Parent-Child Dyads with Greater Parenting Stress Exhibit Enhanced Inter-Brain Synchrony During Shared Play

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Parent-Child Dyads with Greater Parenting Stress Exhibit Enhanced Inter-brain Synchrony 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 overtly, in the form of joint behaviours, and biologically, such as through the temporal coordination of brain signals called inter-brain synchrony. Joint play provides ample opportunities for parent-child dyads to engage in matching interactions which not just facilitate the formation of bonds but also alleviate parenting stress in caregivers. Despite the beneficial effects of play on parents and the parent-child relationship, no study has investigated the dyadic neural mechanism by which this occurs. The present functional Near-infrared Spectroscopy (fNIRS) study aimed to examine the association between parenting stress and inter-brain synchrony in the prefrontal cortex of 31 mother-child and 29 father-child dyads while they engaged in shared play for 10 minutes. Shared play was miro-analytically coded into joint (i.e., in-phase matching of dyadic behaviours) and non-joint (i.e., no matching of dyadic behaviours) segments. Inter-brain synchrony was computed using cross-correlations over 15 s, 20 s, 25 s, 30 s and 35 s fixed-length windows of joint and non-joint play segments. Analyses of Covariance revealed that dyads with more parenting stress exhibited greater inter-brain synchrony in the frontal left cluster of the prefrontal cortex, but only for the 35 s fixed-length window. This finding suggests that continuous and positive instances of joint play may disproportionately benefit dyads who reported greater parenting stress, entraining underlying brain activation patterns involved in social cognition. Mother-child dyads also showed greater inter-brain synchrony than father-child dyads, alluding to possible gender differences in the effect of play on dyads. Findings present evidence of a potential dyadic neural pathway by which play benefits the parent-child relationship.

Keywords: interpersonal synchrony, brain synchrony, parent-child interaction, parent-child play, parenting stress

1 Introduction

Parent-child interactions present invaluable moments that support the child's nascent social development [1–3]. As active social agents in these dyadic exchanges, parent and child strive to nourish mutually sensitive responses that underscore their bond formation [4–7]. These synchronous interactions are a medium through which dyads share their emotional states, engage in joint activities and develop enduring attachments [8, 9]. Over time, parent-child dyads develop a unique rhythm of interpersonal synchrony, distinguished by the temporal matching of micro-level signals that span behavioural and biological dimensions [10] [11]. This biobehavioural model of synchrony [9] postulates that behavioural manifestations of synchrony like parallel gazes, facial expressions and vocalisations, are accompanied by biological mechanisms such as coordinated patterns of brain signals (i.e., inter-brain synchrony) [12]. 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 behaviours such as shared play [9, 13–15].

Shared play is a means through which parent and child well-being are attained. Parenting stress refers to the burden experienced by a parent when the strenuous demands of caregiving is perceived to eclipse the parent's available coping resources [16]. Excessive parenting stress has been linked to less emotional sensitivity [17–20] as well as punitive, harsh and hostile parenting behaviours [20–23]. 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 [20, 24]. Parenting stress has been shown to be alleviated with shared play [25–27] and parent-child play-based interventions [28–33]. While play has long been established to exert beneficial effects in children, spurring the development of executive functioning, prosocial behaviours and emotional regulation (e.g.,[34–37]), 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 [25–27]. 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). These play-derived interventions are not only potent in enhancing the parent-child relationship and improving child outcomes, but also effectively reduce parenting stress in caregivers[28–33].

During shared play, dyads may engage in joint behaviours such as joint play and laughter which occur simultaneously (i.e., in-phase), as well as turn-taking behaviours such as back-and-forth conversations (e.g., anti-phase) which are temporally staggered. Albeit the importance of both types of behaviours in scaffolding biobehavioural synchrony [9, 13], the former has been shown to be more stable in eliciting synchrony across behavioural and neural domains [38, 39]. Recent findings by [40] and [41] within adult-child contexts further supported this principle. Employing a functional near-infrared spectroscopy (fNIRS) hyperscanning paradigm, [40] computed the inter-brain 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, [41] 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 behaviours at being markedly reflected in neural computations of synchrony which hence became the target behaviours for the present study.

Not all moments in parent-child play are homogeneous. Some segments of play are marked by non-joint behaviours, 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 behaviours, characterised by mutual positive affect, concerted gazes and a sustained focus on toys of interest [42–44]. These findings offer evidence for the importance of examining inter-brain synchrony during joint and non-joint segments of play. Similarly, synchrony has been found to be greater during shared tasks compared to individual ones [45–47]. For instance, an fNIRS study by [46] showed that parent-child pairs exhibited greater neural synchrony in the dorsolateral prefrontal cortex (dlPFC) during a cooperative rather than a competitive task. [47] 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 behaviours 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 evidence of shared play being effective in reducing parenting stress (e.g., [25–27]) and in promoting parent-child inter-brain synchrony (e.g.,[42–44]), a glaring research gap pertains to the mechanism by which inter-brain synchrony relates to parenting stress during shared play. The present fNIRS hyperscanning study aims to investigate inter-brain synchrony as a potential

	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)

Table 1 Mean and Standard Deviation Scores of Parenting Stress Index - Short Form

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 2 Inter-brain Synchrony During Joint Behaviours 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)

Table 3 Inter-brain Synchrony During Non-Joint Behaviours in the 35 s Window.

dyadic neural pathway by which parent-child shared play is associated with parenting stress. This study is part of a larger study that examines inter-brain synchrony in mother-child and father-child dyads during passive and active joint activities.

