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Interbrain substrates of role switching during mother–child interaction

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Abstract

Mother–child interaction is highly dynamic and reciprocal. Switching roles in these back-and-forth interactions serves as a crucial feature of reciprocal behaviors while the underlying neural entrainment is still not well-studied. Here, we designed a role-controlled cooperative task with dual EEG recording to explore how differently two brains interact when mothers and children hold different roles. When children were actors and mothers were observers, mother–child interbrain synchrony emerged primarily within the theta oscillations and the frontal lobe, which highly correlated with children's attachment to their mothers (self-reported by mothers). When their roles were reversed, this synchrony was shifted to the alpha oscillations and the central area and associated with mothers' perception of their relationship with their children. The results suggested an observer-actor neural alignment within the actor's oscillations, which was related to the actor-toward-observer emotional bonding. Our findings contribute to the understanding of how interbrain synchrony is established and dynamically changed during mother–child reciprocal interaction.

KEYWORDS

EEG hyperscanning, interbrain synchrony, mother–child cooperation, role

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Yamin Li and Saishuang Wu contributed equally to this work.

1 | INTRODUCTION

Humans are fundamentally social. Social interaction allows individuals of the same species to communicate with each other and such interaction is a matter of survival (Frith & Frith, 2007). Through the very early experience of interactions, children can coordinate their performance toward the smooth execution of social goals and co-related social needs to maximize well-being and thrive (Endevelt-Shapira et al., 2021). Therefore, adult–child interaction, especially the interactions between mother and child, is essentially important for children's social development.

Recently, with the advent of hyperscanning techniques, researchers have been able to characterize the interbrain synchrony by monitoring two or more brains concurrently (Czeszumski et al., 2020; Lindenberger et al., 2009; Montague et al., 2002; Wang et al., 2018), which sheds light on the neural mechanisms of interactions. By implementing this approach to the adult–child interaction studies, connections have been established between some interaction factors and interbrain synchrony. For example, children always showed higher interbrain synchrony with their parents than with a stranger (Endevelt-Shapira et al., 2021; Reindl et al., 2018; Zhao et al., 2021). The interbrain synchrony between children and their parents was uniformly found to be higher in cooperative tasks in comparison to when they solved the same task individually (Nguyen et al., 2020; Reindl et al., 2018; Wang et al., 2020). Moreover, communication signals, such as maternal body odors (Endevelt-Shapira et al., 2021), positive emotion (Santamaria et al., 2020), affectionate touch (Nguyen, Abney, et al., 2021), as well as direct gaze from an adult stranger (Leong et al., 2017), would elicit significant neural entrainment in children. Given these pioneering studies, interbrain synchrony has been considered a biomarker for mutual task engagement (Wass et al., 2020) and might help create an optimal learning environment for children (Atzil & Gendron, 2017; Nguyen et al., 2020). However, these studies only calculated the average level of interbrain synchrony within the whole session/task or even across the whole interaction, but regardless of its in-process dynamics (Endevelt-Shapira et al., 2021; Leong et al., 2017; Miller et al., 2019; Nguyen et al., 2020; Nguyen, Schleihauf, et al., 2021; Quiñones-Camacho et al., 2020; Reindl et al., 2018; Santamaria et al., 2020; Wang et al., 2020). Moreover, many researches on communication signals still focused on the unidirectional communication signals from adults toward children (Endevelt-Shapira et al., 2021; Leong et al., 2017; Nguyen, Abney, et al., 2021; Santamaria et al., 2020). Although some works contributed a major step toward mapping the correlation between interbrain coupling and bilateral communication signals, like reciprocal behaviors (Nguyen et al., 2020; Nguyen, Schleihauf, et al., 2021; Zhao et al., 2021), the evidence thus far is still insufficient to uncover the dynamic coupling between mothers and children during the back-and-forth interactions in daily life.

Mother–child interaction is by nature marked by the “serve and return” behaviors, termed mutual reciprocity (George, 1996). Dyadic reciprocal social interaction requires social partners to explicitly take on complementary and alternating roles, such as sender and receiver, throughout the course of interactions (Redcay & Schilbach, 2019). Recently, increasing studies have demonstrated that even in very early ages, young children acted not only as purely passive recipients of information, but also played an active role as senders (Murray & Trevarthen, 1986; Stahl & Feigenson, 2015; Wass et al., 2020). The roles that each partner takes on are usually not fixed, but alternate throughout the interactions (Schilbach et al., 2013; Wass et al., 2020). Hence, distinguishing roles when investigating the interbrain synchrony during mother–child interaction can largely facilitate modeling and understanding of the mutual reciprocity and might be a key to revealing the neural mechanism underlying the various dynamic social-cognitive processes involved.

Within the existing studies, some findings from naturalistic experimental designs indicated that in mother–child interactions, mothers and children tended to have distinct ways of behavioral and neural alignment toward each other when holding different roles. A study in physiological entrainment found that mothers increased their arousal level to match their child's, with a greater arousal response in mothers associated with lower subsequent child arousal (Wass et al., 2019). An EEG study also observed similar patterns in the behavior–brain association. Theta band oscillations in infants were found to be associated with attentional and encoding processes, while in adults a similar functional relationship was observed but at a higher frequency in the alpha band (Wass et al., 2018). However, during mother–infant joint play, the frequency of the mother's highest association between EEG power and attention was downshifted to the theta range—similar to the infant's peak frequency of association. During this process, when the mother was more neurally responsive, the infant was more attentive (Wass et al., 2018). This study suggested that EEG frequency shifting might be a unique process for mothers to neurally align with their children for effective interactions. However, it still remains unknown whether this neural attunement is mutual or unidirectional as well as its potential association with interbrain alignment. Therefore, it is worth probing into the roles in mother–child interaction and investigating the dynamic properties of this neural entrainment.

Additionally, previous hyperscanning studies also suggested that the neural entrainment was associated with mother–child relationship. Neural processing of self-mother recognition in late childhood was relevant to attachment (Miller et al., 2020). When mothers and children were viewing their prerecorded interaction vignettes, brain-to-brain synchrony only emerged during the perception of synchronous patterns specific to the attachment context (Levy et al., 2017). State-like factors such as maternal stress (Nguyen et al., 2020) and child irritability (Quiñones-Camacho et al., 2020), were also found to be associated with neural synchronization during the task. Nevertheless, whether and how the mother–child relationship, as well as their interaction experience, influence their interbrain synchrony in different role contexts is yet to be discovered.

To overcome the above limitations and examine the concurrent interbrain entrainment along with the alternating roles during mother–child mutual–reciprocal interaction, we designed a role-controlled tangram-solving task that comprised two role contexts, where children acted as actors/senders (who execute the action) and observers/receivers (who observe the action), respectively. We evaluated the effect of interaction in each role context by comparing a high-interactive condition (cooperation) with a low-interactive (accompanied) and a noninteractive (individual) condition, and compared between mother–child and stranger–child interactions. By applying dual EEG recording, we strived to answer the following questions: (1) How do roles in mother–child interaction influence the neural entrainment between the two brains of dyads? (2) Is the interbrain synchrony in two role contexts distinguishable between mother–child and stranger–child interactions? (3) Is the interbrain synchrony in two role contexts associated with the relationship between mothers and their children?

2 | METHODS

2.1 | Participants

Forty-two preschool children were recruited from China Welfare Institute Nursery, Shanghai according to the following inclusion criteria: (1) age from 3 to 4 years; right-handed according to the Edinburgh handedness inventory; (3) with normal or corrected-to-normal vision; and (4) had no known neurological or psychiatric disorders. Twenty-one children participated with their biological mothers (mother–child dyads), and the others performed the task with an unfamiliar female adult experimenter (stranger–child dyads). The mothers and the adult experimenter were also right-handed, with normal or corrected-to-normal vision, and had no known neurological or psychiatric disorders.

Two mother–child dyads and two stranger–child dyads were excluded due to that the children did not well follow the experimental instructions. Another mother–child dyad was excluded because of poor EEG quality. The final sample thus consisted of 18 mother–child dyads (children: 10 boys and 8 girls, mean age: 3.83 ± 0.13 years; mothers: mean age: 36.61 ± 0.94 years) and 19 stranger–child dyads (children: 6 boys and 13 girls, mean age: 3.88 ± 0.11 years). There was no significant difference in children's sex ($\chi(1) = 2.165$, $p = .141$) and age ($t(35) = -0.314$, $p = .755$) between mother–child and stranger–child groups. Each subject (parents on behalf of their child) signed a written informed consent prior to participation. The study was approved by the Review Board of Ethics Committee of Shanghai Children's Medical Center (SCMCIRB-K2020108-1).

2.2 | Behavioral assessments

Children's IQ was measured with the Chinese version of Wechsler Preschool and Primary Scale of Intelligence-Fourth Edition (Wechsler, 2012) which includes verbal and performance tests. The verbal test includes subtests of *Information*, *Vocabulary*, *Arithmetic*, *Similarities*, and *Comprehension*; and the performance test includes subtests of *Zoo Locations*, *Picture Completion*, *Object Assembly* (OA), *Coding*, and *Block Design*. Among all subtests, OA measures skills similar to those required for tangram puzzle-solving. All subtests were then aggregated into a full-scale IQ (FSIQ). FSIQ score and OA subscore (IQ-OA) were used to measure children's cognitive development. Each child was assessed by two standardized trained assessors. One child in the mother–child group couldn't complete the FSIQ test but only the OA subtest. There was no significant group difference in children's FSIQ score (mother–child group: FSIQ = 111.65 ± 3.25, stranger–child group: FSIQ = 117.58 ± 2.76; $t(34) = -1.4$, $p = .171$) as well as their OA subscore (mother–child group: OA = 12.94 ± 1.40, stranger–child group: OA = 16.11 ± 1.39; $t(35) = -1.600$, $p = .117$).

