



# Parent–child dyads with greater parenting stress exhibit less synchrony in posterior areas and more synchrony in frontal areas of the prefrontal cortex during shared play

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## ABSTRACT

Parent–child dyads who are mutually attuned to each other during social interactions display interpersonal synchrony that can be observed behaviorally and through the temporal coordination of brain signals called interbrain synchrony. Parenting stress undermines the quality of parent–child interactions. However, no study has examined synchrony in relation to parenting stress during everyday shared play. The present fNIRS study examined the association between parenting stress and interbrain synchrony in the prefrontal cortex (PFC) of 31 mother–child and 29 father–child dyads while they engaged in shared play for 10 min. Shared play was micro-analytically coded into joint and non-joint segments. Interbrain synchrony was computed using cross-correlations over 15-, 20-, 25-, 30- and 35-s fixed-length windows. Findings showed that stressed dyads exhibited less synchrony in the posterior right cluster of the PFC during joint segments of play, and, contrary to expectations, stressed dyads also showed greater synchrony in the frontal left cluster. These findings suggest that dyads with more parenting stress experienced less similarities in brain areas involved in emotional processing and regulation, whilst simultaneously requiring greater neural entrainment in brain areas that support task management and social-behavioral organization in order to sustain prolonged periods of joint interactions.

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## Introduction

Parent–child interactions present invaluable moments that support the child’s nascent social development (Bornstein et al., 2010; Bornstein, 2005; Sroufe, 2000). As active social agents in these dyadic exchanges, parent and child strive to nourish mutually sensitive responses that underscore their bond formation (Atzil et al., 2014; Atzil & Gendron, 2017; Feldman, 2014; Leclerc et al., 2014). These synchronous interactions are a medium through which dyads share their emotional states, engage in joint activities and develop enduring attachments (Ambrose & Menna, 2013; Feldman, 2012a). Over time, parent–child dyads develop a unique rhythm of interpersonal synchrony, distinguished by the temporal matching of micro-level signals that span behavioral and biological dimensions (Legerstee et al., 2013; Lee et al., 2017). This biobehavioral model of synchrony (Feldman, 2012b) postulates that behavioral manifestations of synchrony, like parallel gazes, facial expressions and vocalizations, are accompanied by biological mechanisms such as coordinated patterns of brain signals (i.e., interbrain synchrony; Markova et al., 2019). Synchrony takes

root in infancy and continues to mature throughout early childhood, during which the child’s fledgling capacity in symbolic thought and language enables the pursuit of more composite behaviors such as shared play (Feldman, 2006, 2007a, 2007b; Feldman 2012b, 2012c).

Parenting stress refers to the burden experienced by a parent when the strenuous demands of caregiving are perceived to eclipse the parent’s available coping resources (Östberg et al., 2007). Excessive parenting stress has been linked to less emotional sensitivity (Chan et al., 2018; Deater-Deckard, 1998; Stack et al., 2012; Wilson & Durbin, 2010) as well as punitive, harsh and hostile parenting behaviors (Azhari et al., 2020a; Chan et al., 2018; Kang, 2011; McMahon & Meins, 2012). The children of stressed parents tend to display minimal responsiveness when interacting with their parents. These maladaptive interactional traits configure poor parent–child relationships and predict attachment insecurity in the child (Chan et al., 2018; Jarvis & Creasey, 1991).

During shared play, dyads may engage in joint behaviors such as joint play and laughter which occur

simultaneously (i.e., in-phase), as well as turn-taking behaviors such as back-and-forth conversations (e.g., anti-phase) which are temporally staggered. Albeit the importance of both types of behaviors in scaffolding biobehavioural synchrony (Feldman, 2012b; Feldman, 2012c), the former has been shown to be more stable in eliciting synchrony across behavioral and neural domains (Rennung et al., 2016; Kelso et al., 1995). Recent findings by Piazza et al. (2020) and Leong et al. (2017) within adult-child contexts further supported this principle. Employing a functional near-infrared spectroscopy (fNIRS) hyperscanning paradigm, Piazza et al. (2020) computed the interbrain synchrony that emerges between an adult experimenter and an infant during naturalistic interactions which later revealed that neural synchrony was enhanced during joint gaze and joint attention to a specific toy. Along the same vein, Leong et al. (2017) used an electroencephalogram (EEG) hyperscanning approach to likewise prove that inter-brain coupling between adult-child pairs was enhanced during joint gaze. These findings support the durability of in-phase joint behaviors at being markedly reflected in neural computations of synchrony which hence became the target behaviors for the present study.

