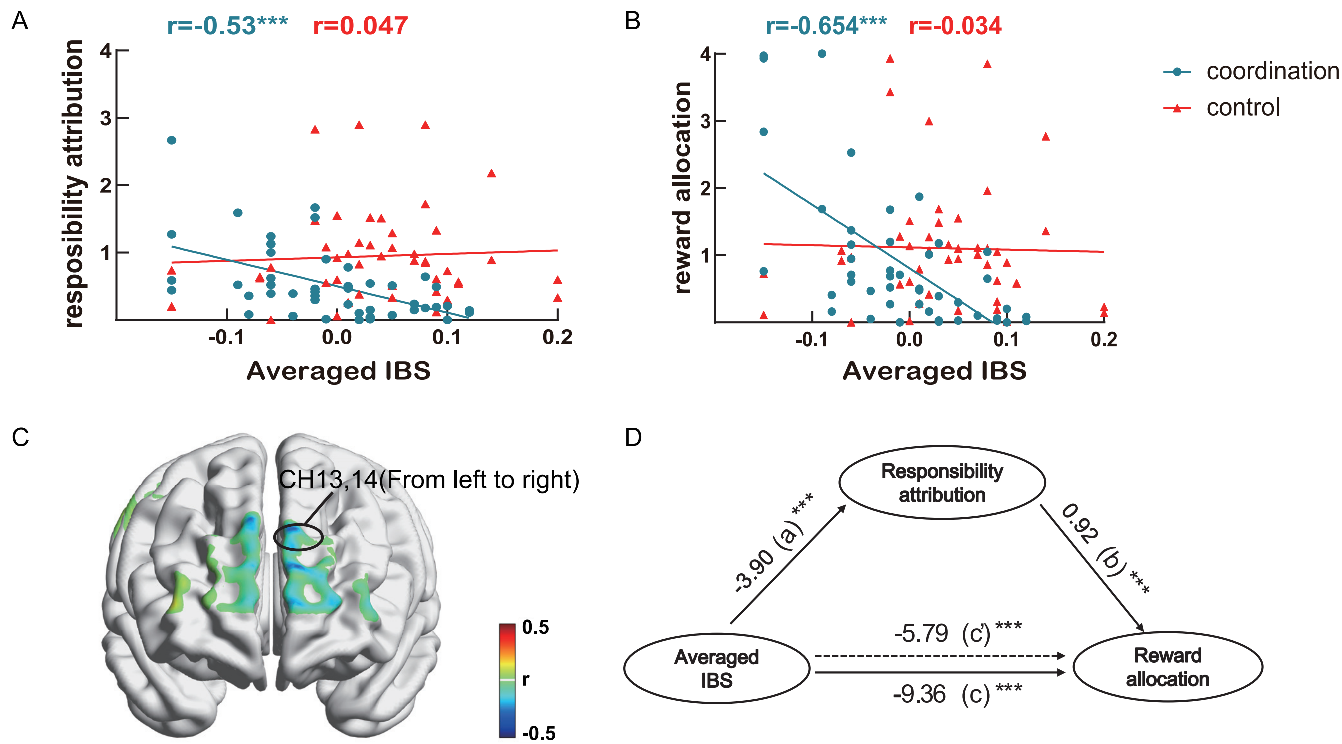


**Fig. 5.** Correlations between IBS in the DMPFC and the behavioral assessment. (A) Correlation between the Averaged IBS and the responsibility attribution. (B) Correlation between the Averaged IBS and the reward allocation. (C) The correlation map between IBS in the coordination group and responsibility attribution scores. (D) The mediation effect. The estimated values are presented. The effect of Averaged IBS on reward allocation is significantly higher when responsibility attribution is added to this model $^{**}p < 0.01$, $^{***}p < 0.001$.

2014). Thus, the increased IBS in the DLPFC in the present study possibly reflects synchronized control during task execution for maintaining coordination.