Children's psychosocial well-being was assessed with the Chinese version of the teacher-reported Strengths and Difficulties Questionnaire (Goodman & Goodman, 2009). The questionnaire contains 25 items in five dimensions (emotional symptoms, conduct problems, hyperactivity or inattention, peer relationship problems, and prosocial behavior), and each item was scored as 0 = not true, 1 = somewhat true or 2 = certainly true. The total score in the first four dimensions (excluding prosocial behavior) was generated as a total difficulties score (TDS) indicative of psychosocial problems. Using the recommended cut-off values of TDS in China (Du et al., 2008), which had been previously validated for children aged 3–16 years, there was only one child in mother–child group categorized as “borderline.” There was no significant difference in children's TDS ($t(35) = .536$, $p = .595$) between the mother–child (TDS = 7.33 ± 0.81) and stranger–child (TDS = 6.68 ± 0.89) groups.

In the mother–child group, mothers' parenting stress and child–mother attachment were also measured. Mothers' parenting stress was assessed with a 36-item self-report Parenting Stress Index-short Form (PSI-SF) (Abidin, 1995; Haskett et al., 2006). It includes three subscales, which are *Parental Distress* (PD), *Parent–Child Dysfunctional Interaction* (P-CDI), and *Difficult Child* (DC). The PD subscale indicates the level of distress resulting from personal factors such as depression or conflict with a partner and from life restrictions due to the demands of child-rearing. The P-CDI subscale provides an indication of parents' dissatisfaction with interactions with their children and the degree to which parents find their children unacceptable. The DC subscale measures parents' perceptions of their children's self-regulatory abilities. Each subscale consists of 12 items and each item was scored on a 5-point scale from 5 (strongly agree) to 1 (strongly disagree). The higher the score, the more parenting stress.

The Child Attachment Relationship Scale was self-reported by the mother. This scale was first developed by Liu (2005). It mainly reflects the child's attachment relationship to the mother based on the mother's responses about how the child usually interacts with her. There are 21 items (see Supplementary Table 1 for details) covering three dimensions: secure attachment (SA), avoidant or disorganized attachment, and ambivalent attachment. Each item was scored from 1 (strongly disagree) to 4 (strongly agree) points. Scores of items in each dimension were added, respectively, and the sum was calculated as the value of each dimension. In our sample, the Cronbach's α coefficients for the three dimensions of the scale were 0.66, 0.77, and 0.80, respectively. Children's child–parent attachment was assigned to the dimension with the highest value, and all children in the mother–

child group in this study were classified as SA. Therefore, we only included the SA score in further analysis.

2.3 | Experiment design

The adult and the child in each dyad were asked to participate in a tangram puzzle-solving video game on a touch screen (23.8-in, NEW-TAP Inc., China). The 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 move puzzles using their right hand.

There were 12 different tangram templates that were equally and randomly assigned for games in individual, accompanied, and cooperative conditions, respectively (individual: accompanied: cooperative = 4: 4: 4 templates). In the individual condition, one participant solved all the puzzles in the template alone and the other one was seated in another room watching the screen recording from the actor. In the accompanied condition, one participant solved all puzzles alone while the other was sitting next to him/her and watching the screen. In these two conditions, each person solved two tangram templates in each condition. While in the cooperative condition, the two participants were seated next to each other and jointly solved four tangram templates together by moving the puzzle pieces by turn (i.e., turn-taking cooperation). Among different interactive conditions, the fundamental events in solving each piece of the puzzles were the same, that is, one participant solving the puzzle (the actor) and the other observing partner's activity (the observer), but with different degrees of interaction. Each interactive condition thus comprised two role contexts, that is, the adult was the actor while the child was the observer or their roles were reversed. Therefore, there were 14 movements × 3 interactive conditions × 2 role contexts for each dyad (14: 14: 14 movements for each role context in each condition). Specifically, for both individual and accompanied conditions, there were 7 (pieces) × 2 (templates) movements for both child-actor-adult-observer and adult-actor-child-observer role contexts. For cooperative condition, there were 4 (pieces) × 2 (templates) + 3 (pieces) × 2 (templates) for both role contexts. The order of the conditions during experiment was also randomized. The participants were asked to move puzzles steadily and keep attending and silent during the whole procedure. The experiment design is illustrated in Figure 1.

2.4 | Data acquisition

During the experiment, EEG signals from the child and the adult were recorded simultaneously using two 32-channel mobile EEG systems (NeuSen.W32, Neuracle, China) with electrodes placed 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. For each EEG system, the sample rate was set at 1000 Hz, with FCz as the reference electrode and AFz as the ground

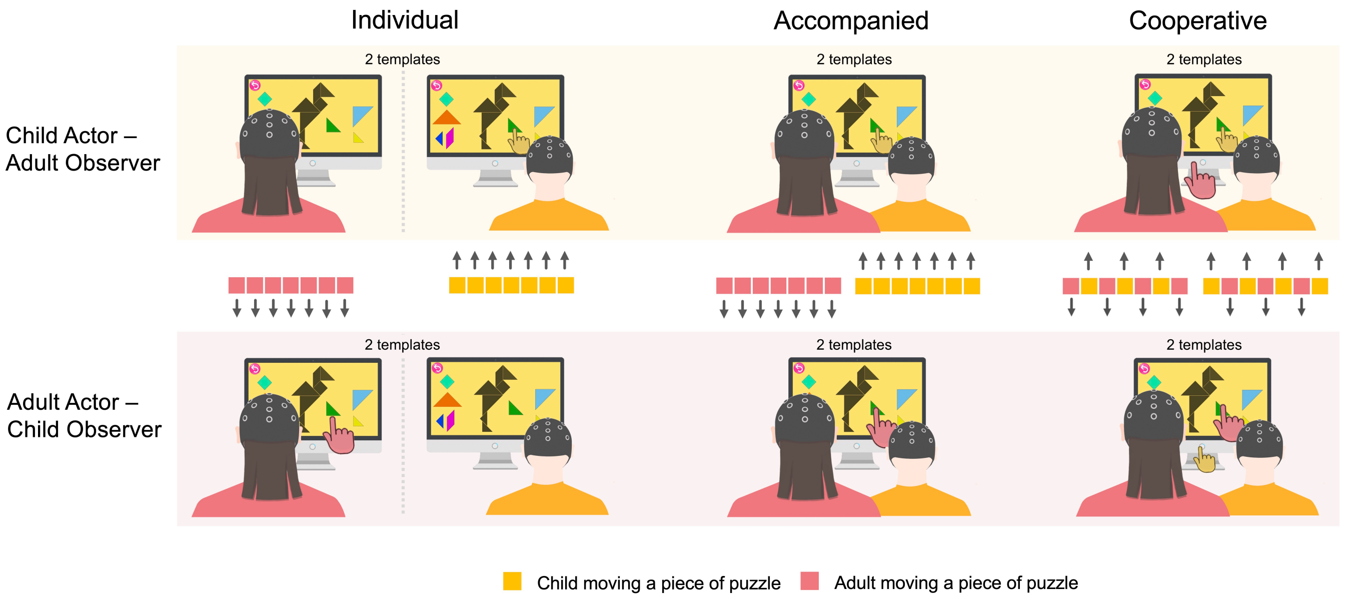

FIGURE 1 Illustration of experiment design. Both the mother–child and stranger–child dyads were asked to solve tangram puzzles in individual, accompanied, and cooperative conditions. In the individual condition, one participant solved all puzzles alone and the other was seated in another room watching the screen recording from the actor. In the accompanied condition, one participant solved all the puzzles alone while his/her partner was sitting next to him/her, watching the screen. In the cooperative condition, the participants were seated next to each other and jointly solved tangram templates by moving the puzzle pieces by turn. Although the degree of interaction was different in three interactive conditions, the fundamental events in solving each piece of the puzzles were the same and could be divided into two contexts according to the participants' roles. One was the child solving the puzzle (child as the actor) and the adult observing the child's activity (adult as the observer), and the other was with their roles reversed (adult as the actor and child as the observer).

electrode. The electrode impedances were kept below 10 kΩ during the recording.

The whole procedure was also monitored and recorded by two cameras. One was set behind the participants to capture their finger actions on the screen, and the other was placed in front to monitor their attention and interactions. Video recordings were synchronized with the EEG systems.

2.5 | EEG preprocessing

The EEG preprocessing was performed to obtain attentive and artifacts-free neural signals during each movement of a puzzle piece using the EEGLAB toolbox (Delorme & Makeig, 2004) in MATLAB (MATLAB R2018b, The MathWorks Inc., Natick, MA). Peripheral temporal channels (T7, T8, Tp9, Tp10) were excluded from the analysis due to the significant contamination of muscular artifacts, and therefore, a total of 26 channels (Fp1, Fp2, F3, F4, Fz, F7, F8, FC1, FC2, FC5, FC6, C3, C4, Cz, CP1, CP2, CP5, CP6, P3, P4, Pz, P7, P8, O1, O2, Oz) were selected for analysis. EEG signals were band-pass filtered into 1–35 Hz and notch filtered at 50 Hz. Filtering was done on continuous data to avoid edge effects. Independent component analysis was further utilized to remove ocular and muscular artifacts. Then, the EEG data were filtered into children's theta (3–6 Hz) and alpha (6–9 Hz) bands which play vital roles in social cognition and internally controlled attention for preschool children (Leong et al., 2017; Santamaria et al., 2020). Additionally, these two rhythms below 10 Hz were found closely related to children's interaction with adults and usually selected as the frequency of interest in mother–child EEG hyperscanning studies (Leong et al., 2017; Orekhova et al., 2006; Wass et al., 2018).

