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Original Article

Parenting links to parent–child interbrain synchrony: a real-time fNIRS hyperscanning study

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Parent–child interaction is crucial for children's cognitive and affective development. While bio-synchrony models propose that parenting influences interbrain synchrony during interpersonal interaction, the brain-to-brain mechanisms underlying real-time parent–child interactions remain largely understudied. Using functional near-infrared spectroscopy, we investigated interbrain synchrony in 88 parent–child dyads ($M_{age\ children} = 8.07$, 42.0% girls) during a collaborative task (the Etch-a-Sketch, a joint drawing task). Our findings revealed increased interbrain synchrony in the dorsolateral prefrontal cortex and temporo-parietal areas during interactive, collaborative sessions compared to non-interactive, resting sessions. Linear regression analysis demonstrated that interbrain synchrony in the left temporoparietal junction was associated with enhanced dyadic collaboration, shared positive affect, parental autonomy support, and parental emotional warmth. These associations remained significant after controlling for demographic variables including child age, child gender, and parent gender. Additionally, differences between fathers and mothers were observed. These results highlight the significant association between brain-to-brain synchrony in parent–child dyads, the quality of the parent–child relationship, and supportive parenting behaviors. Interbrain synchrony may serve as a neurobiological marker of real-time parent–child interaction, potentially underscoring the pivotal role of supportive parenting in shaping these interbrain synchrony mechanisms.

Key words: interbrain synchrony; neural synchrony; fNIRS hyperscanning; parenting; parent–child relationships.

Introduction

Parent–child interaction is pivotal in shaping children's cognitive and affective development (Ratliff et al. 2022). These interactions serve as a foundation for children to learn how to engage in mutually regulated social patterns (Harrist and Waugh 2002; Feldman 2012). Harrist and Waugh (2002) define parent–child synchrony as a subset of parent–child interaction, emphasizing observable patterns of dyadic interaction that are mutually regulated, reciprocal, and harmonious. Interbrain synchrony, also known as neural synchrony or brain-to-brain synchrony, refers to the temporal coordination of brain activity across two or more individuals (Gvirts and Perlmutter 2020). It provides another fundamental and neurobiological basis for understanding parent–child interaction in addition to behavioral and physiological activities (Beauchaine 2015). Hyperscanning, measuring brain activity concurrently in multiple individuals, is often used for studying interbrain synchrony (Quiñones-Camacho et al. 2020; Nguyen et al. 2021; Zhao et al. 2021). We chose functional near-infrared spectroscopy (fNIRS) for its higher tolerance of motion artifact and better balance of spatial and time resolution when compared to electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), making it well suited for real-time brain activation exploration in natural settings (Pinti et al. 2020).

The present study focused on the temporoparietal junction (TPJ) and dorsolateral prefrontal cortex (dlPFC). The TPJ, as a crucial region of the social brain network, is essential for social information processing (Eddy 2016). Furthermore, dyadic interaction involves the regulation of attentional and emotional processes through top-down control, which is associated with activity in the dlPFC (Arnsten and Rubia 2012). Thus, exploring interbrain synchrony within these regions may offer insights into social interactive and relationship processes.

The temporal coordination of brain activity across individuals is proposed to be associated with emotional sharing, cooperation, and trustful relationships (Gvirts and Perlmutter 2020). However, a significant gap exists in our understanding of how interbrain synchrony correlates with real-time dyadic interaction indices in parent–child relationships. Key indices of dyadic relationship quality, such as shared positive affect and collaborative interpersonal interactions, were central to our investigation in this study (Davis et al. 2017). We sought to explore how these behavioral indices are linked with interbrain synchrony.

In addition to dyadic interaction indices demonstrated by parent–child dyads, parenting practices, are vital to shaping parent–child synchrony, as posited in the bio-synchrony model (Feldman 2012). Parents play a crucial role in providing "external regulation"

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to their children's developing systems, aiding in the coordination and regulation of emotions and behaviors within the dyad (Feldman 2012; Ratliff et al. 2022). While previous research by Nguyen and her colleagues explored the relation between real-time parenting and interbrain synchrony, their findings indicated that parental sensitivity did not correlate with interbrain synchrony (Nguyen et al. 2020, 2021). However, these studies focused primarily on a single parenting practice (i.e. sensitivity) and a limited age group of preschoolers ($M_{\text{age children}} = 5$ years old). This focus on a specific age group might clarify why Nguyen et al. found no significant results. Social brain regions could still be immature in 5-year olds (Osterhaus and Koerber 2021), suggesting the need to study older children.

Middle childhood, spanning from ages 6 to 12, is marked by significant shifts in parent–child interactions. Children in this phase exhibit an increased desire for autonomy and develop additional strategies for emotional self-regulation (Geerts and Riggs 2019). Meanwhile, children's Theory of Mind undergoes continuous development, paralleling the maturation of the mentalizing network (Devine and Apperly 2022). This developmental period allows children to acquire more complex and nuanced perspectives about their parents' and peers' mental lives (Osterhaus and Koerber 2021). Considering these substantial changes and the potential role of interbrain synchrony in coregulation (Ratliff et al. 2022), our study focused specifically on middle childhood. Understanding the roles parents play becomes crucial in navigating the unique needs of children in this phase.

During parent–child interactions, parents often serve as either a "safe haven" or "secure base" (Bowlby 1969). In their role as a safe haven, parents prioritize comforting and reassuring children when they are dysregulated, and demonstrate *parental emotional warmth*. Moreover, in providing their children with a secure base, parents encourage and support their children's explorations in novel social and physical environments, reflecting *support of child autonomy* (Paley and Hajal 2022). These two parenting practices, considered essential components of parenting children (Bülow et al. 2022), have been associated with greater dyadic synchrony, both behaviorally and physiologically (Treyvaud et al. 2009; Han et al. 2019). In the context of this study, we conceptualized parental warmth and autonomy support as specific behavioral manifestations of a "safe haven" and "secure base" during an interactive task, directly observed and coded.

