



# Mothers and fathers show different neural synchrony with their children during shared experiences

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## ABSTRACT

Parent-child shared experiences has an important influence on social development in children although contributions of mothers and fathers may differ. Neural synchronicity occurs between mothers and fathers and their children during social interactions but it is unclear whether they differ in this respect. We used data from simultaneous fNIRS hyperscanning in mothers ( $n = 33$ ) and fathers ( $n = 29$ ) and their children (3–4 years) to determine different patterns and strengths of neural synchronization in the frontal cortex during co-viewing of videos or free-play. Mothers showed greater synchrony with child than fathers during passive viewing of videos and the synchronization was positively associated with video complexity and negatively associated with parental stress. During play interactions, mothers showed more controlling behaviors over their child and greater evidence for joint gaze and joint imitation play with child whereas fathers spent more time gazing at other things. In addition, different aspects of child communication promoted neural synchrony between mothers and fathers and child during active play interactions. Overall, our findings indicate greater neural and behavioral synchrony between mothers than fathers and young children during passive or active shared experiences, although for both it was weakened by parental distress and child difficulty.

## 1. Introduction

Parent-child shared experiences, encompassing activities such as co-reading, co-viewing and playing together, play a crucial role in the early social development and functioning of children (Azhari et al., 2023a; Bornstein et al., 2010; Hutton et al., 2015; Martin et al., 2021). These shared activities not only help create precious moments for both parents and children but also have a profound impact on the child's physical and mental development, as well as their parent-child relationship (Dulac et al., 2014). Moreover, positive and nurturing interactions during shared experiences release oxytocin to promote bonding and trust (Feldman, 2012), while also stimulating shared neural pathways,

supporting the healthy development of the child's brain (Cicchetti and Gunnar, 2008). Nonetheless, unhealthy or negative parent-child relationships, such as higher parenting stress, are associated with lower engagement in shared experiences (Crnic and Greenberg, 1990; Nomaguchi and Brown, 2011), which could in turn affect the child's cognitive abilities and disrupt the development of their brain architecture (Blair and Raver, 2012).

Direct parental-child interaction is central to most human societies with varying degrees of engagement in affiliative behaviors and both paternal and maternal behaviors share some common aspects, such as providing care, emotional support, and engaging in joint activities. Notably, some behaviors exhibited by fathers (i.e. carrying or grooming)

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are partly distinct from those of mothers (Dulac et al., 2014; Feldman et al., 2019; Rajhans et al., 2019). Specifically, mothers often engage in more nurturing and soothing behaviors, whereas fathers tend to engage in more stimulating and exploratory activities (Feldman, 2003; Rajhans et al., 2019). These differences may arise from various factors, including evolution, societal expectations, gender roles, and individual parenting styles (Condon et al., 2022). Understanding these nuances is integral to appreciating the complexity of parent-child interactions and their varying impacts on the child's socioemotional and cognitive development.

Brain-to-brain coupling, or neural synchrony, can be determined via hyperscanning methods and has recently been postulated as an evolutionary adaptive mechanism underlying bond formation (Feldman, 2020), including cooperation (Cui et al., 2012), leadership (Jiang et al., 2015), couple (Li et al., 2022) and parent-child bonding (Reindl et al., 2022, 2018). Inter-subject synchronization (ISS) has been used to evaluate temporal correlations of neural responses to dynamic natural stimuli across two or more persons simultaneously (Cui et al., 2012; Jiang et al., 2015; Reindl et al., 2018) and is linked to quality of social interactions (Cui et al., 2012; Jiang et al., 2015; Li et al., 2022; Reindl et al., 2022, 2018). However, the majority of studies exploring the relationship between brain-to-brain coupling and shared social experiences (naturalistic contexts or behaviors) or shared relational variables have only been traditionally limited to specific brain regions (Kingsbury and Hong, 2020). Thus, it is essential to investigate relationships across multiple brain regions in order to measure brain-to-brain resonance from a larger global-level or network-level perspective. In addition, clustering algorithm (i.e. K-means) as a multivariable approach can help us identify specific patterns of ISS across multiple brain regions, thus this approach can help us address the above issue.

While hyperscanning studies have reported that neural synchrony may underlie parent-child bonding (Reindl et al., 2022, 2018), differences in ISS between mother-child and father-child interactions during shared experiences are poorly understood. Significant brain-to-brain coupling between mother and child during affective touch (Nguyen et al., 2021a), face-to-face communication (Nguyen et al., 2021b; Schwartz et al., 2022) and cooperative play (Miller et al., 2019; Reindl et al., 2018), were mainly found in prefrontal cortex (PFC). The prefrontal cortex plays an essential role in many aspects of cognitive and socioemotional development with experience-dependent maturational changes occurring from early childhood through to adulthood (Hodel, 2018; Kolb et al., 2012). For father-child dyads, brain-to-brain coupling has also been observed in PFC during co-viewing of emotionally arousing conflict scenes (Azhari et al., 2020) and cooperative games (Nguyen et al., 2021c). Notably, the age of the children in these studies ranges from 4 months to 13 years old, which suggested the parent-child neural synchrony is stable from infancy to adolescence (Reindl et al., 2018) and this period is pivotal for the development of social understanding and emotional sharing. In addition, parent-child interaction is a dynamic process including many micro-behaviors (i.e. smiles, joint gaze, vocalizations), and mothers and fathers have evolved differential roles. For example, the majority of communicative interactions between infants and mothers tend to lower arousal activity including mutual gazing, co-vocalizations and affectionate touch while interactions between fathers and infants, such as play, tend to increase arousal (Abraham and Feldman, 2022; Feldman, 2003). However, whether the brain-to-brain coupling of mother-child and father-child is modulated by specific micro-behaviors during share experiences is unclear.

In the current study, we therefore used data from a publicly available fNIRS-based hyperscanning dataset with 33 mother-child and 29 father-child dyads to examine ISS differences in mothers and fathers and their children during passive co-viewing of videos and free-play activities. Previous studies using this dataset have separately investigated the neural synchrony between parent and child during passive co-viewing of videos (Azhari et al., 2023b, 2020, 2019) and free-play activities (Azhari et al., 2023a). Results showed that the parent-child synchrony was

inversely associated with parenting stress in some specific regions during two tasks respectively and these synchronizations were all estimated by calculating static correlation or short-term temporal correlation. Unlike these pipelines, we employed phase-locked values (PLV, a dynamic approach) and K-means algorithm (a multivariable approach) respectively to evaluate the synchronization strength and identify specific patterns of ISS across multiple regions during both types of shared experiences (i.e. co-viewing and free-play activities). The PLV has been used in fMRI studies to estimate the instantaneous connectivity between two brain regions (Camacho et al., 2023; Magalhães et al., 2021; Stark et al., 2020), thus the application of PLV to the fNIRS field where hyperscanning is more easily achieved can make novel contributions to the understanding of parent-child interactive behaviors. Additionally, given previous research suggesting different roles for mothers and fathers in interactions with their children we hypothesized that mother-child dyads and father-child dyads would exhibit different neural synchronization patterns during varied interactive activities (Waters et al., 2017) and that the synchronization would generally be modulated by perceptions of parental stress.

