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# Enhanced inter-brain connectivity between children and adults during cooperation: a dual EEG study

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*Abstract*—**Previous fNIRS studies have suggested that adult-child cooperation is accompanied by increased inter-brain synchrony. However, its reflection in the electrophysiological synchrony remains unclear. In this study, we designed a naturalistic and well-controlled adult-child interaction paradigm using a tangram solving video game, and recorded dual-EEG from child and adult dyads during cooperative and individual conditions. By calculating the directed inter-brain connectivity in the theta and alpha bands, we found that the inter-brain frontal network was more densely connected and stronger in strength during the cooperative than the individual condition when the adult was watching the child playing. Moreover, the inter-brain network across different dyads shared more common information flows from the player to the observer during cooperation, but was more individually different in solo play. The results suggest an enhancement in inter-brain EEG interactions during adult-child cooperation. However, the enhancement was evident in all cooperative cases but partly depended on the role of participants.**

## I. Introduction

Adult-child interactions (e.g., parent-child, teacher-student, and stranger-child interactions) play a vital role in the development of children. Although how inter-personal interactions influence the developing brain has been thoroughly discussed, the majority of the experimental settings were restricted to behavioral observations, or neuroimaging approaches examining the individual brain response to social stimuli which try but still hard to exactly simulate social interactions in the real world [1], [2]. In recent years, increasing studies started to conduct the technique monitoring two or more interactive brains concurrently, which is known as hyperscanning [3]. This approach provides an effective way to characterize inter-brain synchrony and largely facilitates unraveling the neural mechanisms underlying social interaction behaviors, e.g., cooperation, competition, as well as adult-child interactions.

The cooperation task is one of the most widely investigated paradigms in adult-child hyperscanning studies. Based on functional near-infrared spectroscopy (fNIRS), increased inter-brain synchrony between adults and children was uniformly found when they were in cooperation, with synchrony distributing principally, but not exclusively, between the prefrontal areas of two brains [4]–[7]. Though fNIRS serves as a powerful tool to monitor brain activity in social interactions with advantages of relatively high spatial resolution, mobility, and resistance to motion artifacts, its low temporal resolution still limits the study on a second-to-minute scale. Electroencephalogram (EEG), which directly measures the scalp electrical potentials, is able to derive strong conclusions on brain dynamics with its high temporal resolution [2]. Using dual-EEG recordings, researchers found that effective adult-child interactions, such as with direct gaze [8] or positive emotions [9], were always associated with stronger inter-brain connectivity in the theta and alpha bands. However, the inter-brain interactions during adult-child cooperation, which have been thoroughly studied by fNIRS, remain unclear in electrophysiological terms. Moreover, the findings from previous fNIRS studies either came from a highly standardized experimental design that was different from naturalistic interactions [5]–[7], or could not exclude the influence of the spurious connectivity that would arise from more common visual stimuli in the cooperative than individual condition [4]. Therefore, in this study, we designed a well-controlled paradigm using a tangram solving video game in which the same visual stimuli were received by children and adults simultaneously either in the cooperative or individual condition. Using dual-EEG recording and generalized partial directed coherence (GPDC) analysis, we assessed and compared the directed inter-brain connectivity between adult-child cooperative and individual conditions. We hypothesize that the traits of adult-child cooperation can also (or even better) be reflected by inter-brain EEG connectivity.

## II. Method

### A. Participants

Ten dyads of typically developing preschool children and female adults were enrolled in this study. All the participants were right-handed according to Edinburgh handedness inventory, and with normal or corrected-to-normal vision. One dyad with poor EEG quality and another not following the experimental instructions were excluded, and therefore only eight dyads were included (children: 3 boys and 5 girls, mean age: 5.61 ± 0.164 years) in EEG analyses. Each subject (parents on behalf of children) signed a written informed consent prior to participation. The experimental protocol was approved by the Review Board of Ethics Committee of Shanghai Children's Medical Center (China).