In this study, we employed fNIRS hyperscanning to explore the associations between interbrain synchrony and in-the-moment parenting behaviors exhibited by parents, and the dyadic interactive relationship quality co-constructed by both parents and children. Drawing upon previous research (Nguyen et al. 2020; Zhao et al. 2021), we examined the TPJ and dlPFC as regions of interest. We hypothesized that there would exist a positive association between behaviorally coded parent–child relationship quality (including shared positive affect and collaborative behaviors) and supportive parenting behaviors (warmth and autonomy support) with dyadic interbrain synchrony.

Materials and methods

Participants

We recruited 88 parent–child dyads ($n = 176$) in Beijing, China, using online fliers. Participants were selected through a convenient sampling method, including school-age children aged 6–11 years ($M_{age} = 8.07$, $SD = 1.16$; 51 boys, 37 girls) and one of their caregivers ($M_{age} = 39.07$, $SD = 3.53$; 27 biological fathers, 60 biological mothers, 1 stepmother). Socio-demographic characteristics are presented in Table 1. The majority of parents were married (95.5%), of Han ethnicity (96.6%), and held a college undergraduate or higher educational degree (94.3%). Regarding family income, 76 families (86.4%) reported an annual income above the city average (i.e. approximately $27,400 per family annually; Beijing Municipal Bureau Statistics, 2022). Three dyads did not complete the fNIRS experiments, and three dyads could not be coded due to poor video quality. Among the 88 dyads, 27 were father–child pairs and 61 were mother–child pairs. Fathers and mothers reported similar marital status, education, and income levels, and children were comparable in age and gender ($ps > 0.062$).

Table 1. Socio-demographic characteristics of participants.

Variables	*n*	%
Parent gender		
Female	61	69.3%
Child gender		
Female	37	42.0%
Ethnicity		
Han	85	96.6%
Minorities	3	3.4%
Marital status		
Married	84	95.5%
Living separately or divorced	4	4.5%
Paternal educational level		
Middle school degree or lower	0	0.0%
High school degree	5	5.7%
Bachelor's degree	43	48.9%
Master's degree or above	40	45.4%
Maternal educational level		
Middle school degree or lower	0	0.0%
High school degree	4	4.7%
Bachelor's degree	44	51.8%
Master's degree or above	37	43.5%
Family income per year		
¥60,000 or lower	0	0.0%
¥60,000–¥12,0000	8	9.1%
¥12,0000–¥18,0000	4	4.5%
¥18,0000–¥24,0000	7	8.0%
¥24,0000–¥30,0000	19	21.6%
¥30,0000 or above	20	56.8%

Procedures

Parents and children were invited to a research laboratory located on a university campus. Before the experimental sessions began, participants were informed about the study's purposes and procedures and provided informed consent. fNIRS caps were placed on both the parent and child, with devices calibrated for signal quality.

During the *experimental paradigm*, two cameras recorded the parent's and child's behaviors (see Fig. 1). In the *resting phase* (6 min), the parent and child were instructed to relax without communication, separated by an opaque screen to prevent visual contact. Before the *interactive session* (5 min), the experimenter introduced the game rules and provided instructions on how to use an Etch-A-Sketch. This drawing toy has a gray screen and two knobs, each controlling a stylus—one for horizontal, the other for vertical lines, creating drawings with aluminum powder. The task involved cooperative joint drawing, where parent and child used their own Etch-A-Sketch knob to draw a tree and a house within a limited time. During the task, the parent and child moved

