A Social Interaction Perspective on the Neural Mechanisms of Interpersonal Fairness Formation

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Abstract

The Ultimatum Game task has been widely employed to investigate fairness behavior. While previous research has primarily focused on examining the decision-making behavior and neural mechanisms of a single party in the game, interpersonal fairness may emerge from repeated interactions between both parties. Consequently, investigating only single-brain activity is insufficient to reveal the brain mechanisms underlying social cognitive processes jointly completed by interacting parties. Therefore, this study integrated a modified Ultimatum Game task with fNIRS-based hyperscanning technology to examine the neural mechanisms of interpersonal fairness formation at the inter-brain level. Behavioral results demonstrated that, compared to the no-punishment condition, proposers offered significantly higher allocations under punishment, and as punishment intensity increased, distributions approached equitable levels. fNIRS results revealed that inter-brain activity synchronization in the right dorsolateral prefrontal cortex, inferior parietal lobule, and temporoparietal junction was significantly stronger under punishment than under no-punishment conditions. Furthermore, the greater the difference in allocation amounts between the two conditions, the larger the difference in inter-brain activity synchronization in the right inferior parietal lobule. In summary, inter-brain activity synchronization can serve as an objective neural marker for interpersonal fairness formation under punishment, and this study provides a novel perspective for investigating the underlying mechanisms of interpersonal fairness.

Full Text

Neural Mechanisms of Interpersonal Fairness Formation from a Social Interaction Perspective

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Abstract

The ultimatum game has been widely used to investigate fairness behavior. Previous research has primarily focused on the decision-making behavior and neural mechanisms of individual players. However, interpersonal fairness may emerge from repeated interactions between both parties, and examining single-brain activity alone is insufficient to reveal the neural mechanisms underlying social cognitive activities jointly completed by interacting individuals. Therefore, the present study combined a modified ultimatum game with fNIRS-based hyperscanning to investigate the neural mechanisms of interpersonal fairness formation at the group brain level. Behavioral results showed that proposers offered higher allocations under punishment conditions compared to no-punishment conditions, with stronger punishment intensity leading to allocations closer to the equal split. fNIRS results revealed significantly stronger interpersonal neural synchronization (INS) in the right dorsolateral prefrontal cortex, inferior parietal lobule, and temporo-parietal junction under punishment conditions compared to no-punishment conditions. Moreover, the greater the difference in allocation amounts between the two conditions, the larger the difference in INS in the right inferior parietal lobule. In summary, INS can serve as an objective neural marker of interpersonal fairness formation under punishment, providing a novel perspective for exploring the intrinsic mechanisms of interpersonal fairness.

Keywords: interpersonal fairness; punishment; interpersonal neural synchronization; functional near-infrared spectroscopy; hyperscanning

Introduction

Since ancient times, the notion that “people worry not about scarcity but about inequality” has driven the persistent human pursuit of fairness. As a fundamental social principle, fairness plays a crucial role in human life, safeguarding individual rights while maintaining social stability. Numerous studies have demonstrated cross-cultural consistency in individuals’behavioral responses to unfairness, specifically manifesting as sacrificing personal interests to punish such behavior. Punishment has proven to be an effective method for sanctioning fairness norm violations and facilitating the formation of interpersonal fairness.

The ultimatum game (UG) represents one of the most widely employed experimental paradigms in behavioral economics for studying interpersonal fairness. The classic UG involves two roles: a proposer and a recipient who must divide a sum of money. The proposer first proposes an allocation, which the recipient can either accept or reject. If accepted, the money is divided accordingly; if rejected, both parties receive nothing. Spitzer et al. (2007) used a modified UG to investigate punishment' s role in enforcing fairness norms. In their punishment condition, recipients could punish proposers by spending their own money at a 1:5 ratio—each yuan spent by the recipient reduced the proposer' s earnings by five yuan. Results showed that proposers allocated only 10% of the total in no-punishment conditions, but 40% under punishment conditions, approaching the equal split (50%). Furthermore, the more unfair the allocation (greater deviation from 50), the more recipients punished. These findings demonstrate punishment' s critical role in promoting interpersonal fairness.