Not all moments in parent-child play are homogeneous. Some segments of play are marked by non-joint behaviors, such as when the parent and child are absorbed in different toys and are playing separately. In play paradigms, inter-brain synchrony emerges most prominently during segments of joint compared to non-joint behaviors, characterized by mutual positive affect, concerted gazes and a sustained focus on toys of interest (Santamaria et al., 2020; Wass et al., 2018, 2020). These findings offer evidence for the importance of examining interbrain synchrony during joint and non-joint segments of play. Similarly, synchrony has been found to be greater during shared tasks compared to individual ones (Liu et al., 2016; Nguyen et al., 2020; Reindl et al., 2018). For instance, an fNIRS study by (Reindl et al., 2018) showed that parent-child pairs exhibited greater neural synchrony in the dorsolateral prefrontal cortex (dlPFC) during a cooperative rather than a competitive task. Nguyen and colleagues later demonstrated that both mother-child and father-child dyads depicted greater synchrony in the bilateral PFC during a cooperative puzzle-solving task compared to a competitive one. Synchrony during joint behaviors has consistently been reported to occur in higher-order social cognitive prefrontal regions, which motivates the present study to delimit the scope of investigation to the PFC.

Despite the extensive literature on parent-child play and parent-child interbrain synchrony, no study has examined the association between synchrony and parenting stress within the context of joint dyadic play,

which the present fNIRS hyperscanning study aims to investigate. This study is part of a larger study that examines interbrain synchrony in mother-child and father-child dyads during passive and active joint activities. Unlike the passive co-viewing paradigm where the parent and child were instructed to simply attend to the movies together and to not interact with each other, the play activity offers opportunities for parent and child to engage in interactions with each other. From the dataset on passive shared activity, our previous studies have demonstrated a negative association between mother-child synchrony and parenting variables like parenting stress (Azhari et al., 2019) and attachment anxiety (Azhari et al., 2020b). As such, the present study differs from and extends these previous works by examining the association between parent-child synchrony and parenting stress during shared play, a context which involves active dyadic interactions.

One primary hypothesis was formulated for this study. Following our previous work in Azhari et al. (2019) which showed that mother-child synchrony was inversely associated with parenting stress during passive co-viewing of movies, we commenced this study with the exploratory hypothesis that a similar negative association between synchrony and parenting stress would be observed during shared play.

## Method

The data from this study is part of a larger parent-child fNIRS dataset which comprises two chapters: (1) co-viewing task and (2) play activity. For the co-viewing chapter where dyads watched animation shows together, studies investigating the link between psychological variables (e.g., parenting stress, attachment, gender differences) and parent-child brain activity have been published (Azhari et al., 2019, 2020b; Azhari et al., 2021; Durnford et al., 2020). For the play chapter, a behavioral study has been published on the association between parenting stress, past bonding experiences and parent-child emotional availability (Azhari et al., 2020a), while a technical paper has been published to determine optimal methodical strategies and parameters when computing interbrain synchrony in interactional paradigms (Bizzego et al., 2022a). The present study examines parenting stress in relation to interbrain synchrony during joint and non-joint segments of mother- and father-child play.

## Participants

Thirty-one mother-child dyads (Mothers' Age: Mean = 34.9 years, SD = 4.3; Child's Age: Mean = 42.1 months,

SD = 6.2; 18 boys, 13 girls), and 29 father–child dyads (Father's Age: Mean = 38.1 years, SD = 3.67; Child's Age: Mean = 42.2 months, SD = 5.25; 18 boys, 11 girls) participated in this study. Recruitment was conducted online through social media avenues such as Facebook groups and forums. To be eligible for this study, participants must meet the following criteria: (1) Mothers and fathers must be at least 21 years; (2) Children must be between 2 and 4 years old; (3) Parent–child dyads must be biologically related; (4) Parent–child dyads must be residing in the same household in Singapore; (5) Participants should not be diagnosed with any cognitive, medical or physiological conditions that might impede their ability to comprehend or perform empirical tasks. Each dyad can be considered as independent data points as mother–child and father–child dyads did not belong to the same family. Consent was obtained from participants at the start of the study. Parents provided consent on their children's behalf and all participants were remunerated upon completing the study. The study received approval from the Institutional Review Board of Nanyang Technological University (IRB-20 18 June 2016), and all procedures abided by the regulations of the Declaration of Helsinki. Data for this study are available (Bizzego et al., 2022b).