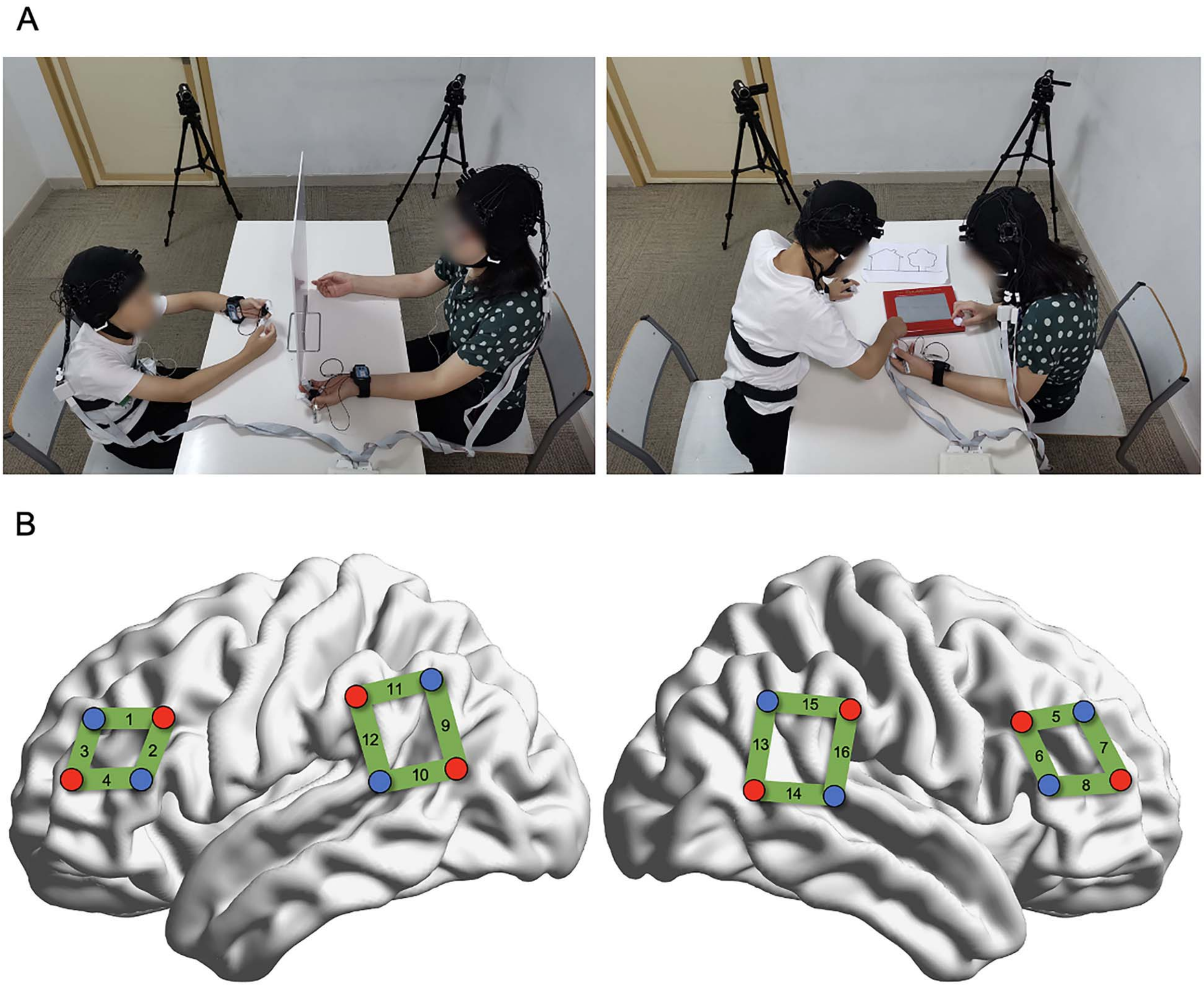

Fig. 1. Experimental paradigm. (A) Experimental set-up during resting session and interactive session. (B) Positions of fNIRS probe sets in the left and right hemispheres. Sources = red; detectors = blue. CH1–4 are located in the left dlPFC; CH9–12 in the left TPJ; CH5–8 in the right dlPFC; CH13–16 in the right TPJ.

closer to each other and were guided to cooperatively engage in a structured joint drawing. This dyadic task is challenging for children in middle childhood, requiring that parents provide comfort when children appear dysregulated (reflecting parental warmth) and encourage them when they initiate picture drawing (indicating autonomy support).

After the visit, each dyad received 100 RMB (approximately $16) compensation, and children received a token of appreciation. All study procedures and materials were approved by the Institutional Review Board of Faculty of Psychology, Beijing Normal University (IRB Number: 202107140039).

fNIRS data acquisition

We used NIRSport 2 optical topography systems (NIRx Medical Technologies, NY, USA) to collect raw data, with wavelengths at 760 and 850 nm and a sampling rate of 10.17 Hz. According to previous studies (Nguyen et al. 2021; Zhao et al. 2021), an 8 × 8 configuration with four sets of optodes covered the dlPFC and TPJ on both left and right hemispheres (see Fig. 1). In each probe set, two sources and two detectors were positioned, forming four measurement channels (CH) with equal distances of 3 cm between each two optodes. To determine the optode locations, we reviewed relevant anatomical literature and used a 3D magnetic digitizer (FastrakTM, Polhemus). We first reviewed literature about the anatomical location of the dlPFC (the side part of BA 9 and the upper part of BA 46; (Hertrich et al. 2021) and TPJ (the inferior parts of BA 39, BA 40, and the upper part of BA 22; (Donaldson et al. 2015). Then, the 3D magnetic digitizer could record locations on the head surface and visualize the corresponding positions on a virtual head model in the user interface. This setup resulted in 16 channels for brain activation data (Fig. 1). The MNI coordinates of the channels are reported in Table 2.

Before placing the caps, experimenters selected the appropriate size of the cap (large, medium, or small) based on the participants' head circumferences. We implemented a standardized cap-placement procedure to further enhance consistency. For instance, the lower edge of the cap was aligned with the eyebrows, and the midline was aligned with the nasal bridge. Additionally, the caps were equipped with adjustable straps and soft padding to enhance participants' comfort.

Behavioral coding

The Etch-A-Sketch session was video recorded. Coders underwent comprehensive training sessions that include a detailed review and discussion of coding systems, clear explanations of criteria, and practice sessions. Training practices continued until a

Table 2. Coordinates of the channels.

Channel	MNI-X	MNI-Y	MNI-Z
1	43.12	38.22	35.13
2	46.21	50.72	9.07
3	55.06	20.43	31.62
4	58.27	26.34	10.90
5	65.26	−33.13	38.47
6	68.34	−41.17	7.98
7	56.43	−58.91	38.70
8	60.25	−61.89	7.93
9	−38.90	45.57	30.14
10	−43.23	53.89	8.04
11	−53.41	22.56	30.58
12	−56.37	29.57	10.59
13	−65.09	−33.42	38.31
14	−68.08	−42.75	12.24
15	−55.65	−58.22	42.54
16	−59.60	−64.60	15.81

satisfactory level of agreement (intraclass correlations, ICCs ≥0.75) was reached among coders. Following training, three research assistants reviewed the videos and reached a consensus on final scores. Inter-rater reliability was gauged using ICCs based on the initial independent ratings of the three coders. Parental warmth, autonomy support, shared positive affect, and collaborative behaviors were assessed using established coding systems derived from the *Minnesota Longitudinal Study of Parents and Children* (Sroufe et al. 2005) and adapted in previous Chinese studies (Han et al. 2019; Wang et al. 2021).