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*B. Experiment procedure*

The adult and the child in each dyad were seated next to each other and asked to participate in a tangram puzzle-solving video game on a touch screen (Fig. 1). This game was designed attractive and easy to accomplish for preschool children. Each tangram template consisted of seven pieces of geometric shape puzzles, and subjects were asked to moving puzzles using their right hand. There were eight different tangram templates which were randomly divided into two conditions. Four templates were solved in a cooperative condition, i.e., the participants moved pieces of puzzles one by one in turn. Four templates were solved in an individual condition, i.e., one participant solved all the puzzles in the template alone and the other one was seated in another room watching the screen recording of the tangram game. Therefore, in both conditions, the game can be segmented into the same fundamental events for solving each piece of the puzzle, i.e., one participant moving the puzzle and the other watching partner's activity on the screen. The only difference was whether or not the cooperation was involved. The participants were asked to keep attending and silent during the task.

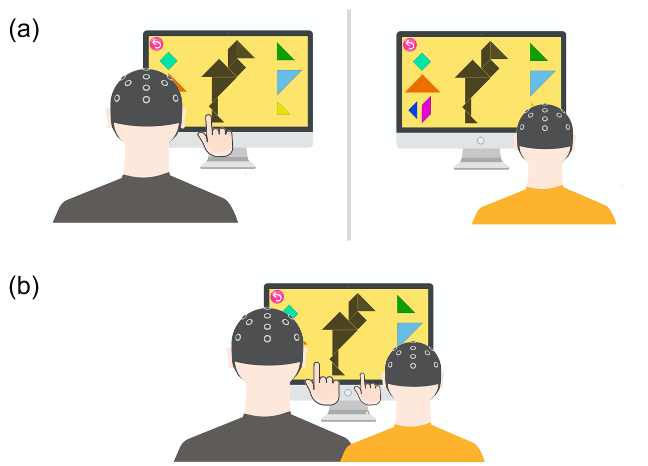


Fig. 1. Illustrations of the experimental setting. (a) Individual condition: one participant solved the tangram individually and the other sat in another room watching the screen recording. (b) Cooperative condition: two participants solved the tangram together by taking turns to move the pieces of the puzzle.

*C. Data acquisition*

For each dyad, EEG signals were recorded using two 32-channel mobile EEG systems (NeuSen.W32, Neuracle, China) that were arranged according to the international 10/20 system. The synchronization of two EEG systems was achieved by sending a trigger signal simultaneously to both EEG systems. In each EEG system, the sample rate was set at 1000 Hz, with FCz as the reference electrode and AFz as the ground electrode. The electrode impedances were kept below 10 kΩ during the recording.

Simultaneously, the activities of participants were monitored and recorded by two cameras. One was set behind the participants to capture their actions of fingers on the screen, and the other was placed in front to monitor whether their sight was focus on the screen. The video recording was integrated into the EEG recording system and synchronized with EEG recording.

*D. EEG preprocessing*

The EEG preprocessing was performed using the EEGLAB toolbox in MATLAB (MATLAB R2018b, The MathWorks Inc., Natick, MA) [10]. First, EEG signals were band-pass filtered into 1-35Hz and notch filtered at 50Hz. Independent component analysis (ICA) was utilized to remove ocular and muscular artifacts. Then the frontal channels (Fp1, Fp2, Fz, F3, F4, F7, and F8) were selected for further analysis, and signals with amplitude values exceeding ±80 µV were rejected. Artifacts-free EEG data in the time windows of interest were segmented into 1-s epochs. The time windows of interest, i.e., when a participant was moving a piece of the puzzle and the other was watching the screen, were manually coded from video. Finally, the EEG data of each participant were z-normalized to their corresponding individual condition to reduce variability across the subjects.