Advances in neuroimaging have enabled researchers to use functional magnetic resonance imaging (fMRI) to explore the neural mechanisms underlying fairness norm compliance in both proposers and recipients. Studies show that compared to no-punishment conditions, punishment conditions yield higher allocations and enhanced activation in bilateral dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC), orbitofrontal cortex (OFC), and bilateral caudate nucleus. Increased activation in right DLPFC, left OFC, and right caudate nucleus under punishment correlates positively with improved fairness compliance (punishment minus no-punishment allocation amounts). This suggests that fairness norm compliance activates brain regions associated with cognitive control, inhibition of prepotent responses (self-interest), evaluation of punishment threats, and processing of uncertain reward and punishment stimuli. Additionally, research indicates lateralized neural pathways for fairness compliance: enhancing right DLPFC activation via transcranial direct current stimulation (tDCS) significantly increases proposers' allocations toward equal splits, while inhibiting this region reduces fairness.

Research on recipients' neural mechanisms reveals two interacting systems supporting fairness compliance: a reflexive and intuitive system (comprising anterior insula, amygdala, and ventromedial prefrontal cortex) that identifies and evaluates norm violations and generates punishment motivation; and a reflective and deliberate system (comprising dorsal anterior cingulate cortex, DLPFC, VLPFC, and dorsomedial prefrontal cortex) that regulates conflict, inhibits self-interest, and executes punishment. Non-invasive interventions similarly demonstrate DLPFC lateralization in recipients: inhibiting right DLPFC significantly reduces punishment of unfair allocations. These findings suggest right DLPFC may be responsible for inhibiting self-interested responses during economic games, enabling better fairness compliance, and implying neural similarity between proposers and recipients in right DLPFC activity during fairness compliance.

Previous research has primarily focused on individual decision-making and neural mechanisms, yet interpersonal fairness likely emerges from repeated interactions between both parties. Repeated bargaining involves reciprocal causality, where each individual' s behavioral outcomes serve as both feedback and prerequisites for their partner' s behavior. Therefore, examining single-brain activity alone cannot reveal the neural mechanisms of social cognitive activities jointly completed by interacting individuals. Consequently, this study shifts from a single-brain to a multi-brain perspective to uncover the neural mechanisms of interpersonal fairness formation at the group brain level by analyzing patterns of brain-brain interaction.

Hyperscanning provides a novel approach for investigating cross-brain mechanisms during interpersonal interaction by simultaneously recording activity from multiple interacting brains and analyzing interpersonal neural synchronization (INS), offering new insights into social interaction mechanisms from a group perspective. This technique has been applied across various domains of social cognitive neuroscience, including cooperation and competition, behavioral imitation, and teacher-student interaction, consistently demonstrating that INS in brain regions related to social cognition—particularly theory-of-mind regions—serves as an important neural marker of interpersonal interaction. In a monetary allocation game, face-to-face interaction enhanced INS in the right temporo-parietal junction (TPJ) compared to a partitioned condition, likely because face-to-face communication provides explicit social cues (facial expressions, body movements) that enable better mental state inference and shared intentionality. Liu, Saito, and Oi (2015) used a turn-taking chess game to investigate cooperation and competition, finding INS in the right inferior frontal gyrus during competition but not cooperation, suggesting higher engagement and more active mental state inference during competitive interactions. Thus, theory-of-mind brain regions show stronger interaction during mutual bargaining.

Functional near-infrared spectroscopy (fNIRS) offers advantages in cost, head movement tolerance, and ecological validity compared to other neuroimaging techniques. Therefore, this study combined a modified ultimatum game with fNIRS-based hyperscanning, establishing punishment and no-punishment conditions to analyze differences in allocation amounts and INS, thereby revealing the neural mechanisms of interpersonal fairness formation from an interactive perspective. Based on previous findings that punishment promotes fairness norm compliance in economic decision-making, we hypothesized that: (1) allocation amounts would be higher under punishment than no-punishment conditions, approaching equal splits; and (2) INS would be stronger between proposers and recipients in right DLPFC and theory-of-mind regions under punishment compared to no-punishment conditions, as fairness compliance requires inhibiting prepotent responses and involves stronger interpersonal interaction.

Method

Participants

Forty-four undergraduate students (M = 21.3 years, SD = 1.6 years) were recruited, including 26 males and 18 females, forming 22 same-sex dyads with no prior acquaintance. All participants were right-handed, had no history of brain or psychiatric disorders, and had normal or corrected-to-normal vision. All provided informed consent before the experiment and received compensation based on their actual performance.