## 2. Methods

We used data from a large publicly available dataset of fNIRS parent-child hyperscanning during a video co-viewing and free-play interaction session collected by the Nanyang Technological University (Bizzego et al., 2022).

### 2.1. Participants and quality control

A total of 33 mother-child and 29 father-child independent dyads were recruited in the study through online forums and social media groups. The dyads lived in the same household in Singapore and participants were free of any severe cognitive, visual, or hearing impairments. All participants provided written informed consent by themselves or their parents before the formal experiment and were remunerated upon completing the study. This study was approved by the Institutional Review Board of Nanyang Technological University, Singapore (IRB-2018-06-016), and conducted in accordance with the Declaration of Helsinki. After quality control, the data from 53 dyads in the co-viewing session (28 mother-child dyads, 25 father-child dyads) and 37 dyads in the free-play session (18 mother-child dyads, 19 father-child dyads) were retained for subsequent analyses (Table 1). The

**Table 1**  
Descriptive statistics of demographic data and questionnaire information.

Variables	Video co-viewing			Free-play		
	Mother-child	Father-child	$p_{bon}$	Mother-child	Father-child	$p_{bon}$
N (boys: girls)	28 (16:12)	25 (14:11)	0.933 <sup>a</sup>	18(9:9)	19(12:7)	0.254 <sup>a</sup>
Parent age (years)	34.89 ±4.23	38.08 ±3.79	0.036 <sup>*</sup>	34.11 ±4.10	37.63 ±3.52	0.048 *
Child age (years)	3.49 ±0.51	3.47 ±0.38	0.847	3.50 ±0.46	3.48 ±0.43	0.907
PSI	89.64 ±22.56	89.60 ±16.67	0.994	80.83 ±16.84	89.74 ±17.95	0.141
-PD	31.50 ±8.85	33.64 ±9.34	0.396	29.39 ±7.95	33.32 ±9.15	0.173
-PCDI	23.68 ±6.85	23.92 ±5.75	0.891	21.61 ±5.37	23.16 ±5.75	0.404
-DC	32.61 ±8.39	32.04 ±7.98	0.803	29.83 ±8.58	33.00 ±7.51	0.240

Statistical analyses were performed with two-sample tests or chi-square tests (for <sup>a</sup>).

PSI: Parenting Stress Index-Short Form, PD: Parenting Distress, PCDI: Parent-Child Dysfunctional Interaction, DC: Difficult Child.

\*  $p_{bon} < 0.05$ , Bonferroni-corrected.

sample size was similar to previous studies that measured neural synchronization using fMRI (Li et al., 2022) and fNIRS (Piazza et al., 2020). Detailed quality control exclusion criteria were reported in the **Supplementary material**.

## 2.2. Assessment of self-reported parenting stress

Before the experimental procedure, all parents were administered the Parenting Stress Index-Short Form (PSI-SF, Fourth Edition). The PSI is a self-assessed questionnaire to assess the parents' perceived parenting stress (Cohodes et al., 2021; Fitzpatrick et al., 2023) and consists of three subscales: parenting distress (PD), parent-child dysfunctional interaction (PCDI), and difficult child (DC), and each domain includes 12 items.

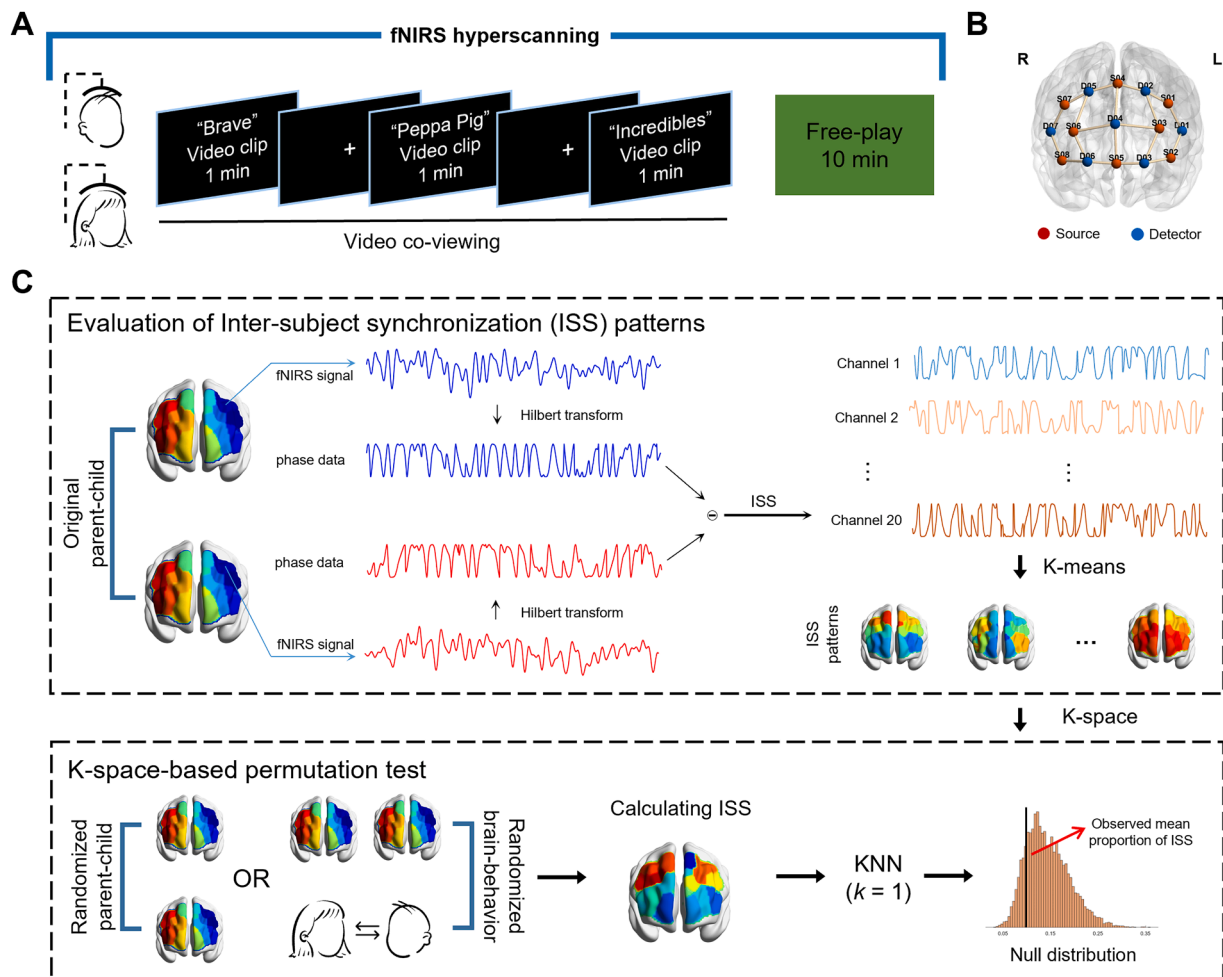
## 2.3. Experimental procedure

All parent-child dyads sat side-by-side at a table and participated in the fNIRS hyperscanning task that included a video co-viewing session and a 10-min free-play session (Fig. 1A). During the first session, three 1-min cartoon clips (*Brave*, *Peppa Pig* and *The Incredibles*) with varying visual complexity, fundamental frequency, audio intensity, and emotional valence (Table S1) were presented in randomized order to increase the generalizability of neural synchrony (Azhari et al., 2019), and were separated by a 10 s fixation cross low level baseline to allow the hemodynamic response to reach a baseline level. Dyads were requested to watch the video stimuli passively without any interaction.