*E. Inter-brain connectivity analysis*

The connectivity between two brains was measured by Generalized Partial Directed Coherence (GPDC) [11]. PDC has been introduced as the frequency domain description of linear Granger-causality measuring the direct flows between channel pairs [12]. GPDC is an adapted version of PDC that achieves better variance stabilization properties and scale-invariance, and can be calculated as:

$$GPDC_{ij}(f) = \frac{\frac{1}{\sigma_i}\left|A_{ij}(f)\right|}{\sqrt{\sum_{n=1}^{N}\frac{1}{\sigma_n^2}\left|A_{nj}(f)\right|^2}}, \tag{1}$$

where $A_{ij}(f)$ stands for the frequency domain representation of the estimated coefficient from channel $j$ to channel $i$ in the multivariate autoregressive (MVAR) model. The model order was estimated according to Schwarz Bayesian information criterion (SBIC) [13] and an optional order of 5 was used in this study. Finally, the GPDC value was averaged within the frequency bands of interest. In this study, θ (4-7 Hz) and α (8-11 Hz) bands were selected for inter-brain analysis since these two bands play vital roles in social cognition and internally controlled attention for both children and adults [14]. Particularly, the θ rhythm of children was found closely related to social interaction with adults [8], [15], [16]. Since the same experimental environment and similar visual stimuli could also cause synchrony between participants in each dyad [8], [9], [17], a threshold method based on surrogating was implemented to reduce the spurious connectivity that was uncorrelated to the task. Specifically, a surrogate dataset (1000 permutations) was generated by randomly pairing the adult's (child's) epoch to the child's (adult's) epoch in different time points. GPDC was calculated for each permutation. Then, for each dyad, a threshold matrix was derived by averaging the surrogate connectivity matrices across conditions. For the real dataset of each participant pair, only the connections that exceeded the threshold value were preserved.

Two graph indices, i.e., strength and density, were calculated in each dyad, condition, and frequency band to characterize the inter-brain network. The strength was calculated as the average value of remaining connections and

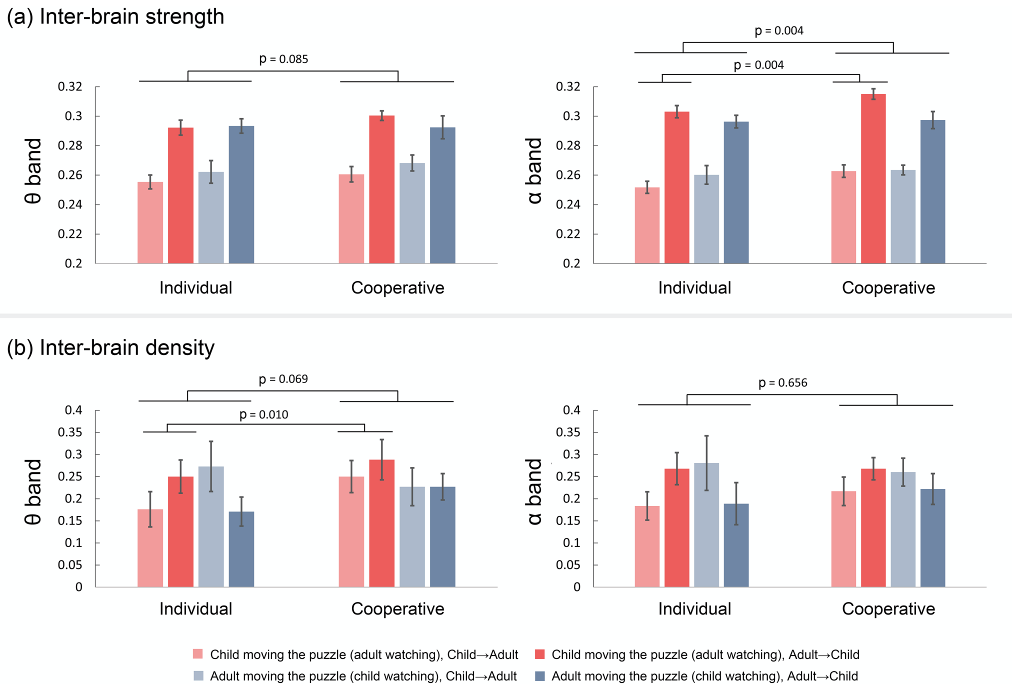


Fig. 2. Inter-brain connectivity in individual and cooperative conditions. (a) Inter-brain strength in the θ and α bands (θ-IBS and α-IBS). (b) Inter-brain density in the θ and α bands (θ-IBD and α-IBD).

the density was the ratio of the number of retained connections to all possible connections.