Importantly, our study further showed that coordinative cooperation influences the subsequent responsibility attribution and reward allocation. First, the coordination dyads showed a higher tendency for responsibility attribution to the collective than dyads in the control group, suggesting that cooperative dyads in the coordination group were more inclined to believe that the reward was generated by cooperation. Second, although responsibility attribution scores highly correlated with reward allocation, the coordination group did not show a more prosocial tendency for egalitarian allocation between partners on group level. In fact, in the allocation phase, both the coordination group and the control group made self-serving allocations. This was not surprising because the allocation task we used here was similar to the classic dictator game in which people frequently performed selfishly (Gąsiorowska and Hełka, 2012; Kahneman et al., 1986; Hoffman et al., 1999).

Although no group difference was observed in reward allocation, further correlation analyses showed that higher IBS in the DMPFC led to more egalitarian allocation decisions in the coordination group. In addition, MVPA demonstrated that responsibility attribution and reward allocation could be decoded from the multivariate pattern of IBS over all channels, supporting the IBS-behavior association from a new perspective (see more details in supplementary materials). Therefore, the present findings partially support one aspect of the second hypothesis (i.e. coordination leads to prosocial allocation) by showing the effect at an individual level. We propose that participants' allocation behavior was modulated collectively by interpersonal coordination and the task feature. Specifically, interpersonal coordination influenced participants' reward allocation on an individual level, whereas the task-dependent character of the dictator game may cause the "ceiling effect" of selfish behavior that reduced the current experimental effect at a group level.

Previous studies required individuals to make allocation decisions using either the equity- or equality-based rule or a combination of both (Deutsch, 1975; Hysom and Fişek, 2011; Melamed, 2012). However, most studies only tested the relationship of the allocation decision and objective contribution, such as money and time consumed by group members (Bierhoff and Rohmann, 2011; Cappelen et al., 2014). Our previous studies have shown that participants' rating of responsibility did not absolutely correspond to objective contribution and could be influenced by context (Li et al., 2018; Yang et al., 2020). Here, we provide further evidence that subjective rating of individual contribution actually mediated the relationship between task related neural activities and reward allocation. Taken together, these evidences suggest that the current resource allocation theories should consider the individual's own evaluation of their contribution rather than the objective and overt input.

The IBS in the DMPFC could predict reward allocation, revealing its supplementary role to the DLPFC in such effort-based allocation tasks. Functional neuroimaging studies generally associate the rTPJ and DMPFC with the psychological state, namely understanding and inferring others' thoughts and the distinction between oneself and others (Lissek et al., 2008). In our study, only IBS in the DMPFC was linked with allocation in the coordination group, which may indicate that the dyads in the coordination group constantly evaluated each other's thoughts while planning a decision in the cooperative task, inferred what decision the partner would make, and thus achieved the final goal of their team. No significant IBS effect was identified in the rTPJ, another key region in social cognition. In previous studies, IBS in the rTPJ has been associated with greater shared intentionality between partners

(Tang et al., 2016), whereas PFC has been linked to positive interpersonal outcomes including effective communication (Stephens et al., 2010) and successful cooperation (Cui et al., 2012). Therefore, the rTPJ and DMPFC cortex may play different roles during coordinative cooperation.

## 5. Conclusion

Taken together, the present work showed that the manner of cooperation—such as interpersonal coordination—influences individuals' ratings of resource allocation. This is an extension of previous findings that entitlements, need, and egalitarianism drive the motivation of distributive justice (Deutsch, 1975). Moreover, the fNIRS and MVPA results elucidated the distinct functional roles of the DLPFC and DMPFC: the former may serve for maintaining interpersonal coordination and the latter may be involved in planning allocation decisions by considering others in the current social context.

## Data and code statement

All data in this study are available upon request by contact with the corresponding author, in consideration of data protection, a formal data sharing agreement is needed when the data is requested.

## Declaration of Competing Interest

None.

## Credit authorship contribution statement

**Can Zhou:** Conceptualization, Data curation, Visualization, Writing – original draft. **Xiaojun Cheng:** Validation, Data curation, Writing – review & editing. **Chengwei Liu:** Formal analysis, Visualization. **Peng Li:** Conceptualization, Formal analysis, Funding acquisition, Writing – review & editing.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2022.119028.

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## Further reading

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