Experimental Design

The experiment employed a monetary allocation task adapted from Spitzer et al. (2007) based on the ultimatum game, requiring two participants to complete multiple rounds of dividing 100 yuan. Two conditions were implemented: punishment and no-punishment. In the punishment condition, the proposer (A) proposed an allocation. If the recipient (B) accepted, the money was divided accordingly. If B found the allocation unfair, they could punish A by spending money from their initial endowment at a 1:5 ratio—each yuan spent by B reduced A' s earnings by five yuan. Thus, to maximize earnings, A should adjust allocations to find the minimum acceptable amount to B, while B should use punishment feedback to find the maximum amount A would offer and maintain it. In the no-punishment condition, B had to accept any allocation from A unconditionally.

Procedure

Upon entering the laboratory, the two participants sat face-to-face with a partition between them [Figure 1: see original paper]A. Before the experiment, they drew lots to determine their roles (proposer A and recipient B), which remained fixed throughout the task. In each trial, both participants first received 25 yuan, ensuring that B had capital to punish A even if A allocated 0 yuan. A then allocated the 100 yuan. Each trial began with a fixation point for 3-6s, followed by a 2s cue: "5:1" indicated the punishment condition, while "0:0" indicated the no-punishment condition. After the cue, A considered the allocation for 2s, then proposed it by using arrow keys to move a green cursor to increase or decrease the amount (no time limit), confirming with the down arrow. The proposed allocation was displayed for 2s, after which B responded. In the 5:1 condition, B could either accept or punish by spending part or all of their 25 yuan to reduce A' s earnings by five times that amount, using "1" and "3" keys to adjust the punishment amount and "2" to confirm. Importantly, punishment could only reduce A' s amount to zero. In the 0:0 condition, B could only press "2" to accept. Finally, the distribution outcome was displayed for 2s. Both participants saw identical screens in real time, allowing B to see A' s allocation and A to see B' s feedback [Figure 1: see original paper]B.

The task comprised 50 trials (25 per condition) presented in pseudo-random order. Participants rested for 40s before the task and for 2 minutes after completing the first 25 trials. They were informed that their compensation would consist of a base payment plus a percentage of their accumulated earnings.

Data Collection

Task stimuli were presented and behavioral data collected using E-Prime 2.0 software. Brain activity was recorded using a Hitachi ETG-4000 system, measuring changes in oxy-hemoglobin (Hbo) and deoxy-hemoglobin (Hbr) concentrations. A 3×5 probe patch was placed in a swimming cap on each participant' s right hemisphere. According to the international 10-20 system, the central detector was positioned at C4, with the patch placed along the sagittal reference curve [Figure 1: see original paper]C, covering frontal and parietal regions. Each patch contained 8 emitters and 7 detectors spaced 3cm apart, yielding 22 channels. Channel locations were referenced using a registration template from Jichi University (http://www.jichi.ac.jp/brainlab/virtual_registration/Result3x5_E.html) (Reindl, Gerloff, Scharke, & Konrad, 2018). The sampling rate was 10Hz.

Data Analysis

Behavioral Data For each proposer, we calculated the average allocation amount to recipients under punishment and no-punishment conditions, as well as average earnings for both roles (including the initial 25 yuan). Paired-sample t-tests compared allocation amounts and earnings across conditions, with Cohen' s d effect sizes (0.2, 0.5, and 0.8 indicating small, medium, and large effects). Additionally, we calculated punishment intensity for unfair allocations (<50 yuan) in the punishment condition as:

$$\frac{5 \times \text{Total punishment amount from B to A}}{\text{Total amount A underpaid B across unfair trials}}$$

where the numerator represents total punishment across unfair trials and the denominator represents the total shortfall. Larger ratios indicate stronger punishment. Pearson correlation assessed the relationship between punishment intensity and average allocation under punishment.

fNIRS Data Data were preprocessed using NIRS-SPM in MATLAB (2014a). A hemodynamic response function (HRF) and discrete cosine transform (DCT) with a 128s cutoff frequency were applied for low-pass and high-pass filtering to remove instrument noise and physiological artifacts (e.g., respiration, heartbeat) (Ye et al., 2009).