Parental warmth was assessed by the *Positive Responsiveness Scale*. The scale reflected the extent to which parents were aware of, and appropriately responded to, their child's emotional needs. Coders used a 7-point Likert scale (from 1 "*very low*" to 7 "*very high*") based on the 5-min interaction. Parents receiving low scores (e.g. 1) were perceived as unavailable or emotionally detached (e.g. ignored the child's emotional expressions). In contrast, parents with high scores (e.g. 7) demonstrated sensitive awareness and appropriate responses to their child's emotional experiences (e.g. comforting a distressed child through physical touch). Parents scoring in the middle of the scale (e.g. 4) exhibited validation of the child's emotional experiences but inconsistently responded to the child's emotional needs. The ICC for this scale was 0.86.

The *Support of Autonomy Scale* measured the degree to which parents recognized and respected their child's individuality, motives, emotions, and perspectives. Coders employed a 7-point Likert scale (from 1 "*very low*" to 7 "*very high*"). Parents scoring low (e.g. 1) were observed dismissing their child's individuality and ideas (e.g. saying "No, this will not work, and you should not do this"). In contrast, parents with high scores (e.g. 7) were seen as acknowledging and supporting their child's perspectives (e.g. stating "Doing wrong is okay. Do you want to try again?"). Parents scoring in the middle of the scale (e.g. 4) exhibited inconsistency in encouraging their child's perspectives, at times eliciting the child's opinions but failing to acknowledge them. The ICC for this scale was 0.88.

The quality of the parent–child relationship was assessed based on shared positive affect and dyadic collaborative behaviors during the interaction. The *Emotional Synchrony Scale* assessed the reciprocity of positive affect between parent–child dyads, using a 7-point Likert scale (from 1 "*very low*" to 7 "*very high*"). Dyads scoring low (e.g. 1) shared little or no positive affect, and the interaction seemed extremely awkward or strained (e.g. neither person expressed any positive affect that could be reciprocated). In contrast, dyads scoring high (e.g. 7) were characterized by smooth and well-coordinated sharing of positive affective expressions. Dyads scoring in the middle of the scale (e.g. 4) demonstrated mixed positive affect, sometimes met with neutral or negative affect. The ICC for this scale was 0.95.

Dyadic Cooperation Scale assessed the extent to which the child and parent actively sought mutual understanding and achieved shared goals, utilizing a 7-point Likert scale (from 1 "*very low*" to 7 "*very high*"). Dyads scoring low (e.g. 1) presented opposition without negotiations, often redefining joint tasks as individual ones and undermining each other's contributions. In contrast, dyads scoring high (e.g. 7) actively contributed ideas, cooperatively responded to suggestions, and engaged in negotiations. Dyads scoring in the middle of the scale (e.g. 4) exhibited little active striving for mutuality but also little or no active distancing. The ICC for this scale was 0.93.

Data analysis

fNIRS data underwent preprocessing using HomER, a Matlab (The MathWorks, Inc., Natick, MA, United States) toolbox. After an initial quality check using Homer3, channels lacking a clear heart band were removed, resulting in a 10.88% exclusion of total channels. Dyads were excluded if over 50% of channels were removed for at least one participant during a single session (six dyads were excluded). Preprocessing involved several steps: conversion of raw data to optical density, motion artifact correction, band-pass filtering, conversion to HbO, and removal of initial and final segments of data. The raw data were converted to optical density using the Homer3 function "hmrR_Intensity2OD." Motion artifacts were detected by using the "hmrR_Motion_Artifacts_By_Channel" function (tMotion = 0.5, tMask = 1, std_thresh = 10, amp_thresh = 5) and they were corrected by using a motion-correction algorithm based on a spline interpolation ("hmrR_MotionCorrectsSpline," $P = 0.99$). A band-pass filter ("fmrR_BandpassFilt: Bandpass_Filter_OpticalDensity") with parameters of 0.01 and 0.5 Hz was applied (Miller et al. 2019; Nguyen et al. 2020). The preprocessed optical density data were converted to HbO and HbR using the "hmrR_OD2Conc" function based on the modified Beer–Lambert Law, assuming a partial path length factor as 6 (Wang et al. 2020). To ensure stable data, the initial 10 s and the last 60 s (mainly due to the head motions) were removed from each session, leaving 290 s for the resting session and 230 s for the interaction session. Given the sensitivity of the HbO signal to changes in cerebral blood flow during fNIRS measurements (Miller et al. 2019), our study focused on the HbO time series.

Interbrain synchrony between parent–child dyads was computed using Wavelet Transform Coherence Analyses (WTC) using the MATLAB function "wcoherence." This method assessed the cross-correlation between two-time series in the task-related frequency band of 0.02–0.3 Hz (corresponding to 3.3–50 s). We illustrate the heat maps of the wavelet coherence values from a representative dyad in Fig. 2. We calculated the WTC values for the corresponding channel in each session, averaging the task-related frequency and time, and converted them into Fisher z-values. Pair-wise *t*-tests (between resting and interactive sessions) were conducted on the WTC values in each channel, with false discovery rate (FDR) adjustment for multiple comparisons (Wang et al. 2020). The increment in interbrain synchrony specific to the parent–child interaction was quantified by subtracting coherence values of the resting session from those of the interactive session for each channel. Channels showing a