In the free-play session, dyads were requested to actively interact with some toys (e.g., toy car, building blocks, doll, etc.) on the table for 10 min. During this session, a camcorder (Sony Handycam) was used to record the dyad's behaviors.

## 2.4. fNIRS data acquisition and preprocessing

During the fNIRS hyperscanning, two NIRSport systems (NIRx Medical Technologies LLC, Berlin, Germany) with LED light sources (sampling rate: 7.8125 Hz, wavelengths: 760 nm and 850 nm) were used to collect the hemodynamic data of the prefrontal cortex (PFC). One optode probe set of 8 sources and 7 detectors with a maximum of 3-cm inter-optode distance was utilized via NIRStar (v15.2, Windows 64 bit) resulting in 20 channels. The optode probes were arranged on each cap according to the international 10–20 system (Fig. 1B) and covered the left/right superior frontal gyrus (SFG), left/right middle frontal gyrus (MFG), left/right inferior frontal gyrus (IFG), and anterior prefrontal cortex (aPFC). The Montreal Neurological Institute (MNI) coordinates of the probes and information on generated channels are provided in Table S2. Before data analysis, the first and last 1-min of fNIRS data during free-play session were removed to obtain the signal within the steady state period, resulting in 8-min of free-play data for subsequent analysis. The preprocessing of fNIRS data was performed via the NIRS-KIT toolbox (Hou et al., 2021) based on MATLAB 2019b. Specifically, the modified Beer-Lambert law was employed to convert the raw data into oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentrations. Subsequently, a polynomial regression model was used to estimate



**Fig. 1.** Experimental procedure and overview of analysis pipeline. (A) Experimental procedure of fNIRS hyperscanning. (B) Optode probe set. (C) Overview of analyses pipeline. ISS = inter-subject synchronization; KNN = K-nearest neighbor.

a linear trend, which was then subtracted from the raw hemoglobin concentration signal using detrending. In addition, the temporal derivative distribution repair (TDDR) algorithm for removing motion artifacts was applied to all signals (Fishburn et al., 2019). Given that high-order Finite Impulse Response (FIR) filters can better filter the noise and recover the hemodynamic response from fNIRS signal, while ensuring that the phase of the filtered signal does not distort (Pinti et al., 2019), a 500th order band-pass FIR filter (0.01–0.09 Hz) was employed in the last step (Pinti et al., 2020, 2019). In this study, we focused on the changes in the HbO concentration as it has the highest signal-to-noise ratio in fNIRS measurements (Hoshi, 2007).

## 2.5. Coding for the video stimuli and play behaviors

For the original dataset, the Python-based *pyaesthetics* package (Gabrieli et al., 2023) was utilized to estimate the visual complexity of still images extracted from the selected video clips at 12 frames per second (FPS) by FFmpeg (v. 3.4.4, Linux 64 bit). Then, we down-sampled the visual complexity from 12 Hz to 7.8125 Hz by “*resample*” function in MATLAB 2019b to keep consistent with the neural signal. After down-sampling, we divided the visual complexity into 5 levels of equal proportions.

Two research assistants from the original dataset evaluated the dyadic interactions between parent and child for each minute during free-play session in a structured way based on the Emotional Availability Scales (EAS) with six indexes: adult sensitivity, adult structuring, adult non-intrusiveness, adult non-hostility, child responsiveness to the adult, and child involvement of the adult (Biringen, 2010), see **Supplementary material** for more details. The higher EAS represents better behavioral or emotional response and interaction between parent and child. We confirmed a high reliability for recording EAS every minute by showing that the six indices measured achieved a high Cronbach’s alpha (Cronbach’s alpha ranged from 0.793 to 0.873), and conducted further exploratory analyses using it. In addition, the Solomon Coder software (Version: 22 March 2017) was utilized to microanalytically annotate the 27 types of emotional behaviors of dyad and interactions between them (e.g., smile, verbal, laugh, joint gaze, etc. See **Table S3** for details) in the video of the free-play session, at a frequency of 7.8125 Hz (1/7.8125 second). For sufficient statistical validity, behaviors used for subsequent analysis were required to satisfy the following conditions: 1) the duration of each single behavior should be at least 1 s (8 sampling points); 2) the average duration of the behavior across all dyads should be at least 5 % (average duration  $\geq 30$  s); and 3) the behavior should be exhibited in at least 80 % of the dyads ( $N \geq 30$ ). After behavioral data quality control, ten types of behaviors and interactions were confirmed in this study: parent gaze other, child object, child gaze away, child toy purpose, parent verbal, child verbal, parent smile, child smile, joint gaze and joint pretend. Detailed descriptions and statistics (after excluding instances of behaviors lasting  $< 1$  s) of all behaviors are reported in **Table S3**.

## 2.6. fNIRS data analyses

An overview of the analysis pipeline is shown in **Fig. 1C**.

### 2.6.1. Evaluation of ISS patterns

Phase-locked value (PLV) has been used in fMRI studies to estimate the instantaneous connectivity between two brain regions (Camacho et al., 2023; Magalhães et al., 2021; Stark et al., 2020), thus the PLV would be suitable for fNIRS data. In this study, PLV and K-means algorithms were employed to evaluate the instantaneous ISS patterns between parent and child at each time point. First, ISS was defined as the PLV between parent-child in each channel, using the following equation:

$$ISS(n, t) = \cos(\theta_{parent}(n, t) - \theta_{child}(n, t))$$

where  $\theta_{parent}(n, t)$  and  $\theta_{child}(n, t)$  are respectively the phases of the fNIRS signal of the parent and child in the  $n$  channel at time  $t$  obtained by the Hilbert transform. A positive ISS ( $n, t$ ) indicates synchronization between parent-child in  $n$  channel at time  $t$  (phase shift  $< 90^\circ$ ), whereas a negative ISS ( $n, t$ ) indicates a lack of synchronization. To evaluate the instantaneous ISS patterns, K-means algorithm with manhattan ( $L_1$ ) distance (Aggarwal et al., 2001) was then adopted to cluster all ISS across all dyads. We varied  $k$  (number of clusters) from 2 to 10 and selected the optimal  $k$  based on the elbow criterion along with the proportion of each cluster at least 10 % (Espinoza et al., 2019). Finally, the mean proportion of each ISS pattern (cluster) was calculated for mother-child and father-child dyads, separately. Convergence analysis was also conducted to investigate the stability of ISS patterns by calculating the mean ISS value and standard error in each region.