### **Experimental procedure**

Mothers and fathers were administered an online demographic and parenting stress questionnaire. Upon completing the questionnaire, parent–child dyads went to the child-friendly laboratory where a research assistant briefed the parent about the experiment. Upon obtaining consent, parent and child were seated side-by-side while a NIRSport, NIRx Medical Technologies LLC fNIRS cap of an appropriate size was placed on them. The fNIRS setup consisted of eight sources and seven detectors arranged on each cap according to the standard 10–20 prefrontal cortex montage to form 20 channels. Sources emitted near-infrared light of 760 and 850 nm. Recording was done at a scan rate of 7.81 Hz in hyperscanning mode using NIRxStar version 14.2. Since participants were video-recorded throughout the entire study, we were able to verify that the caps stayed in place throughout the 10-min play session. No data were discarded due to poor cap placement.

A table with typical preschool-aged toys (Bornstein et al., 1996) was placed in front of the parent–child dyads. Parents were asked to play with their child for a total of 10 min. They were provided with a toy car, two plush balls, a tea party set, building blocks, a doll, a cash register and grocery set and three preschool-aged children's books. To minimize excessive motion during the

play session, we ensured that all toys were placed on the table within reach of both the child and the parent. The child was seated on a barber chair next to the parent, which allowed the research assistants to easily adjust the height of the chair and ensure that child participants could comfortably play with the toys in a seated position. A Sony Handycam camcorder, which was placed on a tripod about 2 meters away from the dyads, was used to record the play sessions in MOV format. Participants were debriefed and remunerated at the end of the play session.

### **Parenting Stress questionnaire**

To measure the sources and degree of mothers' and fathers' parenting stress, the Parenting Stress Index-Short Form (PSI-SF) questionnaire was administered (Abidin, 2012). With a total of 36-item, this self-report questionnaire consists of three subscales with 12-item in each component. Parents were asked to respond to statements using a 5-point Likert scale where 1 corresponds to "strongly disagree" and 5 corresponds to "strongly agree". The Parenting Distress subscale measures parents' appraisal of their parenting roles, including whether they experience feelings of restriction, loss of freedom, and competence. For instance, parents were asked to rate the following statement "Since having my child I have been unable to try new and different things". The Parent–child Dysfunctional Interaction subscale evaluates whether parents perceive the child to be meeting their expectations and whether parents enjoy interacting with their child. An example of a statement that parents respond to is "My child is not able to do as much as I expected". Finally, the Difficult Child subscale assesses how challenging parents perceive their child to be. Parents rated their response to statements such as "My child generally wakes up in a bad mood.". The total parenting stress score was obtained from summing the scores of the three subscales. The PSI instrument is a reliable and valid measure, with Cronbach's alpha scores of 0.70 for each of the three subscales, and 0.85 for the total parenting stress score (Abidin, 2011; Luo et al., 2021).

### **Behavioral coding**

Three types of in-phase joint behaviors (i.e., behaviors of parent and child that occurred concurrently) were examined in this study: joint play, joint gaze and joint laughter. Joint play denoted mother and child playing with the same toy simultaneously. Joint gaze referred to mother and child gazing at the same object and joint laughter indicated that mother and child were laughing

together. Solomon Coder software (Version: 17.03.22) was used to annotate the presence and absence of each joint behavior at a rate of 7.81 Hz to match the sampling rate of the fNIRS signals which allowed analyses of brain and behavioral data of the same signal lengths. Microanalytic coding of the videos was conducted by two research assistants who were trained first using a sample video. To compute inter-rater agreement, the “irr” package from RStudio was used (Garner et al., 2012). The research assistants proceeded to code the actual videos only after obtaining an inter-rater agreement score of 80% on the sample video, after which a minimum inter-rater agreement score of 80% was achieved across all videos. The annotations on Solomon software were exported as.csv files following which the presence of joint behaviors was marked with a “1” while their absence was marked with a “0”. Only stable joint behaviors which lasted for at least 0.5 s were included in subsequent analyses.

### **fNIRS data preprocessing**

#### **fNIRS signals**

For each channel, raw fNIRS signals were preprocessed using a semi-automatic procedure. Coefficient of Variation (CV) and Scalp Coupling Index (SCI) were used as signal quality indicators to automatically determine and omit signals with high levels of noise ( $CV < 5\%$ ,  $0.7 < SCI$ ; Morais et al., 2017; Pollonini et al., 2016). Signals that passed this quality test were further preprocessed, with segments that contained spike artifacts detected and corrected (Huppert et al., 2009). Spike artifacts were detected with a procedure similar to Scholkmann et al. (2010), but using moving range instead of moving standard deviation and avoiding spline interpolation. Specifically, first the moving range (difference between maximum and minimum value in the window, window length = 0.5 s) of the fNIRS signal was computed and normalized by the signal average; portions with a normalized range greater than 5 were identified as containing a spike and substituted with last valid fNIRS value before the spike. The procedure was implemented in custom Python code, based on the “hmrMotionArtifact” function in homer2 (with parameters:  $STDEVthresh = 100$ ). Following that, the output of the automatic process was visually inspected by two independent research assistants to identify and manually remove any remaining spike artifacts in the signals.