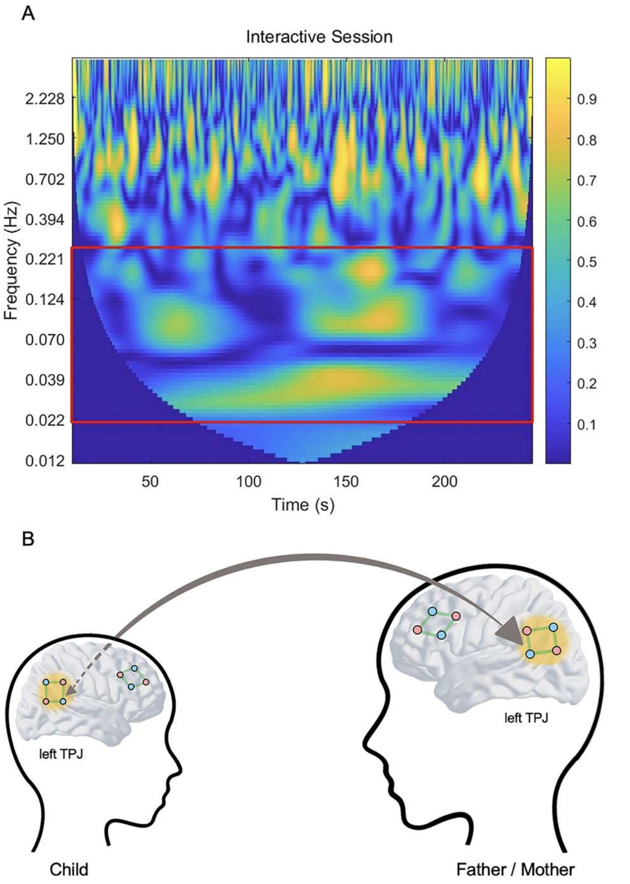

Fig. 2. Interbrain synchrony from Channel 12 in a representative dyad. (A) Interbrain coherence based on HbO signals from Channel 12 in the interactive session. The region between the red lines represents the frequency band of interest (0.02–0.3 Hz). Color bars indicate the amplitude of coherence. (B) Channel 12 is located on the left TPJ. The dashed line represents the back side (e.g. left TPJ of child). The blue and red circles represent detectors and sources of optode probes.

significant difference from zero after FDR corrections were used as indicators of interaction-related interbrain synchrony.

To address the potential common method bias from the observation-based assessments, we conducted a Variance Inflation Factor (VIF) analysis. VIFs ranged from 2.10 to 4.74 (< 10), indicating no significant multicollinearity (Dormann et al. 2013). Associations between interbrain synchrony, parent–child relationship quality, and parenting behaviors were examined through the following analyses. First, we performed Pearson correlation tests to compute the bivariate correlation coefficients between the study variables. Second, we built four linear regression models to examine the link from parental autonomy support, parental warmth, shared positive affect, and collaborative behaviors to interbrain synchrony. Interbrain synchrony served as the outcome variable, while parenting behaviors and relationship quality were predictors. Outliers ($n = 1$ dyad), defined by values over or under three *SD*s from the mean, were winsorized, yielding no significant changes to the main findings (Wilcox 2017).

Results

Parent–child interbrain synchrony

Interbrain synchrony, calculated by subtracting the WTCs during the baseline non-interactive period from the observed parent–child interaction session, revealed significant increases in specific channels: CH2 ($t = 2.06$, $P = 0.043$, Cohen's $d = 0.25$) and CH4 ($t = 3.02$, $P = 0.004$, Cohen's $d = 0.36$) in the left dlPFC, CH5 ($t = 2.69$, $P = 0.009$, Cohen's $d = 0.34$) and CH8 ($t = 2.47$, $P = 0.016$, Cohen's $d = 0.31$) in the right dlPFC, CH12 ($t = 2.65$, $P = 0.011$, Cohen's $d = 0.37$) in the left TPJ, and CH15 ($t = 2.68$, $P = 0.009$, Cohen's $d = 0.33$) and CH16 ($t = 2.41$, $P = 0.020$, Cohen's $d = 0.35$) in the right TPJ. After FDR corrections, interbrain synchrony at CH4 (left dlPFC), CH5 (right dlPFC), CH12 (left TPJ), and CH15 (right TPJ) remained statistically significant ($ps < 0.043$).

Associations between parenting Behaviors, parent–child relationship quality, and interbrain synchrony

Means and standard deviations for parental warmth, autonomy support, shared positive affect, and dyadic collaborative behaviors are presented in Fig. 3. Pearson correlations showed that only interbrain synchrony at CH12 (left TPJ) significantly correlated with emotional warmth ($r = 0.30$, $P = 0.039$), autonomy support ($r = 0.34$, $P = 0.016$), and shared positive affect ($r = 0.35$, $P = 0.014$), and exhibited a marginal correlation with collaborative behaviors ($r = 0.26$, $P = 0.075$) (see Table 3). CH4, CH5, and CH15 showed non-significant correlations with supportive parenting behaviors or positive relationship quality. Subsequently, we focused our further analyses on CH12 at the left TPJ.

Regression analysis results indicated that parental warmth ($\beta = 0.31$, $SE = 0.13$, $P = 0.019$), autonomy support ($\beta = 0.34$, $SE = 0.12$, $P = 0.005$), shared positive affect ($\beta = 0.37$, $SE = 0.12$, $P = 0.003$), and collaborative behaviors ($\beta = 0.26$, $SE = 0.13$, $P = 0.050$) were positively associated with interbrain synchrony at CH12 (see Fig. 4). All regression coefficients remained significant following FDR correction ($Ps < 0.050$). These findings persisted when controlling for demographic variables such as child age, child gender, and parent gender.