EEG data in theta and alpha bands were segmented according to each movement of a puzzle piece. The time window of interest (WOI) was selected from the start to the end times of moving the puzzle piece by manually labeling the video frames. As the duration varied across movements and participants, a 1-s epoch at the middle of each WOI was selected for further analysis. Those epochs when the participants were speaking or not attentive according to the video or with amplitude values exceeding ±100 μV were excluded. Finally, 12.85 ± 0.12 epochs were preserved on average from each participant in each interactive condition and each role context.

2.6 | Interbrain synchrony and thresholding

The interbrain synchrony was characterized by phase locking value (PLV) which measures the consistency of the phase variation over a period of time between two band-pass filtered signals (Lachaux et al., 1999).

Briefly, the instantaneous phase sequences of two narrow-band signals $x(t)$ and $y(t)$, which were $\varphi_x(t)$ and $\varphi_y(t)$, were calculated using Hilbert transform. Sequentially, the PLV between two signals can be derived as

$$PLV_{x,y} = \frac{1}{N}\left|\sum_{t=1}^{N} exp^{j(\varphi_x(t)-\varphi_y(t))}\right|, \qquad (1)$$

where N represents the number of samples within the selected time window. For each dyad, each interactive condition, each context, and each frequency band, the PLV values between the child's channels and the adult's channels were calculated, forming a 26 × 26 asymmetric matrix.

As the common intrinsic properties of the EEG signals and shared external perturbation, like the same experimental environment and similar visual stimuli, could also cause synchrony between participants in each dyad (Burgess, 2013; Leong et al., 2017; Santamaria et al., 2020), a threshold method based on surrogating was implemented to reduce the spurious synchrony that was uncorrelated to the task. Specifically, a surrogate dataset (1000 permutations) was generated by shuffling the time frames between adult and child in each dyad and interactive condition, which means randomly pairing the adult's (child's) epochs to the child's (adult's) epochs at different time. PLV was calculated for each permutation and then averaged. Sequentially, for each dyad, a threshold matrix was derived by averaging the surrogate connectivity matrices across conditions in the same context. The interbrain connections with their strength significantly exceeding their respective threshold values (one-tailed paired t test, $p < .05$, no correction) were regarded as the "real" connections and preserved for further analysis from two following aspects.

First, the global interbrain network density (IBD) and strength (IBS) were calculated. The IBD was calculated as the ratio of real connections to all possible connections. The IBS was used to quantify the average intensity of interbrain synchrony. To ensure the comparability of IBS among different interactive conditions, the least number of significant connections across all three interactive conditions was used for average in each context. Second, at the local level, the node degree and regional IBS were calculated to explore the brain regions involved in adult-child interaction. Node degree is the total number of edges connected to a certain node, and the regional IBS is the average intensity of interbrain synchrony between specific brain regions.

2.7 | Statistical analysis

A four-way repeated measures ANOVA with Greenhouse–Geisser correction for sphericity violation was performed on the global IBS, taking *role* (two levels: adult–actor/child-observer and child–actor/adult-observer), *frequency band* (2 levels: theta and alpha bands), *interactive condition* (three levels: individual, accompanied and cooperative conditions) as the within-group factors, and *group* (two levels: mother–child and stranger–child dyads) as the between-group factor. Bonferroni correction was used to adjust for multiple comparisons in post hoc analysis. In order to explore important brain regions for mother–child interaction, follow-up one-way repeated measures ANOVA was performed on regional IBS of mother–child dyads, taking *interactive condition* as the within-group factor, and *behavior* as covariates (formula: regional IBS $\sim$ *interactive condition* $+$ *behavior*

+ *interactive condition* × *behavior*), in which Akaike's information criterion was applied for model selection. For the regional IBS with significant interactions with behavior, Pearson's correlation (for the variables conforming to the normal distribution) or Spearman's correlation (for the variables not conforming to the normal distribution) was further applied to explore the relationship between the interaction-relevant interbrain synchrony and behavioral measures. In order to extract the interbrain synchrony produced by interaction from the overall IBS which comprised of interaction-irrelevant interbrain synchrony, such as that caused by the same experimental environment and similar sensory stimuli, we calculated the difference of IBS between the cooperative and accompanied conditions. Here, we chose the accompanied but not the individual condition as the control since the accompanied condition shared exactly the same experimental environment and sensory stimuli as the cooperative condition. Such a subtraction (i.e., experimental state–control state) has also been widely used in dual-brain network studies when correlated with behavior (Long et al., 2021; Reindl et al., 2018; Vicente et al., 2023; Zivan et al., 2022). The normality of variables was tested by Shapiro–Wilk's test. Statistical significance was accepted for $p < .05$. False discovery rate (FDR) was used for multiple comparisons correction in regional IBS analysis. All data are presented as mean ± standard error of the mean. All the statistical analyses were conducted using IBM SPSS Statistics 24.0 and MATLAB R2018b.

3 | RESULTS

3.1 | Global network metrics

The interbrain connectivity matrices in different roles, frequency bands, interactive conditions, and groups are shown in Figure 2. These matrices suggested that enhanced interbrain synchrony with interaction degree was primarily in the theta band when the child was the actor and alpha band when the child was the observer, which was further demonstrated by following global IBD and IBS analyses.

From global IBD, we found that interbrain network was more densely connected with increasing degree of interaction in the theta-band when the child was the actor (Figure 3a) and alpha band when the child was the observer (Figure 3g), in either the mother–child (individual: theta-IBD = 0.032, alpha-IBD = 0.012; accompanied: theta-IBD = 0.037, alpha-IBD = 0.036; cooperative: theta-IBD = 0.109, alpha-IBD = 0.112) or the stranger–child (individual: theta-IBD = 0.018, alpha-IBD = 0.012; accompanied: theta-IBD = 0.018, alpha-IBD = 0.047; cooperative: theta-IBD = 0.043, alpha-IBD = 0.067) dyads. However, the IBD in each interactive condition as well as its increment with interaction degree was larger and more prominent in the mother–child dyads compared with the stranger–child dyads. The alpha-IBD in child-actor/adult-observer role context (Figure 3c) and theta-IBD in adult-actor/child-observer role context (Figure 3e) did not show an increasing trend except the theta-IBD when the child was observing the stranger partner solving puzzles.

Results of four-way repeated measures ANOVA on the global IBS are shown in Table 1. We noted that *role* × *frequency band* × *interactive condition* × *group* interaction was significant ($F(2,70) = 15.594$, $p < .001$, $\eta^2_p = 0.308$). Follow-up analysis of *role* × *frequency band* × *interactive condition* × *group* found that *frequency band* × *interactive condition* × *group* was significant in both role context (both $p < .001$) but with distinct patterns.

When the child was the actor solving puzzles and his/her adult partner was the observer, *interactive condition* × *group* was only significant in the alpha band ($F(2,70) = 32.321$, $p < .001$, $\eta^2_p = 0.480$) but not in the theta band ($F(2,70) = 2.701$, $p = .074$, $\eta^2_p = 0.072$). Theta-IBS in both groups showed similar increasing trends with interaction degree (main effect of *interactive condition* in the theta band and child-actor/adult-observer role context: $F(2,70) = 22.611$, $p < .001$, $\eta^2_p = 0.392$, Figure 3b), which was significantly stronger in cooperation (theta-IBS = 0.439 ± 0.003) than accompanied (theta-IBS = 0.412 ± 0.004, $p_{Bonf} < .001$) and individual conditions (theta-IBS = 0.412 ± 0.003, $p_{Bonf} < .001$). Moreover, the mother–child dyads displayed a stronger theta-IBS (theta-IBS = 0.433 ± 0.003) than the stranger–child dyads (theta-IBS = 0.409 ± 0.003, main effect of *group* in the theta band and child-actor/adult-observer role context: $F(1,35) = 40.864$, $p < .001$, $\eta^2_p = 0.539$). In the alpha band, a significant *interactive condition* × *group* interaction was resulted from the group differences in change patterns with interactive conditions (Figure 3D). In mother–child dyads, alpha-IBS didn't change significantly between individual and accompanied conditions ($p_{Bonf} = .414$), but significantly decreased at cooperative condition (both $p_{Bonf} < .001$ compared with individual and accompanied, respectively). Neither group showed an increasing pattern of alpha-IBS.