Given oxy-hemoglobin' s greater sensitivity to task demands (Hoshi, 2003), only Hbo was analyzed further. Wavelet Transform Coherence (WTC) calculated INS during the task period (cue to feedback) (Cui et al., 2012; Grinsted et al., 2004). First, continuous wavelet transform (CWT) was applied to time series x(n):

$$W_n^X(s) = \sqrt{\delta t} \sum_{n'=1}^{N} x(n')\psi_0 \left[\frac{(n'-n)\delta t}{s} \right]$$

where n is time point, s is wavelet scale, t is sampling period (e.g., 0.1s), and N is time series length. Next, cross-wavelet transform (XWT) was performed on two time series x(n) and y(n):

$$W^{XY}(n,s) = W^X(n,s)W^{Y*}(n,s)$$

where * denotes complex conjugation. Finally, wavelet coherence was calculated:

$$R_n^2(s) = \frac{|S(s^{-1}W_n^{XY}(s))|^2}{|S(s^{-1}W_n^X(s))|^2 \cdot |S(s^{-1}W_n^Y(s))|^2}$$

where S is a smoothing operator.

To ensure task-relevant frequency bands, we averaged INS across 0.01-0.2Hz (5-100s) based on previous hyperscanning studies (Nozawa et al., 2016; Pan et al., 2018; Zheng et al., 2018), avoiding physiological signals like heartbeat (~1Hz) and respiration (0.2-0.3Hz) (Kamran & Hong, 2014; Pierro et al., 2014). Averaged values were Fisher-z transformed. Paired-sample t-tests ($p < 0.005$) compared INS across 22 channels for each frequency band. Results showed significantly higher INS under punishment in 0.13-0.2Hz and 0.03-0.04Hz bands, with no bands showing higher INS in the no-punishment condition [Figure 2: see original paper]. These two bands were selected for further analysis. Paired-sample t-tests examined condition differences for each channel's INS, with p-values FDR-corrected (Benjamini & Hochberg, 1995). T-value maps were generated and projected onto 3D brain models using xjView (http://www.alivelearn.net/xjview8/) and BrainNet Viewer (http://www.nitrc.org/projects/bnv/) (Xia et al., 2013).

Results

Behavioral Results

Interaction patterns for the 22 dyads are shown in [Figure 3: see original paper]. Paired-sample t-tests on proposers' allocations revealed significantly higher amounts under punishment (41.39 ± 9.28) versus no-punishment (30.27 ± 17) conditions, $t(21) = 3.91$, $p < 0.001$, Cohen' s $d = 0.83$, 95% CI: [5.21, 17.03] [Figure 4: see original paper]A. Correlation analysis showed that stronger punishment intensity predicted higher allocations under punishment, $r = 0.43$, $p = 0.04$ [Figure 4: see original paper]B. Paired-sample t-tests on earnings revealed no significant difference between proposers (62.76 ± 14.53) and recipients (62.22 ± 11.18) under punishment, $t(21) = 0.15$, $p = 0.88$, Cohen' s $d = 0.03$, 95% CI: [-7.00, 8.07]. However, under no-punishment, proposers' earnings (94.72 ± 17) significantly exceeded recipients' (55.27 ± 17), t(21) = 5.44, $p < 0.01$, 95% CI: [24.38, 54.53] [Figure 4: see original paper]C.

fNIRS Results

INS differences between conditions were examined in 0.13-0.2Hz and 0.03-0.04Hz bands. In the 0.13-0.2Hz band, INS was significantly higher under punishment in channels 12 and 15: Channel 12, t(21) = 3.56, p = 0.04, Cohen' s d = 0.76, 95% CI: [0.01, 0.05]; Channel 15, t(21) = 3.45, p = 0.03, Cohen' s d = 0.74, 95% CI: [0.01, 0.05], with FDR-corrected p-values [Figure 5: see original paper]A&B. Spearman' s rank correlation revealed a positive relationship between the difference in allocation amounts (punishment minus no-punishment) and the difference in INS for channel 12, = 0.45, p = 0.04 [Figure 5: see original paper]C.

In the 0.03-0.04Hz band, INS was significantly higher under punishment in channels 9, 13, and 22: Channel 9, t(21) = 2.99, p = 0.05, Cohen' s d = 0.64, 95% CI: [0.01, 0.05]; Channel 13, t(21) = 4.21, p = 0.01, Cohen' s d = 0.90, 95% CI: [0.02, 0.05]; Channel 22, t(21) = 3.56, p = 0.02, Cohen' s d = 0.76, 95% CI: [0.01, 0.05], with FDR-corrected p-values [Figure 5: see original paper]D&E.