The next stage of the procedure used the modified Beer-Lambert Law to convert optical signals to oxygenated (HbO) and deoxygenated hemoglobin (Hb) concentrations. Since parents and children belong to different age groups, specific differential pathlength

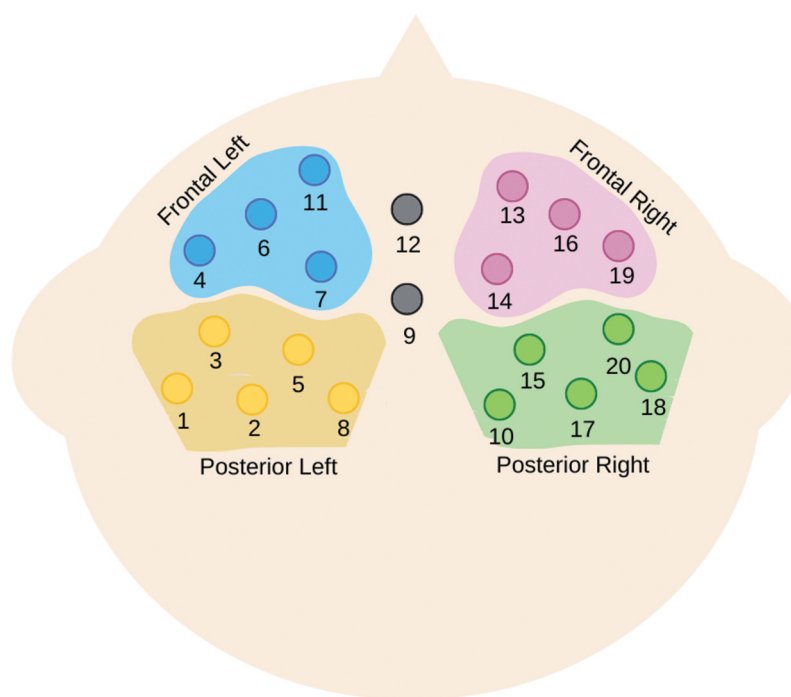
factors (DPF) were used to obtain the HbO and Hb values for adult and child signals (Scholkmann et al., 2013). The following equation was used to compute DPF:  $DPF(AGE, L) = 223.3 + 0.05624 \times AGE^{0.8493} - 5.72e10^{-7} \times L^3 + 0.001245 \times L^2 - 0.9025 \times L$ . Aside from using different DPF values, all other pre-processing settings did not differ between adults and children. Low- and high-frequency noise was removed using an Infinite Impulse Response bandpass filter at 0.01–0.2 Hz. Finally, two independent research assistants visually inspected the typicality of relative concentration changes in HbO and Hb signals for each channel, where an increase in HbO concentration is expected to be accompanied by a decrease in Hb concentration. After this final step, the percentage of channels with good data quality from the mother–child dataset was 66.4% for mothers and 70% for children. For the father–child dataset, the percentage of channels with good data quality was 70.3% for fathers and 70.2% for children.

To obtain regional activation signals, cleaned HbO signals were normalized and aggregated across channels that spatially corresponded to four clusters: frontal left, frontal right, posterior left and posterior right areas of the PFC (Figure 1). For each participant, a minimum of at least three channels with acceptable signal quality was required before regional activation for a specific cluster was computed.

### **Computation of synchrony**

To compute synchrony between the signals of each channel for each parent–child dyad, a cross-correlation approach with a maximum 2-s lag was used on the *physynch* Python package (Bizzego et al., 2021). Based on the findings of Bizzego et al. (2022c), which compared the reliability of computational approaches, cross-correlations were demonstrated to be the most reliable metric among other commonly used synchrony metrics such as Wavelet Transform Coherence (Li et al., 2021).

In a methodical paper that used data from the mother–child sample of this study to assess optimal computational strategies, Bizzego et al. (2022a) found that fixed-length windows of 25, 30 and 35 s were most reliable for synchrony computations compared to shorter (i.e., 15 and 20 s) or longer (i.e., 40 and 45 s) length portions. We computed synchrony for joint and non-joint segments with window lengths of 15, 20, 25, 30 and 35 s. We did not compute synchrony at 40 and 45 s as selecting for these longer window durations would have reduced the sample size significantly (Bizzego et al., 2022c). Since this study adopted a free-play design, each parent–child pair possessed a different number of joint and non-joint portions. Following the approach in Bizzego et al. (2022a), average synchrony for each dyad



**Figure 1.** Schematic spatial representation of the 20 fNIRS channels and four prefrontal clusters.

was computed across each fixed-length portion, for joint and non-joint segments of play.