Conversely, when the child was observing the adult partner solving puzzles, *interactive condition* × *group* was only significant in the theta band ($F(2,70) = 19.130$, $p < .001$, $\eta^2_p = 0.353$) but not in the alpha band ($F(2,70) = 1.730$, $p = .185$, $\eta^2_p = 0.047$). Alpha-IBS in both groups showed similar enhancement with interaction degree (main effect of *interactive condition* in the alpha band and adult-actor/child-observer role context: $F(2,70) = 64.764$, $p < .001$, $\eta^2_p = 0.649$, Figure 3h), which gradually increased from individual (alpha-IBS = 0.376 ± 0.004), accompanied (alpha-IBS = 0.427 ± 0.005, $p_{Bonf} < .001$ compared with individual) to cooperative (alpha-IBS = 0.446 ± 0.004, $p_{Bonf} = 0.028$ and $p_{Bonf} < .001$ compared with accompanied and individual, respectively) conditions. Additionally, the mother–child dyads displayed a stronger alpha-IBS (alpha-IBS = 0.422 ± 0.004) than the stranger–child dyads (alpha-IBS = 0.411 ± 0.004, main effect of *group* in the alpha band and adult-actor/child-observer role context: $F(1,35) = 4.315$, $p = .045$, $\eta^2_p = 0.110$). In the theta band, a significant *interactive condition* × *group* interaction was resulted from the group differences in change patterns with interactive conditions (Figure 3f). The stranger–child dyads showed an increasing pattern of theta-IBS with interaction degree (individual: theta-IBS = 0.400 ± 0.005; accompanied: theta-IBS = 0.426 ± 0.005; cooperative: theta-IBS = 0.440 ± 0.005; all between-condition $p_{Bonf} < .027$). However, in the mother–child dyads, theta-IBS was significantly lower at accompanied compared with individual condition ($p_{Bonf} = .003$).

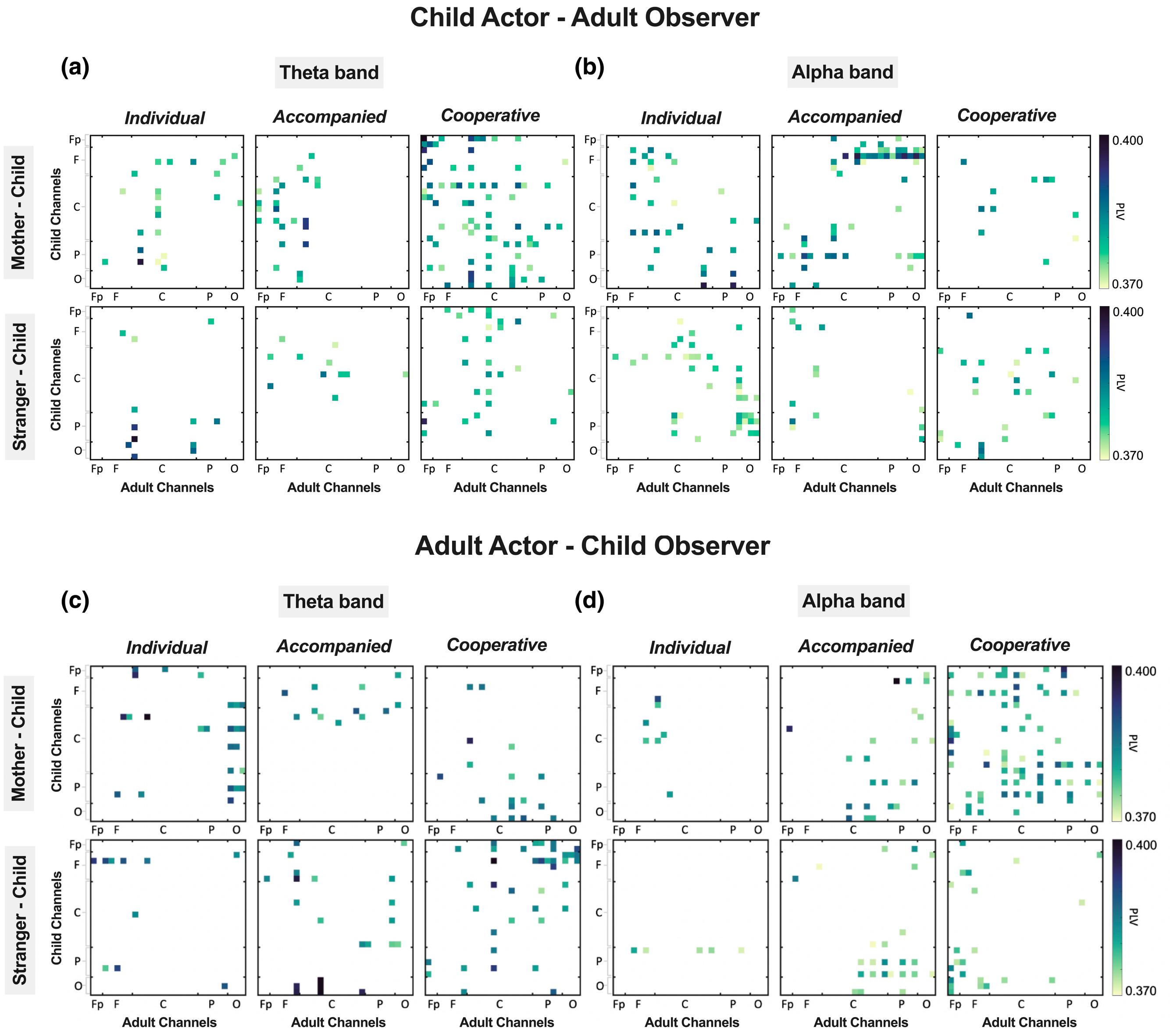

FIGURE 2 Interbrain connectivity matrices of mother–child and stranger–child dyads in different roles, frequency bands, and interactive conditions. (a, b) Interbrain connectivity matrices in theta (a) and alpha (b) bands when the child was the actor and the adult was the observer. (c, d) Interbrain connectivity matrices in theta (c) and alpha (d) bands when the child was the observer and the adult was the actor. Rows of matrices denote the child's channels, and columns denote the adult's channels. In each matrix, only connections with their strength significantly exceeding the corresponding threshold obtained from surrogating (one-tailed paired *t* test, $p < .05$) are shown as small squares, and the color of squares stands for their phase locking value (PLV) strength.

3.2 | Local network metrics

Since the increase of interbrain synchrony with interaction degree was prominent in the theta (alpha) band when the mother (child) was observing her child (mother) solving puzzles, we further calculated the node degree and regional IBS of theta-band child (actor)–mother (observer) interbrain network and alpha-band mother (actor)–child (observer) interbrain network. One-way repeated measures ANOVAs were performed on each regional IBS, taking *interactive condition* as the within-group factor, and *behavior* as covariates.

When the mother was observing her child solving puzzles, more theta-band interbrain connections were established between child's left (pre)frontal (Fp1, F7), right fronto-centro-parietal (FC2, FC6, CP2, Pz) and temporoparietal (CP6, P8) channels, and mother's (pre)frontal (Fp1, Fp2, F3), right fronto-centro-parietal (FC2, Cz, CP2) and left temporospatial (CP5) channels in cooperative condition (each node degree ≥4, Figure 4a). Moreover, regional theta-IBS (Figure 4b) showed overwhelmingly strongest interbrain synchrony in cooperative condition between almost all regions of two brains. However, a significant increase with interaction degree (main effect of *interactive*