### 2.6.2. K-space-based permutation test

To confirm whether the observed parent-child ISS patterns were indeed attributable to the parent-child relationship, we defined a K-space-based permutation test that relies on the K-means and K-Nearest Neighbor (KNN) algorithm to validate the instantaneous ISS pattern. The workflow can be summarized as follows: 1) the mean proportion of each ISS pattern is calculated for the original mother-child and father-child dyads as the observed statistical measure; 2) each child is randomly and non-repetitively assigned to either the other fathers or mothers as a permuted dyad; 3) the ISS is calculated between the randomized parent-child dyads at each time point; 4) using the KNN ( $K = 1$ ) algorithm (Galvão et al., 2021), the ISS patterns between the randomized parent-child dyads are evaluated based on the K-space generated by K-means clustering of the original dyads; 5) the mean proportion of each ISS pattern for the randomized mother-child and father-child dyads is calculated as the estimated statistical measure; 6) steps 2–5 are repeated a large number of times (5000 or 10,000 times) to create a null distribution of statistics; 7) the observed mean proportion is compared to the null distribution of statistics from the permuted dyads to obtain permutation p-values. The above differences in the mean proportion of ISS patterns were considered statistically significant if the observed mean proportion was outside the 95 % CI of this null distribution and p values were Bonferroni-corrected taking into account all the ISS patterns detected.

### 2.6.3. Differences in ISS pattern between mother-child vs. father-child dyads across the video co-viewing session

Considering that the typical hemodynamic response function (HRF) has a lag of 6 s (von Lüthmann et al., 2020), we shifted the fNIRS time series data relative to the video stimulus. Significant differences between randomized mother/father-child and original mother/father-child in the proportion of each ISS pattern in video co-viewing session were then determined with non-parametric testing, i.e. ‘**K-space-based permutation test**’. Specifically, the mean proportion of each ISS pattern in video co-viewing session for mother-child or father-child dyads was calculated (see ‘**Evaluation of ISS patterns**’ for further details) and compared against the null distribution of the same proportion that obtained from 10,000 randomized mother-child or father-child dyads (see ‘**K-space-based permutation test**’ for further details). Subsequently, we compared the ratio of each ISS pattern between mother-child and father-child dyads during three video clips viewing. In addition, the relationship between the probability for each ISS pattern and the visual complexity levels (from 1 to 5) and the parenting stress scores were evaluated.

### 2.6.4. Differences in ISS pattern between mother-child vs. father-child dyads across entire free-play session

For the free-play session, we also shifted the fNIRS time series data (with a delay of 6 s) relative to the free play time series. In addition, the identical analyses (‘**Evaluation of ISS patterns**’ and ‘**K-space-based**



permutation test') were performed during free play session. Here, we only performed 5000 K-space-based permutation tests due to the high computing resource consumption. Subsequently, we compared the ratio of each ISS pattern between mother-child and father-child dyads, and investigated the exploratory relationship between the probability for each ISS pattern for each minute and the EAS indexes with repeated measures correlation (Bakdash and Marusich, 2017) via R and between the total probability for each ISS pattern and behavioral probability or parenting stress scores (PSI, Pearson correlation analysis).

### 2.6.5. Dynamic ISS pattern across single behavior during free-play session

Previous studies suggested that there is a 1–3 second lag in the neural signals between the receiver and the sender during an interactive (smile or verbal) behavior (Piazza et al., 2020; Stephens et al., 2010). In addition, whether the lag was only present in mother-child or father-child for specific interactive behaviors is not clear. Thus, for individualized smile and verbal behavioral analyses, we considered a delay of 0 to 3 s (with a 1 s interval) to fNIRS time series (after accounting for a 6 s HRF lag) for these four behaviors (child smile, child verbal, parent smile and parent verbal) from receiver to the sender depend on who took the leading role (e.g. C-smile, child would be sender, parent would be receiver). For joint gaze and joint pretend, we delay the single behavioral time series relative to the fNIRS time series for 0 to 3 s (with a 1 s interval). 'Evaluation of ISS patterns' and 'K-space-based permutation test' methods were conducted with an identical procedure (except for step 2) of K-space-based permutation tests to randomly re-assign parent-child paired raw neural data and the behavioral indexes from a different dyad. Subsequently, we compared the ratio of each ISS pattern between mother-child and father-child dyads, and evaluated the relationship between the probability for each

ISS pattern and the parenting stress scores.

## 3. Results

### 3.1. Demographic analyses

Descriptive statistical analyses of questionnaire and demographic variables between mother-child and father-child dyads are shown in Table 1. There was no significant difference with respect to parenting stress, as assessed using the Parenting Stress Index-Short Form (PSI-SF, Fourth Edition), and either child age or gender ratio ( $p_{bon} > 0.28$ ). However, parental age differed (video co-viewing:  $t_{(51)} = 2.896$ ,  $p_{bon} = 0.036$ , Cohen's  $d = 0.92$ ; free-play:  $t_{(35)} = 2.797$ ,  $p_{bon} = 0.048$ , Cohen's  $d = 0.79$ ) with fathers being older than mothers and was therefore included as a covariate in analyses.

### 3.2. Coding results for video stimuli and free-play behaviors

During passive co-viewing of videos, three 1-min cartoon clips (from *Brave*, *Peppa Pig* and *The Incredibles*) were presented randomly. We micro-annotated and five-level rated the visual complexity of these three video clips. For the free-play session, fathers had higher EAS scores on the adult sensitivity ( $t_{(294)} = 2.973$ ,  $p_{bon} = 0.019$ , Cohen's  $d = 0.34$ ), non-intrusiveness ( $t_{(294)} = 3.49$ ,  $p_{bon} = 0.003$ , Cohen's  $d = 0.40$ ) and non-hostility ( $t_{(294)} = 5.93$ ,  $p_{bon} < 0.001$ , Cohen's  $d = 0.69$ , Fig. 2B) indices. Furthermore, fathers spent significantly more time than mothers looking at other things rather than the child (Mann-Whitney  $U$  test,  $Z = 2.890$ ,  $p_{bon} = 0.040$ , Fig. 2C) whereas mothers spent more time than fathers gazing jointly at objects with their child ( $Z = 1.975$ ,  $p = 0.048$ , uncorrected) and engaging with them in joint imaginative play with