As a consequence of the rejection of signals due to poor signal quality, and differences in the number of joint and non-joint sessions in the dyads, the actual number of dyads used in the analysis differed between clusters. Table 1 reports the number of dyads for the 35-s windows.

Since all participants were presented with the same set of toys for the play task, some degree of similarity in neural processing could have transpired across participants. As such, it was important to distinguish between synchrony that was specific to the co-presence of parent and child (i.e., synchrony driven by co-presence) from the arbitrary emergence of synchrony driven by similar processing of the play activity (i.e., synchrony driven by task/stimulus). The procedure conducted on true dyads was replicated on surrogate dyads, to obtain a synthetic control group on which we validated the findings. Specifically, the signal of a member of the dyad was

used as a template to generate a surrogate signal, using the Iterative Amplitude Adjusted Fourier Transform (IAAFT) algorithm (Schreiber & Schmitz, 2000). The member of the dyad was randomly selected. Synchrony was then computed between the true signal of the other member and the generated surrogate signal. The procedure was applied for each portion considered in the analysis. As a result, we obtained two sets of synchrony measures: one computed on true signals (true synchrony), which was used to generate the results of the study; the other computed using surrogate signals (surrogate synchrony), which was used for validation. In particular, we expected that the significant results obtained from the true synchrony would not be found on surrogate synchrony.

### Analytical plan

Analyses of covariance (ANCOVA) models were conducted for each fixed-length window (i.e., 15, 20, 25, 30, 35 s), where synchrony was incorporated as the dependent variable, with dyad type and cluster as factors and total parenting stress score as the continuous variable (i.e.,  $\text{Synchrony} \sim \text{Dyad Type} * \text{Cluster} * \text{Total Stress}$ ). Post hoc Spearman's correlation tests and pairwise analyses were subsequently conducted to examine the direction of significant findings.

These analyses were conducted for the joint portions and once again for the non-joint portions. Only dyads

**Table 1.** Number of dyads used in the analysis of 35-s windows, for each cluster.

Cluster	<i>N</i>	<i>N</i> Mother–Child	<i>N</i> Father–Child
Frontal Left	11	6	5
Frontal Right	12	4	8
Posterior Left	5	2	3
Posterior Right	11	5	6



with at least one joint and non-joint segment were included in the analyses. All ANCOVA analyses were conducted on R software (R Core, 2022).

## Results

### Descriptive results

The mean and standard deviation of Parenting Stress Index – Short Form (PSI-SF) scores for mothers, fathers, and pooled parents are reported in Table 2.

### Joint portion analyses

#### Overall behavioral measures

An overall description of the behavioral measures referring to joint portions is reported in Table 3.

On average, dyads showed 25.8 and 28.3 joint sessions of average duration 84.6 and 32.4 s for mother–child and father–child dyads, respectively. The most prevalent joint behavior was joint gaze (60.6% and 53.6% for mother–child and father–child dyads, respectively), followed by joint play (54.3% and 40.9% for mother–child and father–child dyads, respectively). No statistical difference between mother–child and father–child dyads was found.

#### Cluster and total parenting stress

ANCOVAs on HbO signals revealed significant findings for the 35-s fixed-length window. See Supplementary Material for additional and insignificant results from the other window analyses.

For the 35-s window analyses, ANCOVAs revealed a main effect of cluster ( $F(3,23) = 10.88, p = 0.0001206$ ).

An interaction effect of cluster and total stress ( $F(3,23) = 8.83, p = 0.0004433$ ; Figure 2) emerged. Post hoc Spearman's correlation analyses with Benjamini/Hochberg FDR correction indicated that total stress was negatively correlated to synchrony in the posterior right cluster ( $N = 11$ , 95% CI  $[-0.92, -0.21]$ ,  $r = -0.72, p = 0.013$ ), but positively correlated to synchrony in the frontal left cluster ( $N = 11$ , 95% CI  $[0.14, 0.91]$ ,  $r = 0.68, p = 0.021$ ). No significant correlation emerged in the frontal right ( $N = 12$ , 95% CI  $[-0.38, 0.72]$ ,  $r = 0.24, p = 0.44$ ) and posterior left ( $N = 5$ , 95% CI  $[-0.9, 0.86]$ ,  $r = -0.1, p = 0.87$ ) clusters. Fisher  $r$ -to- $z$  transformation analysis showed that the correlation coefficient of the

**Table 2.** Mean and standard deviation scores of Parenting Stress Index – Short Form.

	Mothers Mean (SD)	Fathers Mean (SD)	Parents Mean (SD)
Parenting Distress Subscale	31.09 (8.68)	32.76 (9.92)	31.87 (9.24)
Parent–Child Dysfunctional Interaction Subscale	23.27 (7.03)	23.41 (5.77)	23.34 (6.42)
Difficult Child Subscale	31.91 (7.84)	31.76 (8.13)	31.84 (7.91)
Total Parenting Stress	86.27 (19.39)	87.93 (18.52)	87.05 (8.85)

frontal left cluster is significantly different from the correlation coefficient of the posterior right cluster ( $z$ -ratio =  $-3.47, p = 0.0005$ ).