### F. Statistics

Three-way repeated measures analysis of variances (ANOVAs) with Greenhouse-Geisser correction for sphericity violation were performed on the inter-brain strength (IBS) and the inter-brain density (IBD), taking condition (2 levels: individual and cooperative), connectivity directionality (2 levels: Adult→Child and Child→Adult), and participant status (two levels: adult moving the puzzle (child watching) and child moving the puzzle (adult watching)) as the within-subject factors. Statistical significance was accepted for $p < 0.05$. All data are presented as mean ± standard error of the mean.

## III. Result

### A. Inter-brain connectivity strength (IBS)

Either in the θ or α band, the main effect of condition was near significant or significant on IBS (θ-IBS: $F(1,7) = 4.032$, $p = 0.085$, $\eta_p^2 = 0.365$; α-IBS : $F(1,7) = 17.591$, $p = 0.004$, $\eta_p^2 = 0.715$, Fig. 2). The θ- and α-IBS were (near) significantly stronger in cooperation than those in the individual condition. The main effect of connectivity directionality was also significant on both θ-IBS ($F(1,7) = 22.771$, $p = 0.002$, $\eta_p^2 = 0.765$) and α-IBS ($F(1,7) = 40.754$, $p < 0.001$, $\eta_p^2 = 0.853$), demonstrating greater IBS in Adult→Child than Child→Adult. Meanwhile, a near significant condition × participant status interaction ($F(1,7) = 4.829$, $p = 0.064$, $\eta_p^2 = 0.408$) was observed on α-IBS. Post hoc analysis found that the effect of condition was only significant when the adult was watching the child moving puzzles ($F(1,7) = 18.124$, $p = 0.004$, $\eta_p^2 = 0.721$), which exhibited greater α-IBS in cooperation (0.289 ± 0.002) than solo solving (0.277 ± 0.003) in this kind of status. No significant effect of condition was found on α-IBS when the child was watching the adult moving puzzles ($F(1,7) = 0.679$, $p = 0.437$, $\eta_p^2 = 0.088$).

### B. Inter-brain connectivity density (IBD)

For the IBD, a near significant main effect of condition was found in the θ band ($F(1,7) = 4.603$, $p = 0.069$, $\eta_p^2 = 0.397$, Fig. 2), exhibiting more densely connected network in cooperation (0.248 ± 0.010) than individual condition (0.217 ± 0.018). Meanwhile, a near significant condition × participant status interaction ($F(1,7) = 4.964$, $p = 0.061$, $\eta_p^2 = 0.415$) was also observed on θ-IBD. Post hoc analysis revealed a significantly higher θ-IBD in cooperation (0.269 ± 0.020) versus individual condition (0.213 ± 0.013) when the adult was watching the child moving the puzzle ($F(1,7) = 12.100$, $p = 0.010$, $\eta_p^2 = 0.634$). However, the θ-IBD did not show a significant effect of condition when the adult was the player ($F(1,7) = 0.064$, $p = 0.808$, $\eta_p^2 = 0.009$). In the α band, no significant main effect or interactions with condition was found on α-IBD.

To further illustrate the inter-brain connectivity pattern in different conditions at a group level, we added up the binary network matrices from each dyad (Fig. 3). Specifically, when the adult was watching the child moving the puzzle, more consistent Child→Adult connections appeared in cooperation compared with individual condition. And vice versa, when the child was watching the adult moving the puzzle, more consistent Adult→Child connections appeared in cooperation compared with individual condition. These patterns were exhibited both in the θ and α bands.