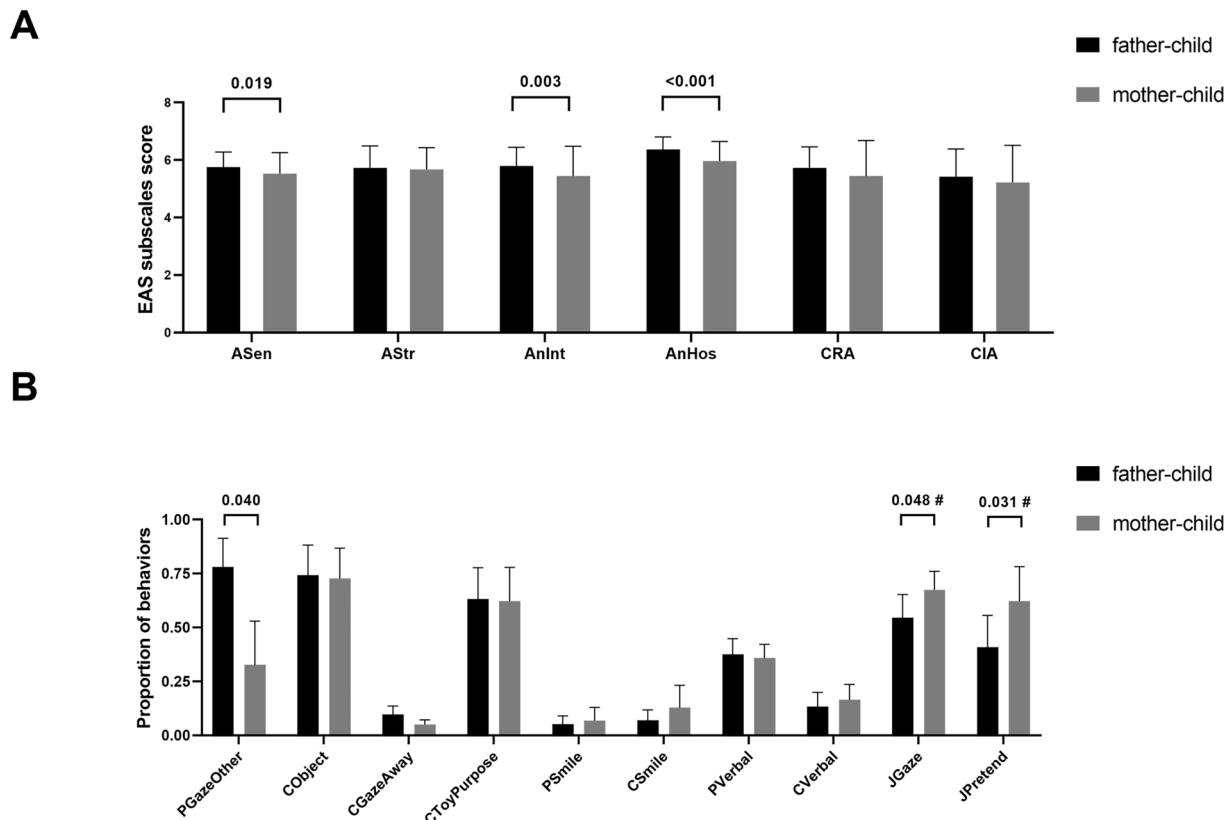


Fig. 2. Coding results for free-play behaviors. (A) The differences in EAS indexes between father-child and mother-child dyads. (B) The differences in the proportions of duration time of behaviors between father-child and mother-child dyads. ASen = adult sensitivity; AStr = adult structuring; AnInt = adult non-intrusiveness; AnHos = adult non-hostility; CRA = child responsiveness to the adult; CIA = child involvement of the adult; PGazeOther = Parent gaze other; Cobject = Child object; CGazeAway = Child gaze away; CToyPurpose = Child toy purpose; PSmile = Parent smile; CSmile = Child smile; PVerbal = Parent verbal; CVerbal = Child verbal; JGaze = Joint gaze; JPrentend = Joint pretend. All  $p$  values are Bonferroni-corrected except for #  $p < 0.05$  uncorrected.

objects ( $Z = 2.158$ ,  $p = 0.031$ , uncorrected). There were no other significant differences in either specific parent ( $ps > 0.118$ ) or child ( $ps > 0.114$ ) behaviors (Table S3).

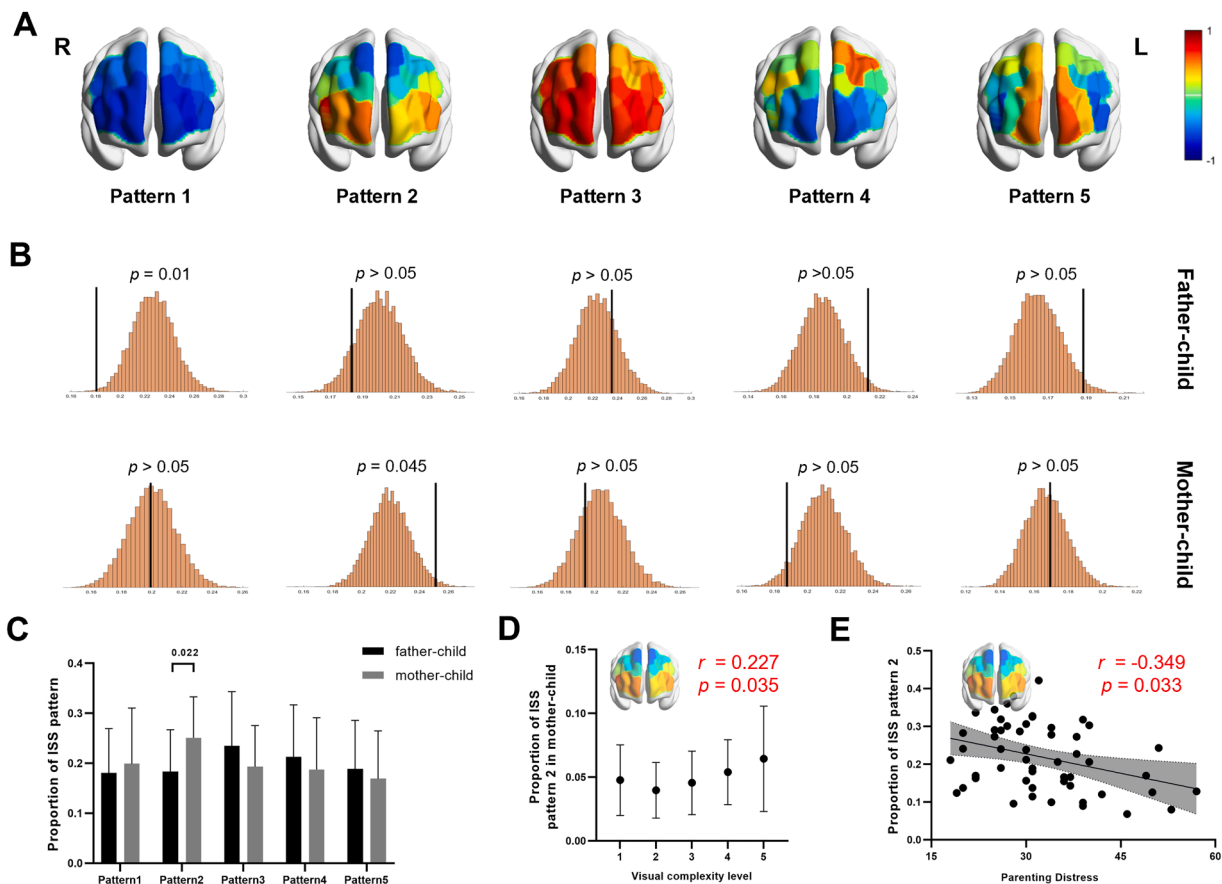
### 3.3. Patterns of neural synchronization observed during passive viewing of videos