For the 35-s window, ANCOVAs also showed a significant effect of dyad type and cluster left cluster ( $F(3, 23) = 5.16, p = 0.0072$ ). However, post hoc paired  $t$ -test with Benjamini/Hochberg FDR correction did not reveal significant results for any cluster.

Analysis for 35-s fixed-length window of surrogate parent–child pairs did not reveal a significant result for cluster ( $F(3,23) = 1.05, p = 0.39$ ), parent by cluster interaction ( $F(3,23) = 0.68, p = 0.58$ ) and cluster by total stress interaction ( $F(3,23) = 0.72, p = 0.55$ ).

The same analyses were conducted on HbR data, but no statistically significant results were found. Previous studies have highlighted that there is no clear consensus between similarity in task sensitivity between HbO and HbR (Scarapicchia et al., 2017). Recently, Klein et al. (2022) showed different task sensitivities between HbO and HbR, whereas Kohl et al. (2020) demonstrated that HbO amplitudes were larger than that of HbR amplitudes in certain regions of the brain.

The mean and standard deviation of synchrony values for mother–child, father–child and pooled parent–child dyads for the 35-s fixed-length window of joint behaviors are reported in Table 4.

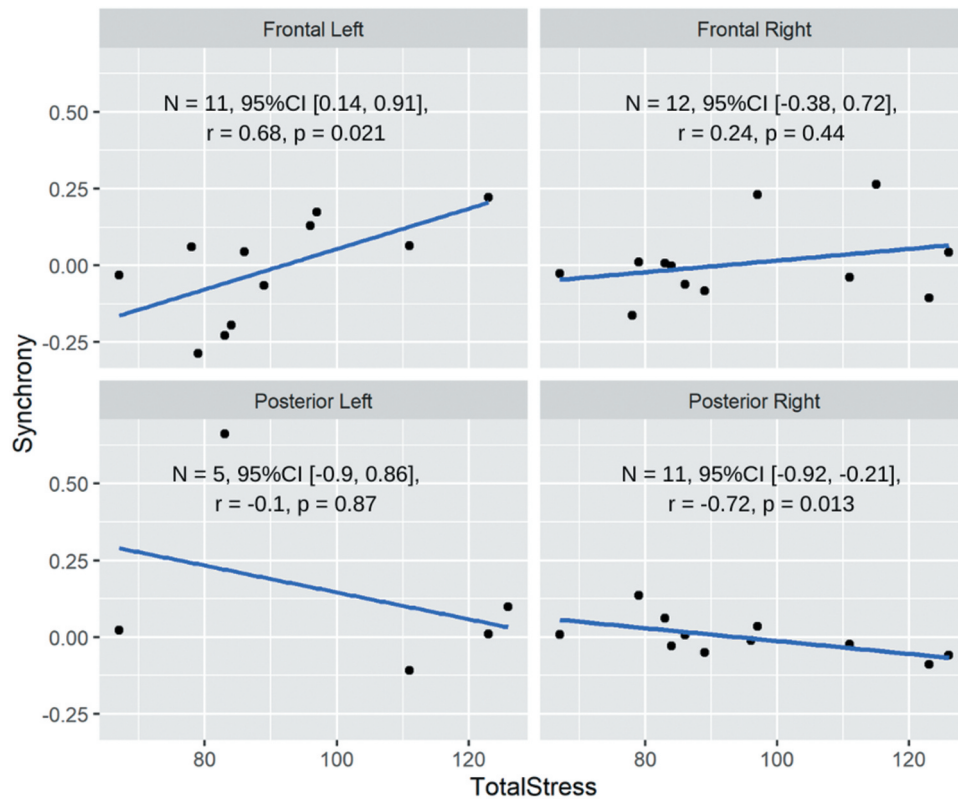
### Non-joint portion analyses

ANCOVA analyses did not reveal any significant effect of cluster, dyad type and total parenting stress for any of the fixed-length windows (i.e., 15, 20, 25, 30, 35 s). See Supplementary Material for results on non-joint portion analyses.