We commenced this study with four hypotheses, of which the first two were confirmatory and the latter two were exploratory hypotheses. First, similar to the studies by [44] and [42] which demonstrated that inter-brain synchrony primarily emerged during joint but not non-joint play, we expected the relationship between inter-brain synchrony and parenting stress to be observed during joint segments only. Second, in line with [44], [42] and [48] which found that sustained durations of joint behaviours were necessary to elicit inter-brain synchrony during play, we hypothesised that the association between inter-brain synchrony and parenting stress would be most prominent when dyads engaged in continuous periods of joint behaviours. Third, since shared play benefits parental well-being by significantly alleviating parenting stress (e.g.[25–27]), we hypothesised that greater inter-brain synchrony would be observed in dyads with higher parenting stress levels as we postulate that synchrony would serve as a dyadic neural pathway by which shared play strengthens parent-child attunement and reduces parenting stress. Fourth, we expected to observe a significant difference in inter-brain synchrony displayed between mother- and father-child dyads given their characteristically different interactional strategies during play, where mothers tend to engage in more scaffolding and didactic behaviours compared to fathers [49–52].

2 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 1.

Joint Portion Analyses

Cluster and Total Parenting Stress

ANCOVA analyses revealed significant findings only for the 35 s fixed-length window. See Supplementary Material for insignificant results from the other window analyses.

For the 35 s window analyses, an interaction effect of cluster and total stress (F(3,31) = 6.455, p = 0.0016, (Figure 1)) emerged. Post-hoc Spearman's correlation analyses indicated that total stress was significantly correlated to synchrony only in the frontal left cluster (rho = 0.955, S = 10, p = 4.989e-06), but not in the frontal right (rho = 0.147, S = 244, p = 0.649), posterior left (rho = -0.5, S = 30, p = 0.391) or posterior right clusters (rho = -0.445, S = 318, p = 0.17). Contrast analyses showed that the frontal left cluster depicted significantly greater synchrony than the posterior left (z-ratio = 4.081, p = 0.0003) and posterior right clusters (z-ratio = 3.17, p = 0.0083, Tukey's p-value adjustment for comparing 4 family estimates). ANCOVA analysis for 35 s fixed-length window of surrogate parent-child pairs did not reveal a significant result for cluster (F(3,31) = 1.09, p = 0.37), total stress (F(1,31) = 0.161, p = 0.69) and cluster by total stress interaction (F(3,31) = 2.84, p = 0.054).

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 behaviours are reported in Table 2.

Dyad Type and Total Parenting Stress

For the 35 s window analyses, only synchrony in the frontal left cluster was found to significantly interact with parenting stress. As such, exploratory analyses on the effects of dyad type were conducted only for this cluster. ANCOVA analyses showed a significant effect of dyad type (F(1, 7) = 78.33, p = 4.76e-05) and total parenting stress score (F(1, 7) = 37.91, p = 0.000464). Pairwise comparison between dyad types showed that mother-child dyads exhibited significantly greater synchrony than their father-child counterparts (t-value =3.28, df = 6.71, p = 0.014, Bonferroni correction, (Figure 2)). Spearman's correlations test demonstrated that total parenting stress was positively correlated with synchrony in the frontal left cluster (rho = 0.955, S = 10, p = 4.989e-06, Figure 1)).