To test our initial hypothesis, we estimated the strength and number of ISS patterns that recurrently emerged over time with PLV and K-means algorithm. Fig. 3A shows the optimal 5 ISS patterns (Fig. S1) found during the video co-viewing session. Convergence analysis for each ISS pattern is reported in Fig. S2. The results of 10,000 K-space-based permutation tests suggested that the mean proportion of ISS pattern 1 (ISS < 0 in all regions) in the original father-child dyads was significantly lower than that in randomized dyads (permutation  $p_{bon} = 0.01$ , Fig. 3B), whereas the mean proportion of ISS pattern 2 (ISS > 0, mainly including aPFC and bilateral IFG) in the original mother-child dyads was significantly higher than that in the randomized pairs (permutation  $p_{bon} = 0.045$ , Fig. 3B). Additionally, in the original dyads, only the proportion of ISS pattern 2 in mother-child dyads was significantly greater compared to that in father-child dyads ( $t_{(51)} = 2.98$ ,  $p_{bon} = 0.022$ , Cohen's  $d = 0.82$ , Fig. 3C) and positively correlated with the level of visual complexity ( $r_{(138)} = 0.227$ ,  $p_{bon} = 0.035$ , Fig. 3D). More correlations between mean proportions of all ISS patterns and visual complexity in mother/father-child dyads are shown in Fig. S2. Furthermore, a significant correlation was observed between the proportion of ISS pattern 2 and parenting distress scores in the entire sample (with parental age as

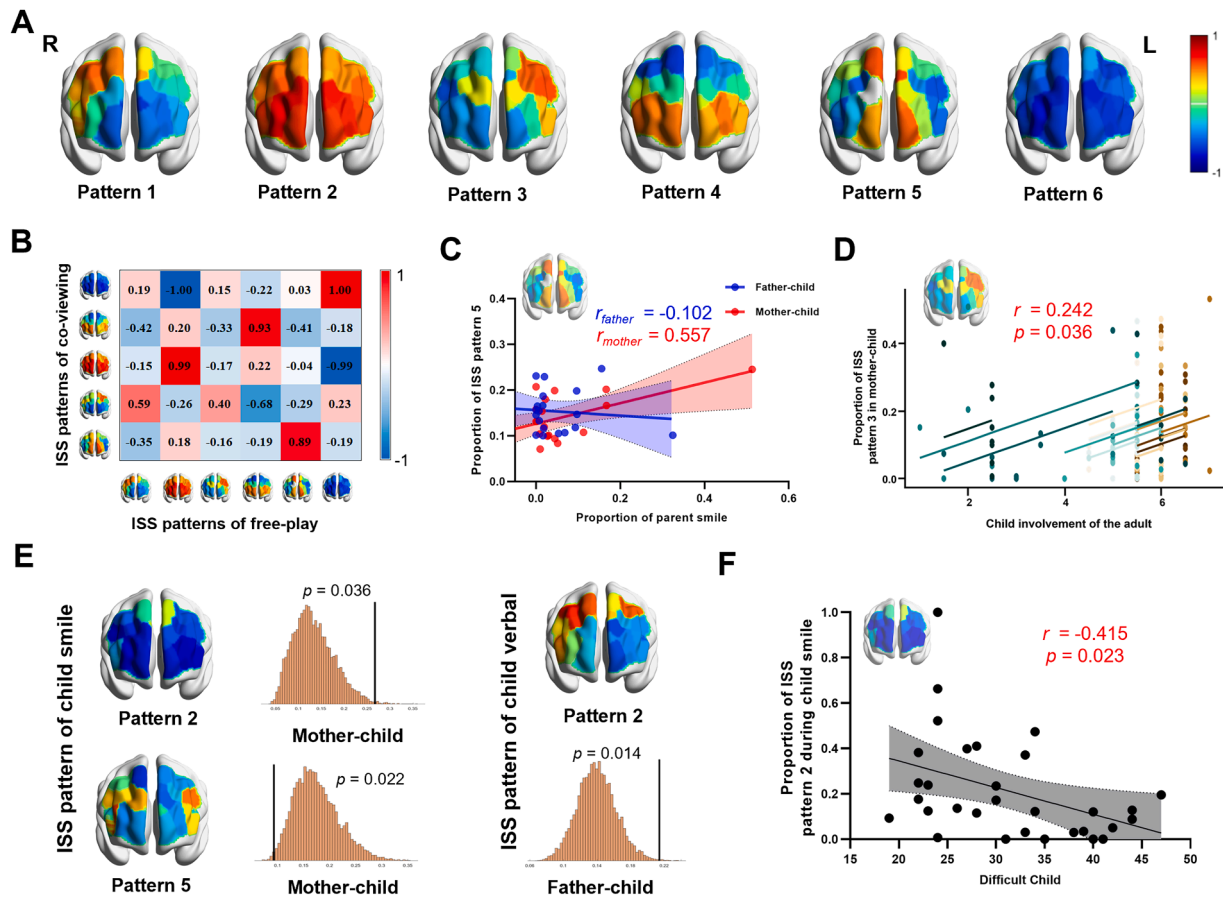
a covariate,  $r_{(51)} = -0.349$ ,  $p_{bon} = 0.033$ , Fig. 3E).