## IV. Discussion

In this study, using dual-EEG recording and GPDC analysis, we demonstrated an enhancement in directed inter-brain connectivity during adult-child cooperation. Consistent with previous fNIRS studies, our EEG results found elevated

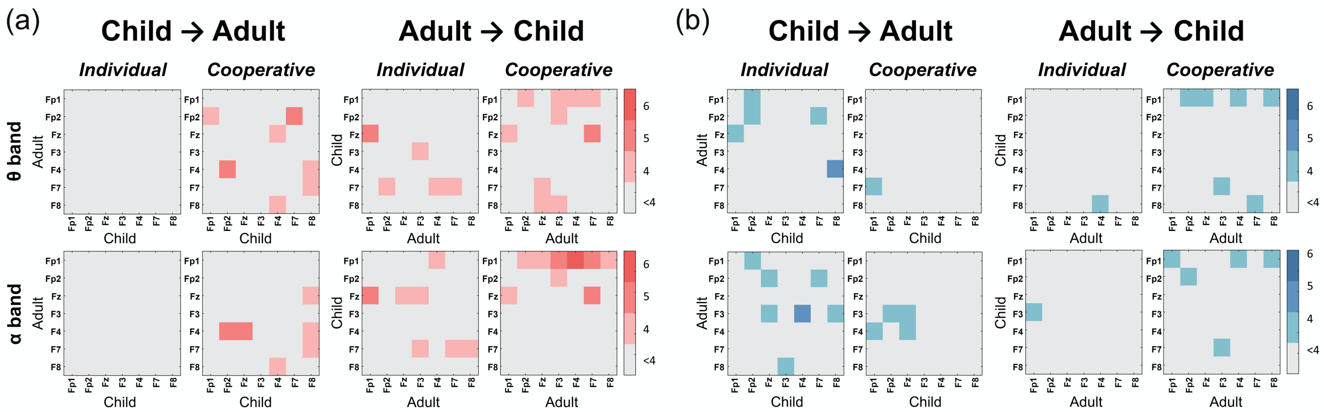


Fig. 3. The heat maps of group-level inter-brain connections in the θ and α bands. For each inter-brain connection, the number of dyads with this connection strength exceeding the corresponding individual threshold are shown in shades of colors. (a) Connectivity patterns when the child was solving the puzzles (red). (b) Connectivity patterns when the adult was solving the puzzles (blue).

neural synchrony in frontal areas in adult-child dyads during a cooperative puzzle-solving task [4] or a cooperative game based on synchronous reactions [5]–[7]. However, all these fNIRS-based studies only focused on the strength of inter-brain synchrony. Our results suggest that adult-child cooperation was not only accompanied by enhanced inter-brain strength, but also induced more inter-brain connections so as to result in a more densely connected inter-brain network. Moreover, our results were conducted in a more naturalistic and well-controlled interaction in which the visual stimuli were designed strictly the same between the two conditions. It should be noted that the effects of adult-child cooperation on the inter-brain strength and density seemed particularly evident when the adult was watching the child moving the puzzle. One possible explanation is that the adult's neural activity may be more likely to follow the child's attention, but not vice versa, which was supported by a previous study that found parents' theta power closely tracked and responded to their infants' attention during joint play [16].

On the other hand, the inter-brain network across different dyads shared some common connections during adult-child cooperation, but was more individually different during solo play. Specifically, when the adult was watching the child playing, the common inter-brain connections during cooperation emerged primarily in Child→Adult directionality; and when the child was watching the adult playing, the cooperation related common inter-brain connections emerged primarily in Adult→Child directionality (see Fig. 3), indicating a more general information flow pattern from the player to the observer during cooperation.

As far as we know, this is the first study exploring the inter-brain electrophysiological synchrony during adult-child cooperation. The results enriched our understanding of the neural mechanism underlying adult-child interactions.

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