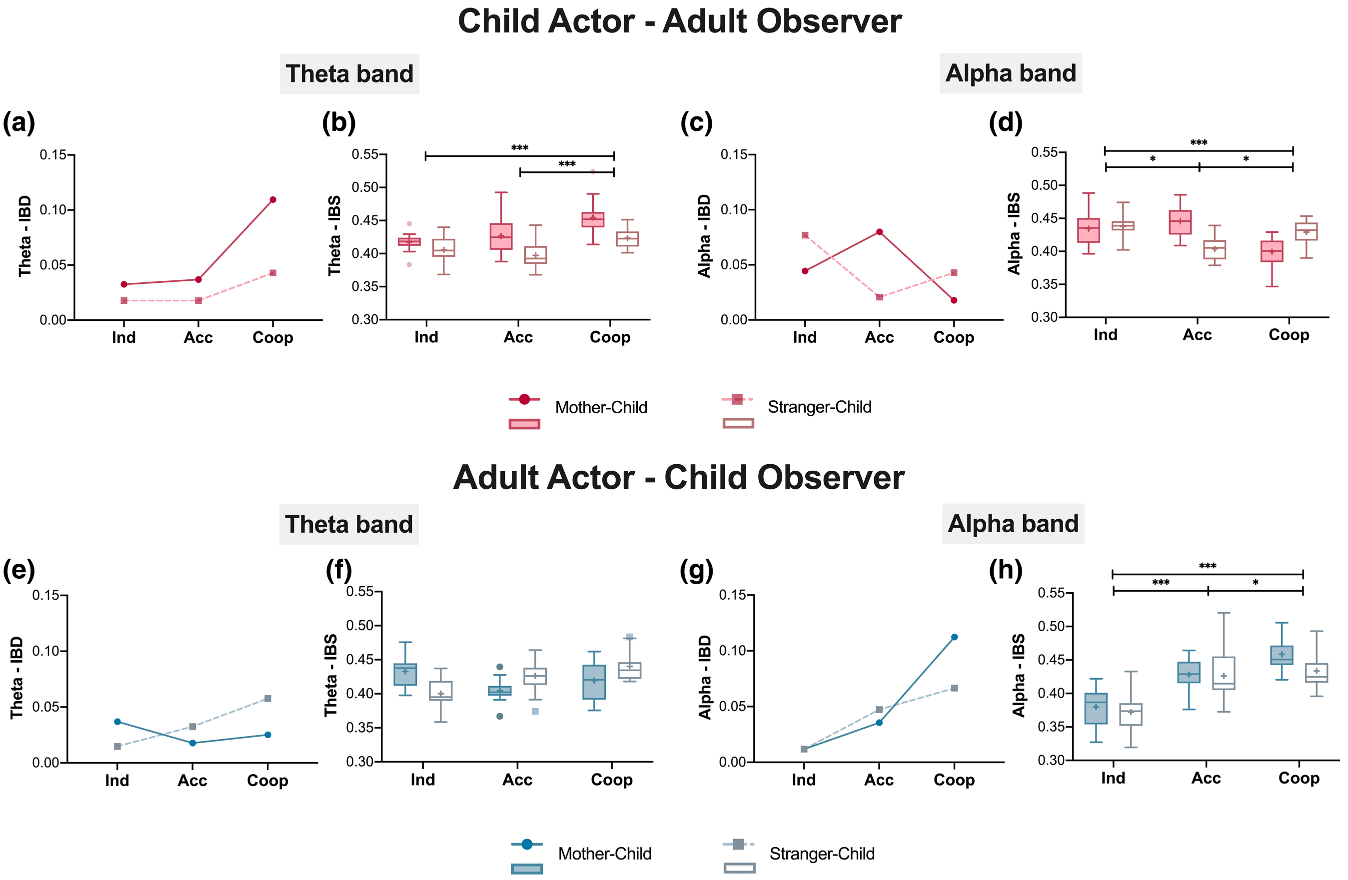

FIGURE 3 Global features of interbrain network of mother–child and stranger–child dyads in different roles, frequency bands, and interactive conditions. (a–d) Interbrain density (IBD) and interbrain strength (IBS) in theta (a, b) and alpha (c, d) bands when the child was the actor and the adult was the observer. (e–h) IBD and IBS in theta (e, f) and alpha (g, h) bands when the child was the observer and the adult was the actor. $^{*}p_{Bonf} < .05$, $^{***}p_{Bonf} < .001$.

TABLE 1 Statistical results of four-way repeated measure ANOVA on the global IBS.

Effect	*F*	η^2_p	*p*
Role	4.489	0.114	.041
Frequency band	<0.001	<0.001	.982
Interactive condition	36.552	0.511	<.001
Group	12.289	0.260	.001
Role × frequency band	6.542	0.156	.016
Role × interactive condition	36.658	0.512	<.001
Role × group	4.934	0.124	.033
Frequency band × interactive condition	8.362	0.193	.001
Frequency band × group	0.347	0.010	.560
Interactive condition × group	3.097	0.081	.051
Role × frequency band × interactive condition	46.512	0.571	<.001
Role × frequency band × group	29.457	0.457	<.001
Role × interactive condition × group	22.621	0.393	<.001
Frequency band × interactive condition × group	6.849	0.164	.002
Role × frequency band × interactive condition × group	15.594	0.308	<.001

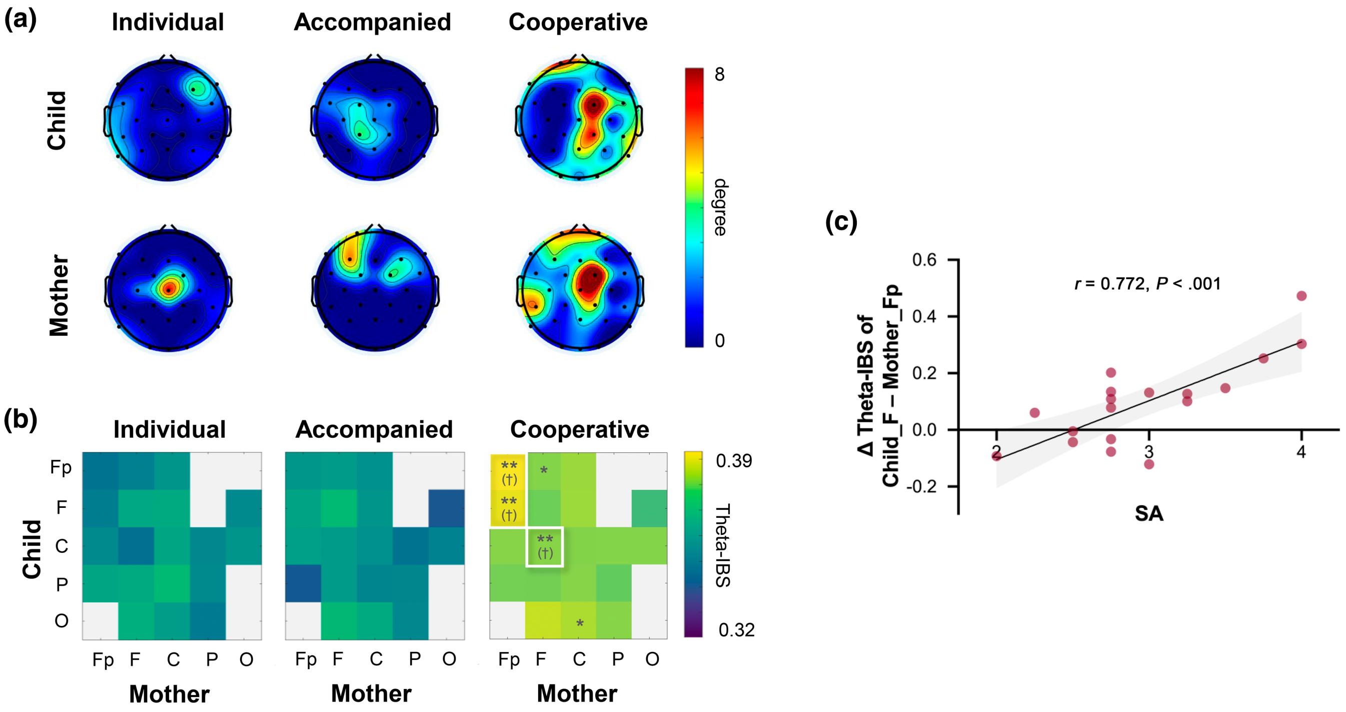

FIGURE 4 Local features of mother–child interbrain network in the theta band when the mother was observing her child solving puzzles in individual, accompanied, and cooperative conditions. (a) Topographies of node degree of interbrain networks. (b) Theta-band interbrain strength (IBS) between specific brain regions (i.e., regional theta-IBS), including prefrontal (Fp), frontal (F), central (C), parietal (P), and occipital (O) regions. $^*p_{uncorrected} < .05$, $^{**}p_{uncorrected} < .01$, $^\dagger p_{FDR} < .05$ for the main effect of *interactive condition*. (c) Correlation between the secure attachment (SA) score and the increment of theta-IBS from accompanied to cooperative condition (Δtheta-IBS) at Child_F–Mother_Fp.

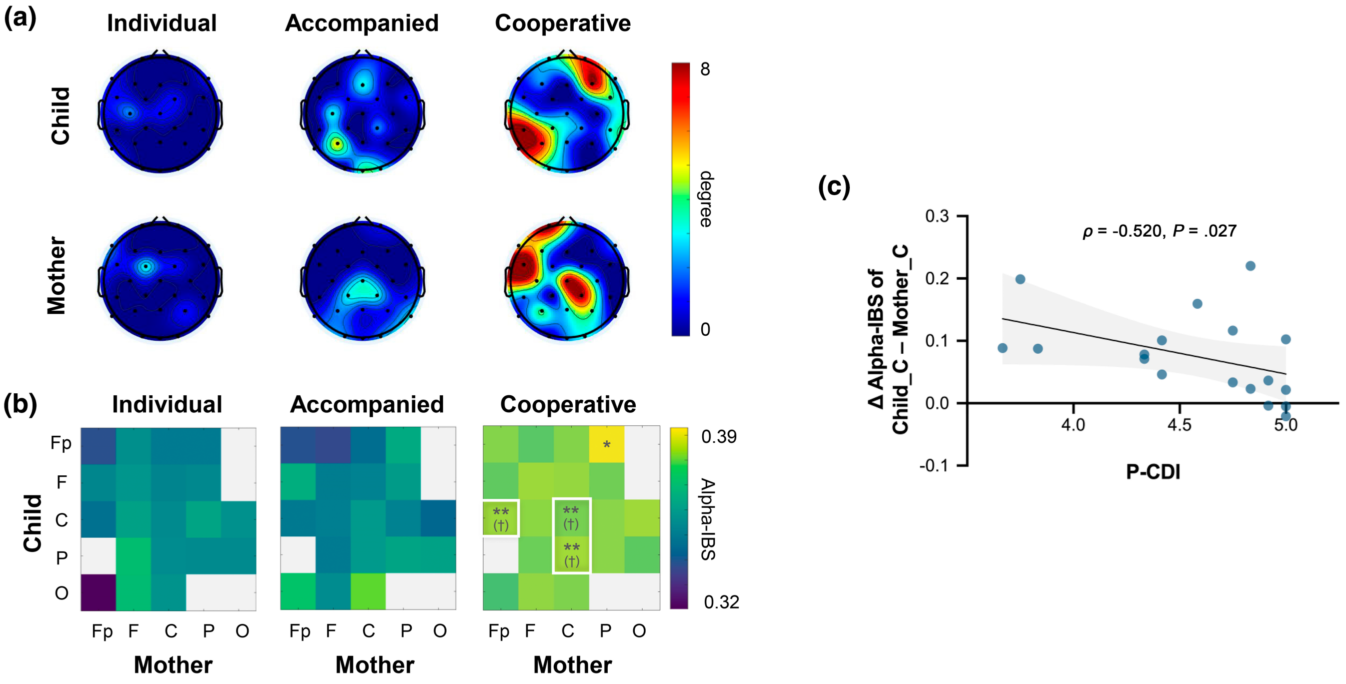

FIGURE 5 Local features of mother–child interbrain network in the alpha band when the child was observing his/her mother solving puzzles in individual, accompanied, and cooperative conditions. (a) Topographies of node degree of alpha-band interbrain networks. (b) Alpha-band interbrain strength (IBS) between specific brain regions (i.e., regional alpha-IBS), including prefrontal (Fp), frontal (F), central (C), parietal (P), and occipital (O) regions. $^*p_{uncorrected} < .05$, $^{**}p_{uncorrected} < .01$, $^\dagger p_{FDR} < .05$ for the main effect of *interactive condition*. (c) Correlations between the parent–child dysfunctional interaction (P-CDI) score and the increment of alpha-IBS from accompanied to cooperative condition (Δalpha-IBS) at Child_C–Mother_C.

condition, $p_{FDR} < .05$) was only found between child's (pre)frontal and mother's prefrontal areas (Child_Fp–Mother_Fp and Child_F–Mother_Fp) and between child's central and mother's frontal areas (Child_C–Mother_F). Especially, the interaction between Child_F–Mother_Fp theta-IBS and SA was significant ($F(2, 48) = 7.05$, $p = .002$, $\eta^2_p = 0.23$). Further correlation analysis found that the increment of Child_F–Mother_Fp theta-IBS from accompanied to cooperative condition was significantly and positively correlated with the SA score ($r(18) = .772$, 95%CI: [0.477, 0.911], $p < .001$, Figure 4c).