Discussion

This study combined a real person-to-person interactive ultimatum game with fNIRS-based hyperscanning to investigate the neural mechanisms of interpersonal fairness formation from a group interaction perspective. Behavioral results demonstrated higher allocations under punishment that approached equal splits. Stronger punishment of unfair allocations predicted allocations closer to equality. fNIRS results revealed enhanced INS between proposers and recipients in right DLPFC and theory-of-mind regions under punishment, with increased INS in the inferior parietal lobule correlating significantly with the difference in allocation amounts between conditions.

We implemented punishment and no-punishment conditions, where recipients could punish unfair allocations in the former but were powerless in the latter. Results confirmed punishment' s effectiveness in promoting proposers' fairness compliance. Compared to previous findings (Spitzer et al., 2007), proposers' allocations in the no-punishment condition were 20 yuan higher, possibly because participants completed multiple rounds under both conditions, creating potential carryover effects of punishment threat. We also found that stronger punishment more effectively promoted fairness compliance. Fairness formation requires both voluntary norm compliance and appropriate punishment of violations. If recipients are myopic and fail to punish adequately, proposers may maximize self-interest by maintaining or even reducing allocations to test recipients' limits. Additionally, punishment can eliminate disparities when unfairness occurs. The absence of significant earnings differences under punishment may reflect two factors: first, people generally dislike unfairness, including both disadvantageous and advantageous inequality; second, moderate punishment may deter proposers while recipients minimize punishment to maximize their own earnings.

fNIRS results showed significantly enhanced INS under punishment in right DLPFC (channel 15), right inferior parietal lobule (IPL; channels 12 and 13), and right temporo-parietal junction (TPJ; channel 9). Previous research indicates right DLPFC is associated with cognitive control and goal maintenance during economic games. Both proposers making fair offers and recipients rejecting unfair offers activate right DLPFC. Under punishment, proposers tend toward fairness to avoid losses, while recipients may "cut off one' s nose to spite one' s face" to enforce norms. Both parties must inhibit self-interested responses to maximize earnings, and the consistency of right DLPFC activity reflects this shared psychological process.

In the ultimatum game, proposers engage in strategic considerations, estimating recipients' emotional and behavioral reactions to allocations. Similarly, when recipients can punish, they must infer proposers' responses to punishment. This cognitive activity of explaining and predicting others' mental states is termed mentalizing. We found enhanced INS under punishment in theory-of-mind regions including right IPL and TPJ. IPL is part of the mirror neuron system, which facilitates self-processing and social understanding. Right TPJ is crucial for mentalizing, involved in inferring beliefs, representing intentions, and integrating intentions with outcomes. Theory-of-mind INS appears across various social interactions (joint attention, synchronized singing, teacher-student interaction, conversation) and stronger INS predicts better cooperation. Thus, INS serves as an objective marker of interaction quality and shared intentionality. The positive correlation between increased IPL INS and increased allocation amounts may reflect that enhanced interpersonal fairness under punishment is accompanied by stronger mentalizing between bargaining partners.

This study represents the first attempt to use hyperscanning to investigate interpersonal fairness formation from a social interaction perspective, yielding novel findings but with limitations. First, some individuals consistently complied with fairness norms regardless of condition, while others made minimal allocations under no-punishment, possibly reflecting individual differences in self-interest levels. Future research should incorporate personality traits when examining interpersonal fairness. Second, fairness compliance is a complex social cognitive process involving not only cortical regions but also subcortical structures like the insula and amygdala. However, fNIRS cannot detect subcortical signals. Future studies could employ high-density EEG source imaging or fMRI to more comprehensively reveal the brain-to-brain mechanisms of interpersonal fairness while maintaining ecological validity.

In conclusion, this study combined a modified ultimatum game with hyperscanning to explore the brain-to-brain mechanisms of interpersonal fairness formation during social interaction. Our findings demonstrate that punishment promotes interpersonal fairness through enhanced interpersonal neural synchronization in prefrontal and temporo-parietal regions between interacting partners.

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Note: Figure translations are in progress. See original paper for figures.