Exploratory follow-up analyses in parent gender comparison

We conducted exploratory analyses to examine potential parent gender effects in the associations between parenting behaviors, parent–child relationship quality, and interbrain synchrony. Figure 4 illustrates that maternal warmth ($\beta = 0.53$, $SE = 0.13$, $P < 0.001$) and autonomy support ($\beta = 0.55$, $SE = 0.13$, $P = 0.023$), as well as mother–child shared positive affect ($\beta = 0.49$, $SE = 0.14$, $P = 0.001$) and collaborative behaviors ($\beta = 0.37$, $SE = 0.16$, $P = 0.023$) displayed significant and positive associations with interbrain synchrony. These associations were non-significant for father–child dyads ($Ps > 0.511$). No significant differences were found in parenting behaviors, parent–child relationship quality, and interbrain synchrony between father– and mother–child dyads ($P \geq 0.116$). Notably, due to the relatively small sample size of fathers, these results provide preliminary insights.

Discussion

In this study, we explored whether and how interbrain synchrony was associated with real-time parenting behaviors provided by the parents or the dyadic interaction that is co-constructed by both parents and children. Our findings revealed positive associations between observed parental warmth, autonomy support, shared positive affect, collaborative behaviors, and interbrain synchrony.

During the interactive session, we observed significant increases in interbrain synchrony in bilateral dlPFC (CH4,

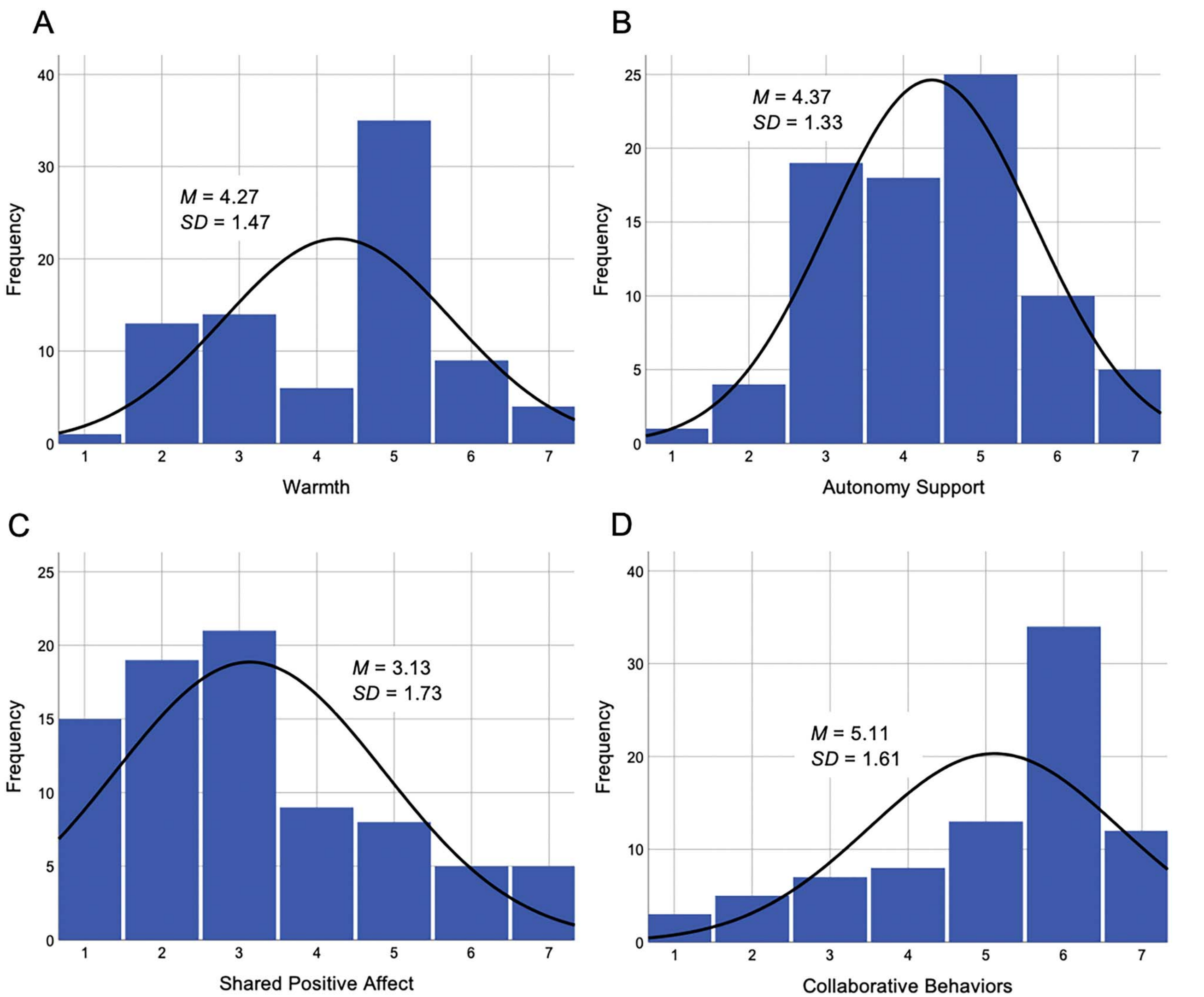

Fig. 3. Mean and standard deviations for behavioral observation variables. (A)–(D) Mean and standard deviations for (A) Warmth, (B) Autonomy support, (C) Shared positive affect, and (D) Collaborative behaviors.

Table 3. Pearson correlations for study variables.