When the child was observing her mother solving puzzles, there were more alpha-band interbrain connections between the child's right (pre)frontal (Fp2, F4, FC6) and left centro-parietal (CP1, CP5, P3, P7) channels, and the mother's left fronto-central (Fp1, F3, F7, FC5, C3) and right centro-parietal (Cz, CP2, P4) channels in cooperative condition (each node degree ≥4, Figure 5a). Regional IBS (Figure 5b) showed overwhelmingly strongest alpha-band interbrain synchrony in cooperative condition, with significant increase with interaction degree (main effect of *interactive condition*, $p_{FDR} < .05$) between child's centro-parietal and mother's central areas (Child_C–Mother_C and Child_P–Mother_C) and between child's central and mother's prefrontal areas (Child_C–Mother_Fp). Especially, the interaction between Child_C–Mother_C alpha-IBS and P-CDI score ($F(2, 44) = 4.32$, $p = .019$, $\eta^2_p = 0.16$), as well as the interaction between Child_C–Mother_Fp alpha-IBS and PD score ($F(2, 39) = 4.37$, $p = .019$, $\eta^2_p = 0.18$) were significant. Further correlation analysis found that only the increment of Child_C–Mother_C alpha-IBS from accompanied to cooperative condition was significantly and negatively correlated with the P-CDI score in PSI-SF ($\rho(18) = -0.520$, 95%CI: [0.037, 0.806], $p = .027$, Figure 5c).

4 | DISCUSSION

Using a tangram puzzle-solving video game, we designed a well-controlled adult–child interaction experiment with gradually increasing interaction degree from individual, accompanied to cooperative conditions, and distinguished different interaction contexts where the child in the dyads acted as an actor/sender or an observer/receiver. By taking the advantage of high temporal resolution of EEG, we depicted the dynamic properties of interbrain synchrony along with the alternating roles during adult–child interaction. Furthermore, by comparing the mother–child and stranger–child dyads as well as correlating the scores for mother–child relationship, we examined the association between interbrain synchrony and interpersonal relationship.

First, we found enhanced interbrain synchrony during adult–child cooperation and demonstrated that the enhancement was actually induced by interpersonal interaction rather than shared external perturbation (e.g., common stimulation). Although previous studies have consistently reported increased interbrain connectivity during adult–child interaction (Miller et al., 2019; Nguyen et al., 2020; Nguyen, Schleihauf, et al., 2021; Reindl et al., 2018), the naturalistic experimental settings in these studies introduced more common stimulation to the cooperative than the individual condition, and therefore cannot exclude the spurious synchrony which was boosted by triggering similar neural responses to the common stimulation in both partners of the dyad (comment by Noreika et al., 2020). In this study, we designed an individual condition with shared visual stimuli (i.e., one watching the screen recording of his/her partner solving the puzzle) as a control to reduce the spurious synchrony. Meanwhile, we also designed an accompanied condition between the individual and cooperative conditions. With such a careful experimental design, we found a gradual increase of interbrain synchrony with the increasing degree of interaction (individual < accompanied < cooperative) within the children's theta (3–6 Hz) and alpha (6–9 Hz) bands, but not within the traditional theta (4–8 Hz) and alpha (8–12 Hz) bands (Supplementary Figure 1), which was consistent with previous mother–child EEG hyperscanning studies (Leong et al., 2017; Orekhova et al., 2006; Wass et al., 2018). Our results not only demonstrated the association between interbrain synchrony and interpersonal interaction, but also revealed the importance of interaction quality or engagement in adult–child interaction with objective neural electrophysiological evidence.

Most importantly, we captured the characteristics of interbrain synchrony in response to the alternating roles during adult–child interaction, and for the first time, proposed an association between the roles in adult–child interaction and the EEG oscillations of interbrain synchrony. Specifically, when the child was the actor and the adult partner was the observer, the interaction-induced interbrain synchrony was found in the theta band; and when their roles were reversed, this synchrony was shifted to the alpha band. Noted that both theta and alpha rhythms have been suggested to be closely related to adult–child interaction by previous EEG hyperscanning studies (Endevelt-Shapira et al., 2021; Leong et al., 2017; Santamaria et al., 2020). Leong et al. found that direct gaze increased bidirectional interbrain connectivity between the female experimenter and infants in both theta and alpha bands (Leong et al., 2017). Santamaria et al. found that mothers' emotion would influence the mother–infant interbrain network in the alpha band (Santamaria et al., 2020). Endevelt-Shapira et al. found that maternal body odors enhanced adult-infant interbrain synchrony specifically in the theta band (Endevelt-Shapira et al., 2021). Although these pioneering studies demonstrated the involvement of theta and/or alpha rhythms in adult–child interactions especially in mother–child interactions, the underlying mechanism of why and how these two rhythms synchronize across two brains is still insufficiently understood. In this study, through a turn-taking cooperation experimental design, we were able to distinguish different interaction contexts where dyads played different roles, and found the frequency band where the synchronization took place was highly dependent on the roles in adult–child interaction. The theta rhythm is vital for infants and preschool children in cognitive functioning, anticipatory and sustained attention, and encoding (Orekhova et al., 2006; Saby & Marshall, 2012; Sperdin et al., 2018; Wass et al., 2018). However, when the children grow into adults, these attention- and cognition-related oscillations were shifted to the alpha band (Marshall et al., 2002; Wass et al., 2018). Interestingly, we found that the interbrain synchrony during adult–child interaction prominently arose in the frequency band related to the actor's attention and cognitive functioning. One possible mechanism here we speculated is that in real interaction, especially in high-engaged interaction like cooperation, the observer may shift his/her attention- and cognition-related EEG frequency to the actor's to achieve neural synchrony with the actor. The proposed EEG frequency shift during adult–child interaction has been observed by Wass et al. (2018). That is, during mother–infant joint play, the attention-related EEG frequency of mother was downshifted from her own alpha band to the infant's attention-related theta range (Wass et al., 2018), implying a mother-toward-child neural alignment. However, our results suggested that the neural alignment was not only from adults to children, but also vice versa, that is, "from the observer to the actor." A mutual prediction theory can be used to explain the interbrain synchrony during interaction (Kingsbury et al., 2019). During turn-taking cooperation, the observer tried to understand and predict the behavior of the actor, and to achieve this, the observer might implicitly shift his/her EEG frequency to the actor's and synchronize his/her brain activity with the actor's. We think the EEG frequency shift and synchronization from the observer to the actor (or from receiver to sender) should be a vital neuroelectrophysiological mechanism underlying adult–child interaction.

It should be noted that both the mother–child and stranger–child dyads presented the interbrain synchrony within the actor's oscillations, implying that they shared some common neural mechanisms in interaction. However, the strength of interbrain synchrony was more prominent in the mother–child dyads compared with stranger–child dyads. This is in line with previous studies which compared the average interbrain synchrony between parent–child and stranger–child interactions. Endevelt-Shapira et al. observed greater interbrain synchrony in parent–child dyads than in stranger–child dyads during free play (Endevelt-Shapira et al., 2021), while Reindl et al. found significant enhancement of interbrain synchrony during cooperation only between parents and their children but not between strangers and children (Reindl et al., 2018). These findings demonstrated that the interbrain synchrony can effectively reflect the relationship of individuals during interactions, and more than that, from our results, a possible neural mechanism can be inferred, that is, it might be easier for the dyads with stronger emotional bonds like mothers and children to achieve neural alignment by shifting one's own EEG rhythms to the other's frequency.