### 3.4. Parental differences neural synchronization during the free-play session

For the whole free-play session, an optimal of 6 synchronization patterns (Fig. S3A) were determined (Fig. 4A). A convergence analyses for these ISS patterns is given in Fig. S4 and there was considerable overlap with the 5 patterns observed during passive viewing of videos (4 patterns with cosine similarity > 0.89) suggesting a high degree of coherence between contexts (Fig. 4B). Meanwhile, significant parent-child differences were observed in the correlation between the proportion of parent smile and ISS pattern 5 primarily involving the SFG and MFG (father-child:  $r = -0.102$ ,  $p = 0.679$ ; mother-child:  $r = 0.557$ ,  $p = 0.016$ ; Fisher z-trans = 2.033,  $p = 0.042$ ; Fig. 4C). However, we did not find any significant differences between original mother/father-child dyads and randomized mother/father-child dyads in the mean proportion of ISS patterns during whole free-play session via 5000 K-space-based permutation tests (all permutation  $p > 0.05$  with Bonferroni correction; see Fig. S4). Furthermore, no ISS pattern was found to differ significantly in terms of probability of occurrence between mother-child and father-child dyads during this session (all  $ps > 0.05$ , Bonferroni-corrected). Next, repeated measures correlation showed that the proportion of ISS pattern 3 (ISS > 0, mainly including left SFG, MFG and IFG) was positively correlated with the parent's involvement with the child in mother-child dyads ( $r_{(125)} = 0.242$ ,  $p_{bon} = 0.036$ , Fig. 4D) but not in father-child dyads ( $r_{(132)} = -0.037$ ,  $p_{bon} = 0.667$ ; group



**Fig. 3.** Different ISS pattern between mother-child and father-child dyads across video co-viewing session. (A) The ISS patterns estimated by PLV and K-means algorithm during video co-viewing session. (B) The null distributions of the mean proportion of ISS pattern in randomized parent-child dyads. Top: original father-child vs. randomized father-child dyads; bottom: original mother-child vs. randomized mother-child dyads. The black line represents the mean proportion of ISS pattern in original parent-child dyads. (C) The differences in the proportion of ISS pattern between father-child and mother-child dyads. (D) The correlation between the proportion of ISS pattern 2 in mother-child and visual complexity level. (E) The correlation between the proportion of ISS pattern 2 and parenting distress. ISS = inter-subject synchronization; PLV = phase-locked value. All  $p$  values are Bonferroni-corrected.



**Fig. 4.** Different ISS pattern between mother-child and father-child dyads across free-play session. (A) The ISS patterns estimated by PLV and K-means algorithm during whole free-play session. (B) The cosine similarity between the ISS pattern of video co-viewing session and free-play session. (C) The correlation between the proportion of parent smile and ISS pattern 3 during whole free-play session. (D) The exploratory repeated measures correlation between the proportion of ISS pattern 3 in mother-child and EAS index (child involvement of the child). Dots indicate the proportion of ISS pattern 3 and EAS index corresponding to a mother-child dyad in a minute. The dots with same color were from the same dyad, with corresponding lines to show the repeated measures correlation fit for this dyad. (E) The ISS patterns and null distributions during child smile (column 1 and column 2) and child verbal (column 3). The black line represents the mean proportion of ISS pattern in original parent-child dyads. (F) The correlation between the proportion of ISS pattern 2 during child smile and difficult child. ISS = inter-subject synchronization; PLV = phase-locked value. All  $p$  values are Bonferroni-corrected except for (F).

difference: Fisher  $z$ -trans = 2.42, two-tailed  $p = 0.015$ ). The proportions of other ISS patterns were not correlated with EAS indexes in either mother- or father-child dyads (all  $p_{bon} > 0.05$ ).

### 3.5. Dynamic neural synchronization observed during individual interactive behaviors

In terms of individual interactive behaviors (i.e. smile, verbal, joint gaze and joint pretend) during free-play, we first conducted 10,000 K-space-based permutation tests to examine whether the parent-child coupling would be enhanced if a delay (sender leading) between the sender and receiver of the interaction behavior was included. An optimal of 6 different patterns of neural synchrony were found for parent and child when the child smiled (at a lag of 1 s with child leading). When the child smiled, original mother-child dyads showed a higher mean proportion of ISS pattern 2 (ISS > 0 in SFG, permutation  $p_{bon} = 0.036$ , Fig. 4E) and a lower mean proportion in ISS pattern 5 (ISS > 0 in IFG and right SFG and MFG, permutation  $p_{bon} = 0.022$ , Fig. 4E), compared to the randomized mother-child brain-behavior dyads. On the other hand, for the optimal 6 different patterns when the child verbal (child-leading by 2 s), the mean proportion of ISS pattern 2 in original father-child dyads was higher than randomized father-child brain-behavior dyads (ISS > 0 in SFG and right MFG and IFG, permutation  $p_{bon} = 0.014$ , Fig. 4E). No significant results were found for other delays in

child smile and child verbal. Detailed results of optimal selection of ISS patterns (Fig. S3B and C), K-space-based permutation test and convergence analyses for child smile (Fig. S5) and child verbal (Fig. S6) are reported in Supplementary material. Furthermore, the proportion of ISS pattern 2 during child smile was negatively correlated with difficult child scores ( $r_{(35)} = -0.415$ ,  $p = 0.023$ , uncorrected; Fig. 4F), with parental age as a covariate. Similarly, we also found stronger parent-child neural coupling compared with the randomized parent-child brain-behavior dyads during parent smile (at a lag of 2 s, parent leading), parent verbal (at a lag of 2 s, parent leading), and joint pretend (at a lag of 2 s, neural signal leading; see Figs. S7–S9) conditions without multiple comparison corrections. No significant results were found for all delays in joint gaze.

## 4. Discussion

The present study utilized fNIRS hyperscanning and behavioral assessments in naturalistic contexts to reveal compelling evidence for different strengths of specific synchronization patterns in frontal cortex and behavioral associations between mothers and fathers and their children. A novel step was to first apply PLV to determine the synchronization strength and then use K-means algorithm and K-space-based permutation test to identify and confirm the specific patterns of parent-child synchronization across different brain regions. Our findings

provide evidence for greater neural synchrony between young children and their mothers, relative to random mother-child pairings, during shared passive activities in some regions of the frontal cortex and greater joint attention during play interactions, although strength of synchrony was weakened by levels of parental distress and perceived child difficulty. Additionally, different aspects of child communication may promote neural synchrony between mothers and fathers and their children during active play interactions.

Inter-subject synchronization may serve as a neural mechanism that facilitates the emotional connection between parent and child dyads, which is linked to the child's development of social, cognitive and affective skills, such as attention (Gabouer and Bortfeld, 2021), learning, emotional regulation (Reindl et al., 2018), as well as cooperation (Miller et al., 2019). The degree of parent-child synchrony is also predictive of child development (Feldman and Greenbaum, 1997; Hoyniak et al., 2021). Accumulated evidences also suggest that interbrain synchrony may be an important neural marker of social interaction (Bi et al., 2023) and could be helpful for validating the effectiveness of parent-child interaction therapy for individuals with autism spectrum disorder (Solomon et al., 2008). The current results that highlight separate roles of mothers and fathers during shared experience with their children provide initial evidence supporting the importance of different kinds of shared activities between parents and their children for the development of neural synchronization between them. For mothers and children, more non-verbal emotional exchanges such as smiling may be of greatest importance whereas verbal exchanges may be more important for fathers and children. Together these different but complimentary parental roles in developing neural synchrony with their children may combine to optimally shape a child's social, cognitive and affective skills. Thus, the traditional view that mothers are primarily important for safety seeking and comfort for the child is changing (Dulac et al., 2014; Feldman et al., 2019; Rajhans et al., 2019) and currently evidence supports the importance that both mother and father attachment may play on child development through their respective influences on neural synchronization (Davis et al., 2018).