Variables	1	2	3	4	5	6	7	8
1. Interbrain Synchrony-CH4	—							
2. Interbrain Synchrony-CH5	.04	—						
3. Interbrain Synchrony-CH12	.14	.20	—					
4. Interbrain Synchrony-CH15	.04	.04	.19	—				
5. Warmth	−.05	−.03	.30*	−.03	—			
6. Autonomy Support	.02	−.04	.34*	.16	.79***	—		
7. Shared Positive Affect	.23	−.12	.35*	.11	.44***	.41***	—	
8. Collaborative Behaviors	.04	.05	.26†	−.02	.67***	.56***	.34**	—

†$P < 0.10$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$. CH = channel.

CH5) and TPJ (CH12, CH15) compared to the resting phase, aligning with previous fNIRS hyperscanning studies involving mother–child dyads (Nguyen et al. 2020). Our task's demand for top-down control engaged dlPFC functions related to task-relevant attention, in which synchrony in the dlPFC may suggest collaborative cognitive efforts within parent–child dyads (Arnsten and Rubia 2012). Additionally, TPJ activation indicated social stimulus-driven attention and social connectedness, acting as a hub for processing social signals (Eddy 2016; Hoehl et al. 2021). Thus, synchrony in the TPJ may demonstrate functional and mutual engagement in social interactions among dyads.

A notable finding was the significant association between real-time interactive behaviors and synchrony in CH12 of the left TPJ. This differs from prior research on European families (Nguyen et al. 2020), in which both TPJ and dlPFC synchrony related to dyadic behavioral reciprocity during a problem-solving task. The absence of significant associations between dlPFC interbrain synchrony and real-time interactive behaviors aligns with

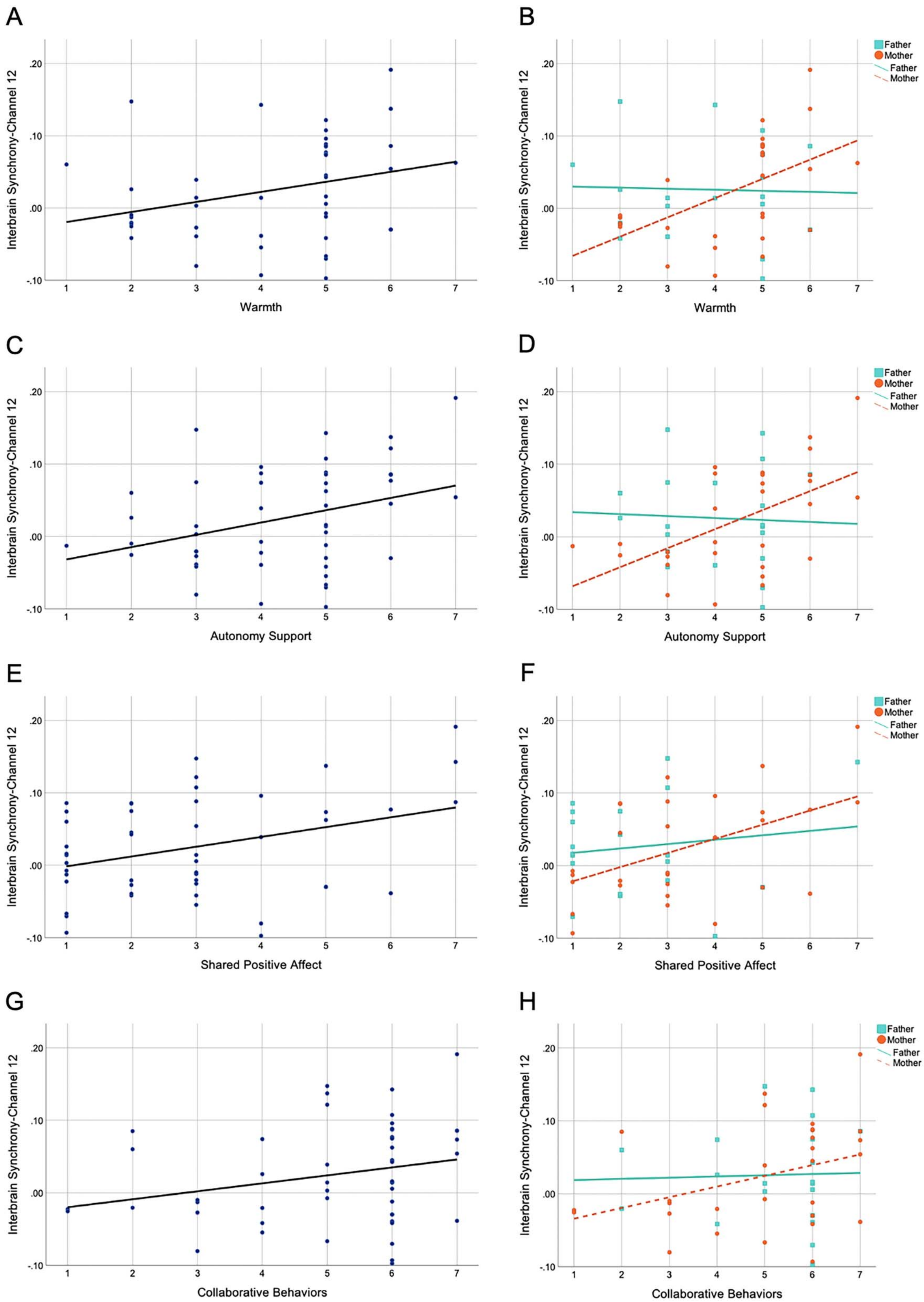

Fig. 4. Linear regressions from parenting Behaviors and relationship quality to interbrain synchrony. *Note.* (A) Warmth predicted interbrain synchrony in the entire sample of dyads. (B) Warmth predicted interbrain synchrony in father–child and mother–child dyads, separately. (C) Autonomy support predicted interbrain synchrony in the entire sample of dyads. (D) Autonomy support predicted interbrain synchrony in father–child and mother–child dyads, separately. (E) Shared positive affect predicted interbrain synchrony in the entire sample of dyads. (F) Shared positive affect predicted interbrain synchrony in father–child and mother–child dyads, separately. (G) Collaborative behaviors predicted interbrain synchrony in the entire sample of dyads. (H) Collaborative behaviors predicted interbrain synchrony in father–child and mother–child dyads, separately.