The mean and standard deviation of synchrony values for mother–child, father child and pooled parent–child

**Table 3.** Summary of the behavioral observations referring to joint sessions. Average values with standard deviation (between parentheses).

	N Joint Sessions	Duration	%Gaze	%Laughter	%Play
Mother–child	25.8 (20.9)	84.6 (151.9)	60.6 (19.5)	0.1 (0.2)	54.3 (30.8)
Father–child	28.3 (19.6)	32.4 (33.5)	53.6 (22.4)	0.2 (0.5)	40.9 (28.9)



**Figure 2.** Figure depicting scatter plot of total stress score against synchrony values for each dyad, in each of the four clusters for the 35-s fixed-length window. Total stress is positively correlated with synchrony in the frontal left cluster, and negatively correlated in the posterior right cluster.

dyads for the 35-s fixed-length window of joint behaviors are reported in Table 5.

## Discussion

The present study demonstrated significant relationships between interbrain synchrony and parenting stress during parent–child play. Our hypothesis, that a negative association between interbrain synchrony and parenting stress would be observed during play, was partially fulfilled. Synchrony was negatively correlated with parenting stress in the posterior right cluster of the brain, which maps to the inferior frontal gyrus and the dorsolateral prefrontal cortex. Unexpectedly, synchrony was also found to be positively associated with parenting stress in the frontal left cluster corresponding to the left anterior, inferior and middle frontal gyrus of

the PFC during joint segments of play only. These associations were significant during a 35-s fixed-length window of joint behaviors only, but not for shorter periods of joint behaviors, which suggests that the significant association between synchrony and parenting stress emerged for more prolonged periods of joint play.

Similar to our previous study, which investigated synchrony during a passive shared activity of co-viewing animation shows together (Azhari et al., 2019), the present study corroborated that stressed dyads displayed less synchrony in the posterior PFC when engaging in active shared play. The posterior cluster encompasses the inferior and dorsolateral PFC which are involved in higher-order cognitive functions, processing and regulation of our emotional experiences, working memory and selective attention (Badre & Wagner, 2004; Brunoni & Vanderhasselt, 2014; Hart et al., 2013). According to

**Table 4.** Interbrain synchrony during joint behaviors in the 35-s window.

Cluster	Mother–child Synchrony Mean (SD)	Father–child Synchrony Mean (SD)	Parent–child Synchrony Mean (SD)
Frontal Left	0.069 (0.14)	−0.057 (0.25)	−0.0099 (0.22)
Frontal Right	0.067 (0.14)	−0.054 (0.25)	−0.0063 (0.22)
Posterior Left	0.079 (0.13)	−0.054 (0.28)	−0.024 (0.22)
Posterior Right	0.068 (0.14)	−0.064 (0.25)	−0.0067(0.22)

**Table 5.** Interbrain synchrony during non-joint behaviors in the 35-s window.

Cluster	Mother-child Synchrony Mean (SD)	Father-child Synchrony Mean (SD)	Parent-child Synchrony Mean (SD)
Frontal Left	-0.082 (0.15)	0.13 (0.23)	0.047 (0.22)
Frontal Right	-0.065 (0.17)	0.12 (0.23)	0.049 (0.22)
Posterior Left	-0.11 (0.15)	0.18 (0.26)	0.072 (0.23)
Posterior Right	-0.057 (0.17)	0.14 (0.23)	0.053 (0.22)

Azhari et al. (2019), diminished synchrony in posterior areas of the PFC when co-viewing narrative scenes together could have reflected less similar emotional coordination and mentalization processes between stressed mothers and their children. Applying this understanding to the context of shared play in the present study, parents who reported elevated levels of parenting stress could have experienced less similar intersubjective emotional processes with their child, despite overtly engaging in joint play together. It is important to note that the negative correlation between parenting stress and synchrony in joint co-viewing and joint play differentially implicated the left and right posterior regions of the PFC respectively. This lateralization could be due to task-related differences. For instance, the left dorsolateral PFC is recruited more dominantly when processing sequences of events, and hence could have been robustly recruited in the co-viewing task when dyads were presented with narrative scenes. The right dorsolateral PFC, by comparison, has an important role in combining information across events. Since the free play session was less sequentially structured compared to the viewing task, where sequential processing was important to the overall understanding of the scenes, we posit that the lateralized effect could be driven by task-related differences in recruitment of left and right PFC resources (Huey et al., 2006).