Maternal and paternal caregiving engage a number of common neural pathways, in particular in systems engaged in vigilance, salience, reward, motivation, social understanding, and cognitive empathy (Abraham et al., 2014; Feldman, 2020; Feldman et al., 2019; Insel and Young, 2001), although there are also some differences (Rajhans et al., 2019). Notably, neural responses of parents to the suffering of their own child occur in the three frontal regions included in the present study (i.e. SFG, IFG and MFG) (Wever et al., 2021). During co-viewing of children's videos common patterns of synchronization occurred between parent and child in this frontal network although the strength of synchronization of a pattern including the aPFC and IFG was significantly stronger in mothers and children. Furthermore, the strength of this synchronization was associated with the visual complexity of the different videos tested which may indicate that it is influenced by a greater level of mutual joint attention due to being a form of dyadic interaction involving shared attention to an object (Gabouer and Bortfeld, 2021).

During the free-play interaction session between individual parents and children, a number of different behaviors were found to differ significantly between mothers and fathers. The EAS measures taken indicated that fathers scored higher on sensitivity, non-intrusiveness and non-hostility than mothers, suggesting that mothers were more active in controlling their children during play interactions. In terms of specific individual behaviors recorded during the session fathers spent significantly more time than mothers not looking at the child and mothers spent longer than fathers gazing jointly at objects with their child and engaging in joint imaginative play with objects. Overall, this suggests that mothers were more actively engaged in play with their children than fathers although fathers were less interfering and controlling. Previous studies have reported varying behavioral differences between fathers and mothers and their young children during play and context as well as the measures used may be influential in this respect (Schilbach

et al., 2010). Thus, our current findings of parental differences may have been influenced to some extent by these factors.

We did not find any ISS pattern differences between specific mother-child and father-child dyads and random pairings during the whole interactive play session, however the strength of a neural synchronization pattern involving left frontal regions (IFG, MFG and SFG) was positively associated with child involvement only in mothers. Moreover, mothers and children exhibited stronger brain-to-brain coupling in a highly specific pattern involving only the SFG when the child smiled in line with the importance of SFG/supplementary motor area in expressions or happiness and mirth (Fried et al., 1998; Krolak-Salmon et al., 2006) while fathers showed stronger coupling in a pattern involving the right MFG, right IFG and bilateral SFG when the child spoke, consistent with right IFG and MFG involvement in inhibition of action and attentional control (Choo et al., 2022; Shulman et al., 2010). These findings also seem to support the observation that mothers are involved in more low arousing (i.e. child smile) and fathers with more high arousing aspects of interactions with their children (i.e. child verbal) during play (Feldman, 2003). Furthermore, the strength of the synchronization pattern involving the SFG when the child smiled was negatively associated with how difficult parents rated their child to be.

Interestingly, there was considerable overlap with the 4 patterns (cosine similarity > 0.89) observed during passive viewing of videos and free-play. This suggests a high degree of coherence between contexts showing a stable common synchronization pattern during co-viewing and free-play activities. While some specific results indicate that the ISS pattern mainly included aPFC and bilateral IFG contributed more to co-viewing activity, on the other hand, the ISS pattern primarily involving the SFG and MFG and ISS pattern including left SFG, MFG and IFG was found to play a key role in free interactive play. Overall, our convergence analysis suggests that parent-child neural synchrony is stable (Reindl et al., 2018), but some prominent and distinct patterns were found in father-child and mother-child social interactions in terms of specific types of share experiences.

A number of factors may have contributed to our observed parental differences in neural synchrony and behavior during both passive and active interactions with their children. Firstly, we were unable to control for whether the mothers and fathers included in the study spent more time routinely interacting with their children and so possibly differences may have been contributed by mothers spending more time with their children than fathers. Greater mother-child synchrony might also be contributed by biological rhythms in utero, such as heart rhythms and sleep-wake cycles with mothers entraining these familiar rhythms into subsequent post-partum dyadic exchanges (Feldman, 2020; Feldman et al., 2011). On the other hand, parental differences in hormonal and neural control of paternal and maternal bonds and during interactions with their children may result in complimentary but also slightly different roles (Feldman, 2003; Rajhans et al., 2019).

Some limitations of the current study should be acknowledged. Firstly, patterns for synchronization were only assessed in the frontal cortex and there may be differences in other cortical or subcortical regions. Secondly, the current dataset does not include metrics for the relative amount of caregiving normally provided by the mothers and fathers in the study so it is difficult to control for the influence of this on behavior and patterns of neural synchronization. Meanwhile, the existence of potential differences between father-child and mother-child synchronization within the same family and the moderating role of family and couple relationships needs to be further explored. Thirdly, children's cognitive ability and personality such as autistic traits may also affect the quality of parent-child interaction (Beurkens et al., 2013; Magiati et al., 2015), which may in turn affect the brain synchronization between parents and children. Finally, there may be some cultural differences involved with the current dataset only involving Asian parents and children. Paternal interaction in particular exhibits greater variability (amount and range) across cultures (Feldman et al., 2019). Larger sample sizes and more rigorous methods are necessary to confirm our



exploratory findings and determine their broader implications. Additionally, further validation of the EAS methods used in this study needs to be carried out.

Overall, the current study investigated differing roles in share experiences between mother-child and father-child dyads using an fNIRS-hyperscanning technique and results suggest that mother-child dyads and father-child dyads exhibit different neural synchronization patterns during varied co-viewing and free-play activities and the synchronization is generally modulated by perceptions of parental stress. In all, the findings from the current study therefore further support this view by demonstrating that both mothers and fathers do indeed have differences in their patterns of neural synchronization with their children and which can also involve different interaction contexts. Given that the current study was the first to perform PLV-measure to evaluate the ISS patterns in the fNIRS field, it is important to validate these results in more parent-child synchronization studies in the future. More importantly, this study provides evidence for a pronounced parent-difference in neural synchronization to shared experience with their children and contributes a significant insight into understanding parent-child relationships. As parent-child interaction therapy is effective for improving social adaptation for the individuals with autism spectrum disorders (Solomon et al., 2008), future research should also investigate the relationship between the quality or effectiveness of parent-child brain-to-brain synchronization and whether mother-child or father-child synchronization may play a dominant role during this therapy.

#### CRediT authorship contribution statement

**Qi Liu:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Formal analysis, Conceptualization. **Siyu Zhu:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Xinqi Zhou:** Writing – review & editing, Methodology, Formal analysis, Funding acquisition. **Fang Liu:** Writing – review & editing, Resources, Methodology. **Benjamin Becker:** Writing – review & editing, Resources, Conceptualization. **Keith M. Kendrick:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Weihua Zhao:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare no competing interest.

#### Data availability

I have shared the link to my data and code at the Attach File step.

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#### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.neuroimage.2024.120529](https://doi.org/10.1016/j.neuroimage.2024.120529).

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