Zhao et al. (2021) in Chinese parent–child dyads. The emphasis on social harmony, a collectivistic orientation, and context sensitivity in Chinese culture might amplify the role of the TPJ that is crucial for processing social information. Examination of interbrain synchrony in the dlPFC across diverse cultural groups in future studies could offer insights into the universality or cultural specificity of these associations.

While both left and right TPJ regions are implicated in mentalizing, our findings reveal nuanced functional distinctions. Left TPJ activity is more strongly correlated with the quality of communication, emphasizing its sensitivity to the contextual relevance of sensory stimuli (Kucyi et al. 2012; Dai et al. 2018). It is posited that the left TPJ codes both matched and mismatched cognitive and behavioral information, while the right TPJ predominantly codes mismatched information (Doricchi et al. 2022). This nuanced processing suggests that the left TPJ may play a more pivotal role in capturing the intricacies of parent–child interactions during activities such as the Etch-a-Sketch task, compared to the right TPJ.

Interbrain synchrony emerged as a marker of higher-quality dyadic relationships, reflecting emotional resonance and collaboration. This implies that interbrain synchrony could serve as an indicator of positive relationship quality. Additionally, fundamental parenting behaviors, such as parental warmth and autonomy support (Maccoby and Martin 1983), were positively associated with increased parent–child interbrain synchrony, extending Feldman's bio-behavioral synchrony model into the neural domain (Feldman 2012). When parents respond to children's emotional needs and encourage independence, dyads are more likely to exhibit greater synchronization in interbrain activity, reflecting mentalizing and functional interaction (Leclère et al. 2014; Kelly 2018; Gvirts and Perlmutter 2020). This challenges prior research findings (Nguyen et al. 2020, 2021) but underscores the significant link between real-time parenting behaviors and parent–child interbrain synchrony.

Age-related disparities in prior research may explain differences, with our study focusing on school-aged children ($M_{age} = 8$ years) compared to preschoolers ($M_{age} = 5$ years) in Nguyen's study. Middle childhood brings advanced capacities for understanding perspectives, fostering a more mutually responsive interaction pattern with parents (Osterhaus and Koerber 2021). This heightened mutual responsiveness during middle childhood contributes to stronger dyadic synchrony, evident in the significant associations between interbrain synchrony and real-time parenting behaviors observed in our study (Harrist and Waugh 2002; Geerts and Riggs 2019).

Interestingly, the associations between interbrain synchrony and real-time parenting behaviors, as well as dyadic relationship quality, remained significant in mother–child dyads but not in father–child dyads. This asymmetry prompts reflection on the unique dynamics underlying maternal and paternal interactions, potentially influenced by the traditional primary caregiving role of mothers (Liu et al. 2023). Children typically spend more time with mothers than fathers (Gueron-Sela et al. 2015), where observed interbrain synchrony, functioning as an indicator of social mentalizing, might be more closely linked to maternal behaviors than paternal behaviors (Cohen-Zimerman et al. 2021), even though they were observed at similar levels. However, the limited representation of fathers ($n = 27$) in our sample hinders conclusive comparisons.

Limitations and future directions

Some caveats should be considered in the interpretation of our findings. First, while our results have supported Feldman's (2012) bio-behavioral synchrony model of parenting, the cross-sectional design limits causal inferences, thereby urging researchers to employ longitudinal designs in the future. Second, the resting period is often used as a control condition; however, it does not disentangle social interaction from cognitive effort, suggesting a need for an independent control task. Third, the imbalanced and relatively small father–child ($n = 27$) and mother–child dyadic samples ($n = 61$) limit the investigation of father–mother differences. Additionally, the examination of mother–son/daughter and father-son/daughter dyads could comprehensively understand gender-specific parenting behaviors and their implications for dyadic interbrain synchrony. Future research with larger and more balanced samples is encouraged to unravel the complexities of these dynamics.

Implications

Despite the imbalanced sample size between father–child and mother–child dyads, our study highlights the nuanced roles of mothers and fathers in shaping parent–child interactions neurobiologically. Tailoring interventions to these nuances could enhance program effectiveness. For example, fostering fundamental parenting behaviors, such as warmth and autonomy support, may contribute to increased parent–child neural synchrony, particularly within mother–child dyads due to their longer times spent together. Thus, promoting paternal involvement in parenting and encouraging supportive parenting may be beneficial for enhancing parent–child interaction and child development (e.g. Rubin and Chung 2006). Moreover, considering that parent–child interbrain synchrony could serve as a potential bio-neurological indicator of parent–child relationship quality, expanding our understanding of interbrain synchrony to diverse social contexts is crucial for a comprehensive grasp of neural mechanisms in social interactions beyond the parent–child relationship.

Conclusion

In summary, our utilization of fNIRS hyperscanning to assess parent–child interbrain synchrony during an interactive task represents an insightful investigation. Our findings underscore the positive association between interbrain synchrony and two crucial parenting behaviors—support for autonomy and emotional warmth, potentially suggesting the substantial role of supportive parenting in shaping parent–child interbrain mechanisms.

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