The present study also revealed an unexpected positive association between stress and synchrony in the frontal left cluster during shared play. Spanning the left anterior, inferior and middle frontal gyrus, the frontal left cluster primarily subserves task management, attentional regulation and planning of self-initiated social behaviors, all of which are functions which a complex social task such as dyadic free play requires (Dreher et al., 2008; Koechlin et al., 1999; Kovach et al., 2012). It might be possible that dyads with less stressed parents engaged in play more often in their daily lives and found shared play to be less effortful and cognitively demanding, hence they did not need to entrain their neural signals to each other during this task. By comparison, dyads with more stressed parents tend to engage in less play on an everyday basis and could have needed to exercise greater neural entrainment during prolonged shared play in order to maintain dyadic engagement.

Further research is required to provide a more in-depth explanation underlying these observations.

Findings from this study showed that synchrony emerged during joint but not non-joint portions of play. Joint segments of play were characterized not only by mutual attention (i.e., joint gaze) and mutual engagement in the same task (i.e., joint play) but also by a metric of mutual positive affect (i.e., joint laughter). In line with the expanding literature on inter-rain synchrony during play, we found synchrony to emerge only during joint segments of play (Liu et al., 2016; Nguyen et al., 2020; Reindl et al., 2018; Santamaria et al., 2020; Wass et al., 2018, 2020). Contributing to this body of work, the present study likewise demonstrated that instances of positive simultaneous joint interaction in particular drives interbrain synchrony in parent-child dyads during play.

The results from this study should be interpreted with several limitations in mind. First, this study used a self-report measure of parenting stress which incorporated an element of subjectivity. Depending on their own perception of experienced stress, parents could have either overstated or understated their stress levels when responding to the questionnaire. However, the use of a self-report measure in our study is valid as parenting stress is inherently a personal and unique experience for each parent. Second, the study did not investigate immediate changes in stress levels before and after dyadic play, which would have otherwise provided directional information on the association between interbrain synchrony and parenting stress during play. Parenting stress has been shown to be alleviated with shared play (Berkule et al., 2014; Brazelton et al., 1979; Cates et al., 2016) and parent-child play-based interventions (Hirsh-Pasek et al., 2004, 2009; Hosogane et al., 2018; Kohlhoff et al., 2021; Lieneman et al., 2020; Weisleder et al., 2019). While play has long been established to exert beneficial effects in children, spurring the development of executive functioning, prosocial behaviors and emotional regulation (e.g., Atkinson et al., 2016; Blair et al., 2006; Garner



et al., 2012; Hibel et al., 2015), studies have also begun to document its benefits on adult caregiver well-being. Through shared play, parent and child engage in dyadic interactions that promote emotional attunement and mutual joy that serves to reduce parenting stress while simultaneously fostering the parent–child relationship (Berkule et al., 2014; Brazelton et al., 1979; Cates et al., 2016). In child clinical populations, play is typically incorporated as a central component of parent–child interventions such as focal play therapy (FPT) and parent–child interaction therapy (PCIT). Hence, future work could investigate the dyadic brain mechanisms underlying how these play-derived interventions enhance the parent–child relationship, improve child outcomes, and effectively reduce parenting stress in caregivers (Hirsh-Pasek et al., 2004, 2009; Hosogane et al., 2018; Kohlhoff et al., 2021; Weisleder et al., 2019). Third, the study did not consider anti-phase reciprocal interactions and defined joint play exclusively as in-phase dyadic behaviors that occur at the same time. However, in defining this narrow scope of joint behaviors, we were able to provide distinct comparisons between joint and non-joint segments of play. The decision to limit our scope to in-phase joint behaviors was also supported by previous studies which found neural synchrony to emerge most stably and prominently when dyadic behaviors occur simultaneously (Rennung et al., 2016; Kelso, 1995). Future studies could be conducted to discern the effect of reciprocal behaviors on interbrain synchrony in relation to parenting stress. Finally, interbrain synchrony was only assessed within the prefrontal cortex which might have led to an incomplete understanding of synchrony mechanisms that could have transpired in other areas of the brain. Future studies could expand the region of interest and examine synchrony in other areas of the brain involved in higher-order social cognition, such as the temporo-parietal junction.

## Conclusion

This study was the first to investigate the association between interbrain synchrony and parenting stress during shared play. We showed that synchrony was negatively correlated with parenting stress in the posterior right cluster of the prefrontal cortex. Contrary to our expectations, we also demonstrated that dyads with more parenting stress showed greater synchrony in the frontal left cluster. Taken together, these findings suggest that dyads who reported greater levels of parenting stress experienced less similar emotional processing. At the same time, these dyads experienced greater entrainment of brain signals in regions responsible for complex social and behavioral planning which could have

occurred to support extended durations of continuous joint play. More importantly, this result highlights the need to address fundamental questions pertaining to the significance of synchrony in different areas of the brain, and in the context of parenting.

## Disclosure statement

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