The importance of emotional bonds in adult–child interbrain synchrony was further supported by the significant correlation between the strength enhancement of interbrain synchrony and parent–child relationship in the mother–child dyads, which also showed role-dependent characteristics. When the child was the actor and the mother was the observer, their theta-band interbrain synchrony enhanced in cooperation was primarily between the child's frontal, central, and mother's (pre)frontal areas, and this increment was significantly and strongly correlated with the child's attachment to their mother (i.e., SA score). From the age of 12 months, children become aware of how to actively coordinate their attention to both the objects and the adults simultaneously and use gestures to affect the adults' behavior (Chris & Philip, 1995). Children with SA have been found to show more joint attention (Naber et al., 2007) or seek to share experiences with the caregiver more than children with other attachment types (Humber & Moss, 2005). In the current study, although all the children in the mother–child dyads were classified as SA, children with stronger SA level to their mothers may be better at "inviting" their mothers to interact with them, which potentially, in turn, enabled their mothers to be more engaged in interaction and easier to align with children's neural activity. In this process, the frontal areas of both sides of the dyads seemed to play a crucial role. As one of the vital brain regions associated with the mentalizing process, the frontal area has been implicated to be responsible for understanding and predicting others' intentions and joint attention (Pan et al., 2017; Schilbach et al., 2013; Wang et al., 2018). Both mothers' and children's frontal activities have shown modulations by child–mother attachment in accumulated single-brain neuroimaging studies (Feldman, 2017; Laurent & Ablow, 2012; Long et al., 2020; Minagawa-Kawai et al., 2009; Perry et al., 2017; Young et al., 2017); however, the evidence from the interbrain network is still lacking. Although Miller et al. had tried to explore the link between attachment and the parent–child interbrain network (Miller et al., 2019), they only found a tendency that the avoidant child attachment might associate with less cooperation-related synchrony in the right frontopolar prefrontal cortex. To our knowledge, our work is the first to establish the correlation between attachment level and interbrain synchrony, and associate this correlation with the frontal lobe. Herein, we conjectured that stronger attachment between mothers and children might facilitate the mentalizing process and contribute to their interbrain synchrony in the frontal lobe.

When the mother was the actor, the central area was more prominent in mother–child cooperation. The alpha-band interbrain synchrony between the mother's and child's central area displayed not only a significant increase with interaction degree, but also a negative correlation with the mother's perception of their relationship with their child (i.e., P-CDI score). It means, the more dissatisfaction that the mother felt when interacting with her child in daily life, the less increment of central-central interbrain synchrony in cooperation. One recent study by Leong et al. also highlighted the role of central region during mother–child interaction, where they observed that the concurrent alpha-band neural entrainment across the central electrodes of mother–infant dyads was predictive of infants' social learning (Leong et al., 2019). Parent–child interactions were considered to provide the primary social learning context from infancy (Smelser & Baltes, 2001), during which children's social learning is mainly accomplished through observing their parents' activities. Therefore, one possible interpretation for our results is that when children were observing their mothers solving puzzles, those who had better parent–child interactions during daily life reported by their mothers may be more advanced in their social learning abilities, thus found it easier to attend to and follow their mothers' intentions in cooperation. This was neurally indicated by higher increment of alpha-band interbrain synchrony with their mothers in the central area.

It is worth mentioning that during mother–child cooperation, actor-observer interbrain synchrony was related to the emotional bonding from the actor toward the observer rather than the observer's affection toward the actor. These findings suggest that stronger actor-toward-observer emotional bonding in a mother–child relationship seems to have provided a better context for mutual interaction with higher increment of interbrain synchrony.

Several limitations of this study should be mentioned. First, as this is an exploratory study involving many factors, the conclusions remain preliminary and should be further validated by confirmatory studies with a large sample size. Second, the relationship between interbrain synchrony and behavioral traits was only explored with child–mother attachment and interaction quality in daily life but not with the interaction behavior during the task, since participants were asked to minimize unnecessary interaction behavior (such as talking and task-irrelevant interactive motions) to reduce EEG artifacts. In addition, child–mother attachment and interaction quality in daily life were assessed using parent-report questionnaires rather than direct observation, which may generate bias. However, the bias was minimized by choosing standardized and widely used instruments. The structure of our attachment questionnaire was also different from widely used attachment assessments like the Experiences in Close Relationships-Revised and Relationship Scales Questionnaire. These established measures typically separate attachment avoidance from disorganization, whereas our questionnaire does not have a distinct disorganized dimension. This might affect direct comparability with existing literature and standardized measures. Moreover, in our study, the score of SA showed a negative association with ambivalent attachment but not with avoidant/disorganized attachment (Supplementary Table 2). This suggests that SA dimension in our scale appears to capture the ambivalent aspect of insecurity but not the avoidant aspect of insecurity. Or to be more accurate, our findings in attachment pattern are related to secure versus insecure-ambivalent specifically. Third, the tangram puzzle-solving game was easy for most of the 3-year-old children, and therefore we were not able to detect any association between the task performances of children (e.g., willingness, speed, or accuracy) and the interbrain synchrony. Further studies are strongly encouraged to explore the correlation between concurrent behaviors and interbrain synchrony during interaction. Fourth, channel-level analysis was not able to find the exact brain regions that were involved in mother–child interaction. Further source-level study with more channels is needed to get more accurate inferences about the important brain regions. Finally, since previous studies have uniformly found higher interbrain synchrony in cooperative tasks than that in individual tasks (Cui et al., 2012; Li, Wu, et al., 2021; Miller et al., 2019; Nguyen et al., 2020; Nguyen, Schleihauf, et al., 2021; Reindl et al., 2018), this study only focused on the interbrain synchrony with an increasing trend with interaction degree. There were also some changing patterns of interbrain synchrony that were disordered and difficult to interpret, which is worth future investigation with a larger sample size.

Overall, our study is the first in this area to reveal the dynamic properties of mother–child interbrain synchrony along with the alternating roles during interaction. The role-specific effects were found on the interbrain synchrony within different EEG oscillations and between different brain regions, which also showed a significant relationship with actor-toward-observer emotional bonding. Our results help us understand how interbrain synchrony is established, maintained, and changed during this mutual–reciprocal interaction, and provide new insights into the neural mechanisms underlying social-cognitive processes in mother–child interactions, such as mentalization and social learning. Our findings also suggest that the interaction dynamics should be considered in future research on the interbrain synchrony between adults and children, not only through computational approaches (Li, Mayseless, et al., 2021), but also by specifying and considering vital elements (such as alternating roles) of the interaction dynamics in experimental design (Li, Wu, et al., 2021).

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT

Anonymized data are available from the authors upon request.

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REFERENCES

Abidin, R. (1995). *Parenting stress index* (3rd ed.). Psychological Assessment Resources.

Atzil, S., & Gendron, M. (2017). Bio-behavioral synchrony promotes the development of conceptualized emotions. *Current Opinion in Psychology*, *17*, 162–169.

Burgess, A. P. (2013). On the interpretation of synchronization in EEG hyperscanning studies: A cautionary note. *Frontiers in Human Neuroscience*, *7*, 1–17.

Chris, M., & Philip, J. D. (1995). *Joint attention: Its origins and role in development*. Routledge.

Cui, X., Bryant, D. M., & Reiss, A. L. (2012). NIRS-based hyperscanning reveals increased interpersonal coherence in superior frontal cortex during cooperation. *NeuroImage*, *59*, 2430–2437.

Czeszumski, A., Eustergerling, S., Lang, A., Menrath, D., Gerstenberger, M., Schuberth, S., Schreiber, F., Rendon, Z. Z., & König, P. (2020). Hyperscanning: A valid method to study neural inter-brain underpinnings of social interaction. *Frontiers in Human Neuroscience*, *14*, 1–17.

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*, 9–21.

Du, Y., Kou, J., & Coghill, D. (2008). The validity, reliability and normative scores of the parent, teacher and self report versions of the strengths and difficulties questionnaire in China. *Child and Adolescent Psychiatry and Mental Health*, *2*, 1–15.

Endevelt-Shapira, Y., Djalovski, A., Dumas, G., & Feldman, R. (2021). Maternal chemosignals enhance infant-adult brain-to-brain synchrony. *Science Advances*, *7*, 6867.

Feldman, R. (2017). The neurobiology of human attachments. *Trends in Cognitive Sciences*, *21*, 80–99.

Frith, C. D., & Frith, U. (2007). Social cognition in humans. *Current Biology*, *17*, 724–732.

George, C. (1996). A representational perspective of child abuse and prevention: Internal working models of attachment and caregiving. *Child Abuse & Neglect*, *20*, 411–424.

Goodman, A., & Goodman, R. (2009). Strengths and difficulties questionnaire as a dimensional measure of child mental health. *Journal of the American Academy of Child and Adolescent Psychiatry*, *48*, 400–403.

Haskett, M. E., Ahern, L. S., Ward, C. S., & Allaire, J. C. (2006). Factor structure and validity of the parenting stress index-short form. *Journal of Clinical Child and Adolescent Psychology*, *35*, 302–312.

Humber, N., & Moss, E. (2005). The relationship of preschool and early school age attachment to mother-child interaction. *The American Journal of Orthopsychiatry*, *75*, 128–141.

Kingsbury, L., Huang, S., Wang, J., Gu, K., Golshani, P., Wu, Y. E., & Hong, W. (2019). Correlated neural activity and encoding of behavior across brains of socially interacting animals. *Cell*, *178*, 429–446.e16.

Lachaux, J. P., Rodriguez, E., Martinerie, J., & Varela, F. J. (1999). Measuring phase synchrony in brain signals. *Human Brain Mapping*, *8*, 194–208.

Laurent, H. K., & Ablow, J. C. (2012). The missing link: Mothers' neural response to infant cry related to infant attachment behaviors. *Infant Behavior & Development*, *35*, 761–772.

Leong, V., Byrne, E., Clackson, K., Georgieva, S., Lam, S., & Wass, S. (2017). Speaker gaze increases information coupling between infant and adult brains. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 13290–13295.

Leong, V., Noreika, V., Clackson, K., Georgieva, S., Santamaria, L., Brightman, L., Nutbrown, R., Fujita, S., Neale, D., & Wass, S. (2019). Mother-infant interpersonal neural connectivity predicts infants' social learning. Pre-print.

Levy, J., Goldstein, A., & Feldman, R. (2017). Perception of social synchrony induces mother-child gamma coupling in the social brain. *Social Cognitive and Affective Neuroscience*, *12*, 1036–1046.

Li, R., Mayseless, N., Balters, S., & Reiss, A. L. (2021). Dynamic inter-brain synchrony in real-life inter-personal cooperation: A functional near-infrared spectroscopy hyperscanning study. *NeuroImage*, *238*, 118263.

Li, Y., Wu, S., Shi, W., Tong, S., Zhang, Y., & Guo, X. (2021). Enhanced inter-brain connectivity between children and adults during cooperation: a dual EEG study, in: 2021 43rd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). pp. 6289–6292.

Lindenberger, U., Li, S. C., Gruber, W., & Müller, V. (2009). Brains swinging in concert: Cortical phase synchronization while playing guitar. *BMC Neuroscience*, *10*, 1–12.

Liu, C. (2005). *The relationships between preschoolers' attachment styles, verbal intelligence, interpersonal intelligence, and their theory of mind*. National Chengchi University.

Long, M., Verbeke, W., Ein-Dor, T., & Vrtička, P. (2020). A functional neuro-anatomical model of human attachment (NAMA): Insights from first- and second-person social neuroscience. *Cortex*, *126*, 281–321.

Long, Y., Zheng, L., Zhao, H., Zhou, S., Zhai, Y., & Lu, C. (2021). Interpersonal neural synchronization during interpersonal touch underlies affiliative pair bonding between romantic couples. *Cerebral Cortex*, *31*, 1647–1659.

Marshall, P. J., Bar-Haim, Y., & Fox, N. A. (2002). Development of the EEG from 5 months to 4 years of age. *Clinical Neurophysiology*, *113*, 1199–1208.

Miller, J. G., Shrestha, S., Reiss, A. L., & Vrtička, P. (2020). Neural bases of social feedback processing and self–other distinction in late childhood: The role of attachment and age. *Cognitive, Affective, & Behavioral Neuroscience*, *20*, 503–520.

Miller, J. G., Vrtička, P., Cui, X., Shrestha, S., Hosseini, S. M. H., Baker, J. M., & Reiss, A. L. (2019). Inter-brain synchrony in mother-child dyads during cooperation: An fNIRS hyperscanning study. *Neuropsychologia*, *124*, 117–124.

Minagawa-Kawai, Y., Matsuoka, S., Dan, I., Naoi, N., Nakamura, K., & Kojima, S. (2009). Prefrontal activation associated with social attachment: Facial-emotion recognition in mothers and infants. *Cerebral Cortex*, *19*, 284–292.

Montague, P. R., Berns, G. S., Cohen, J. D., McClure, S. M., Pagnoni, G., Dhamala, M., Wiest, M. C., Karpov, I., King, R. D., Apple, N., & Fisher, R. E. (2002). Hyperscanning: Simultaneous fMRI during linked social interactions. *NeuroImage*, *16*, 1159–1164.

Murray, L., & Trevarthen, C. (1986). The infant's role in mother–infant communications. *Journal of Child Language*, *13*, 15–29.

Naber, F., Swinkels, S. H. N., Buitelaar, J. K., Dietz, C., Van Daalen, E., Bakermans-Kranenburg, M. J., Van Ijzendoorn, M. H., & Van Engeland, H. (2007). Joint attention and attachment in toddlers with autism. *Journal of Abnormal Child Psychology*, *35*, 899–911.

Nguyen, T., Abney, D. H., Salamander, D., Bertenthal, B. I., & Hoehl, S. (2021). Proximity and touch are associated with neural but not physiological synchrony in naturalistic mother-infant interactions. *NeuroImage*, *244*, 118599.

Nguyen, T., Schleihauf, H., Kayhan, E., Matthes, D., Vrtička, P., & Hoehl, S. (2020). The effects of interaction quality on neural synchrony during mother-child problem solving. *Cortex*, *124*, 235–249.

Nguyen, T., Schleihauf, H., Kungl, M., Kayhan, E., Hoehl, S., & Vrtička, P. (2021). Interpersonal neural synchrony during father-child problem solving: An fNIRS hyperscanning study. *Child Development*, *92*, e565–e580.

Noreika, V., Georgieva, S., Wass, S., & Leong, V. (2020). 14 challenges and their solutions for conducting social neuroscience and longitudinal EEG research with infants. *Infant Behavior & Development*, *58*, 101393.

Orekhova, E. V., Stroganova, T. A., Posikera, I. N., & Elam, M. (2006). EEG theta rhythm in infants and preschool children. *Clinical Neurophysiology*, *117*, 1047–1062.

Pan, Y., Cheng, X., Zhang, Z., Li, X., & Hu, Y. (2017). Cooperation in lovers: An fNIRS-based hyperscanning study. *Human Brain Mapping*, *38*, 831–841.

Perry, R. E., Blair, C., & Sullivan, R. M. (2017). Neurobiology of infant attachment: Attachment despite adversity and parental programming of emotionality. *Current Opinion in Psychology*, *17*, 1–6.

Quiñones-Camacho, L. E., Fishburn, F. A., Camacho, M. C., Hlutkowsky, C. O., Huppert, T. J., Wakschlag, L. S., & Perlman, S. B. (2020). Parent–child neural synchrony: A novel approach to elucidating dyadic correlates of preschool irritability. *The Journal of Child Psychology and Psychiatry and Allied Disciplines*, *61*, 1213–1223.

Redcay, E., & Schilbach, L. (2019). Using second-person neuroscience to elucidate the mechanisms of social interaction. *Nature Reviews. Neuroscience*, *20*, 495–505.

Reindl, V., Gerloff, C., Scharke, W., & Konrad, K. (2018). Brain-to-brain synchrony in parent-child dyads and the relationship with emotion regulation revealed by fNIRS-based hyperscanning. *NeuroImage*, *178*, 493–502.

Saby, J. N., & Marshall, P. J. (2012). The utility of EEG band power analysis in the study of infancy and early childhood. *Developmental Neuropsychology*, *37*, 253–273.

Santamaria, L., Noreika, V., Georgieva, S., Clackson, K., Wass, S., & Leong, V. (2020). Emotional valence modulates the topology of the parent-infant inter-brain network. *NeuroImage*, *207*, 116341.

Schilbach, L., Timmermans, B., Reddy, V., Costall, A., Bente, G., Schlicht, T., & Vogeley, K. (2013). Toward a second-person neuroscience. *The Behavioral and Brain Sciences*, *36*, 393–414.

Smelser, N. J., & Baltes, P. B. (2001). *International encyclopedia of the social & behavioral sciences*. Elsevier Amsterdam.

Sperdin, H. F., Coito, A., Kojovic, N., Rihs, T. A., Jan, R. K., Franchini, M., Plomp, G., Vulliemoz, S., Eliez, S., Michel, C. M., & Schaer, M. (2018). Early alterations of social brain networks in young children with autism. *eLife*, *7*, 1–23.

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, *348*, 91–94.

Vicente, U., Ara, A., & Marco-Pallarés, J. (2023). Intra-and inter-brain synchrony oscillations underlying social adjustment. *Scientific Reports*, *13*, 11211.

Wang, M. Y., Luan, P., Zhang, J., Xiang, Y. T., Niu, H., & Yuan, Z. (2018). Concurrent mapping of brain activation from multiple subjects during social interaction by hyperscanning: A mini-review. *Quantitative Imaging in Medicine and Surgery*, *8*, 819–837.

Wang, Q., Han, Z., Hu, X., Feng, S., Wang, H., Liu, T., & Yi, L. (2020). Autism symptoms modulate interpersonal neural synchronization in children with autism spectrum disorder in cooperative interactions. *Brain Topography*, *33*, 112–122.

Wass, S. V., Noreika, V., Georgieva, S., Clackson, K., Brightman, L., Nutbrown, R., Covarrubias, L. S., & Leong, V. (2018). Parental neural responsivity to infants' visual attention: How mature brains influence immature brains during social interaction. *PLoS Biology*, *16*, 1–18.

Wass, S. V., Smith, C. G., Clackson, K., Gibb, C., Eitzenberger, J., & Mirza, F. U. (2019). Parents mimic and influence their infant's autonomic state through dynamic affective state matching. *Current Biology*, *29*, 2415–2422.e4.

Wass, S. V., Whitehorn, M., Marriott Haresign, I., Phillips, E., & Leong, V. (2020). Interpersonal neural entrainment during early social interaction. *Trends in Cognitive Sciences*, *24*, 329–342.

Wechsler, D. (2012). *Wechsler preschool and primary scale of intelligence* (4th ed.). Psychological Corporation.

Young, K. S., Parsons, C. E., Stein, A., Vuust, P., Craske, M. G., & Kringelbach, M. L. (2017). The neural basis of responsive caregiving behaviour: Investigating temporal dynamics within the parental brain. *Behavioural Brain Research*, *325*, 105–116.

Zhao, H., Cheng, T., Zhai, Y., Long, Y., Wang, Z., & Lu, C. (2021). How mother-child interactions are associated with a child's compliance. *Cerebral Cortex*, *31*, 4398–4410.

Zivan, M., Gashri, C., Habuba, N., & Horowitz-Kraus, T. (2022). Reduced mother-child brain-to-brain synchrony during joint storytelling interaction interrupted by a media usage. *Child Neuropsychology*, *28*, 918–937.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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