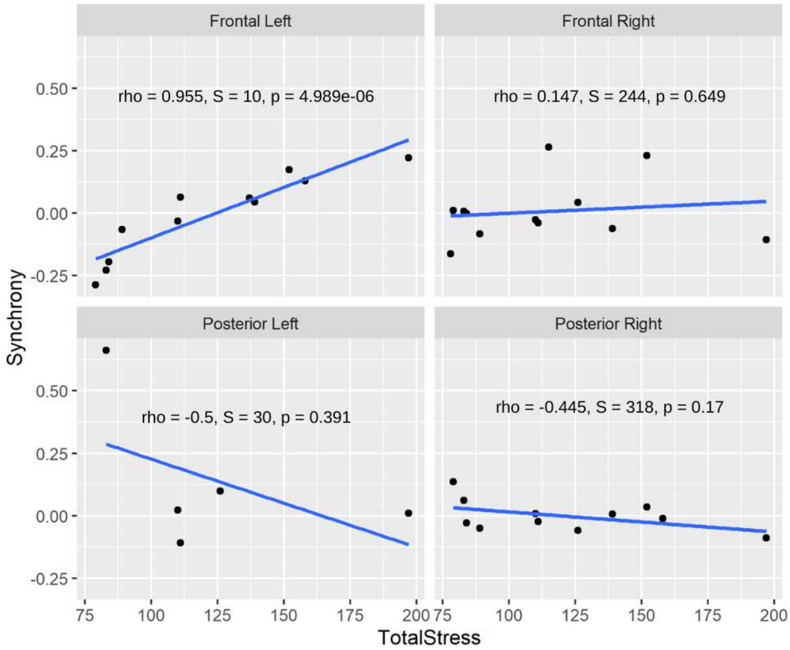

Fig. 1 Figure depicting scatter plot of total stress score against synchrony values for each dyad, in each of the four clusters for the 35 s fixed-length window. Total stress is significantly positively correlated with synchrony in the frontal left cluster only.

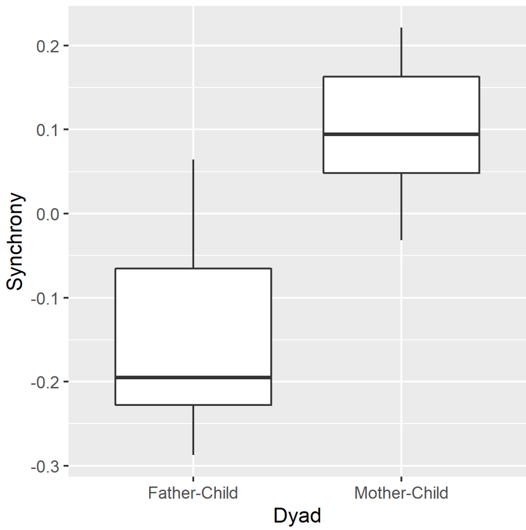

Fig. 2 Boxplot depicting greater synchrony in the mother-child dyads compared to father-child dyads in the frontal left cluster for the 35 s fixed-length window.

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 s, 20 s, 25 s, 30 s, 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 dyads for the 35 s fixed-length window of joint behaviours are reported in Table 3.

3 Methods

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 [53–56]. For the play chapter, a behavioural study has been published on the association between parenting stress, past bonding experiences and parent-child emotional availability [23], while a technical paper has been published to determine optimal methodical strategies and parameters when computing inter-brain synchrony in interactional paradigms [48]. The present study examines parenting stress in relation to inter-brain synchrony during joint and non-joint segments of mother- and father-child shared play.

3.1 Participants

31 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-2018-06-016) and all procedures abided by the regulations of the Declaration of Helsinki. Data for this study is available

3.2 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 8 sources and 7 detectors arranged on each cap according to the standard 10-20 prefrontal cortex montage to form 20 channels. Sources emitted near-infrared light of 760nm and 850nm. Recording was done at a scan rate of 7.81Hz in hyperscanning mode using NIRStar version 14.2.

A table with typical preschool-aged toys [57] was placed in front of the parent-child dyads. Parents were asked to play with their child for a total of 10 minutes. 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 . 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.

3.3 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 [58]. 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 [59, 60].

3.4 Behavioural Coding

Three types of in-phase joint behaviours (i.e., behaviours 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) [61] was used to annotate the presence and absence of each joint behaviour at a rate of 5 Hz or every 0.2 s. Microanalytic coding of the videos was conducted by two research assistants who were trained using a sample video first. To compute inter-rater agreement, the "irr" package from RStudio was used [62]. The research assistants proceeded to code the actual videos only after obtaining an inter-rater agreement score of 80% on the sample video, afterwhich 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 behaviours was marked with a '1' while their absence was marked with a '0'. Only stable joint behaviours which lasted for at least 0.5 s were included in subsequent analyses.

3.5 fNIRS Data Preprocessing

3.5.1 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 ($CV < 5\%$, $0.7 < SCI \leq 1$)[63, 64]. Signals which passed this quality test were further preprocessed, with segments that contained spike artifacts detected and corrected [65]. Following that, the output of the automatic process was inspected to correct for any further noise artifact. The next stage of the procedure used the modified Beer-Lambert Law to convert optical signals to oxygenated (HbO) and deoxygenated haemoglobin (Hb) concentrations. Since parents and children belong to different age groups, specific differential pathlength factors were used to obtain the HbO and Hb values for adult and child signals [66]. Low- and high-frequency noise was removed using an Infinite Impulse Response band-pass filter at 0.01 to 0.2 Hz. Finally, HbO and Hb time-series signals for each channel were inspected to ensure that the final output corresponds to typical oxygenated and deoxygenated waveforms.

To obtain regional activation signals, cleaned HbO signals were normalised and aggregated across channels that spatially corresponded to four clusters: frontal left, frontal right, posterior left and posterior right areas of the PFC (Figure 3). For each participant, a minimum of at least 3 channels with acceptable signal quality was required before regional activation for a specific cluster was computed.

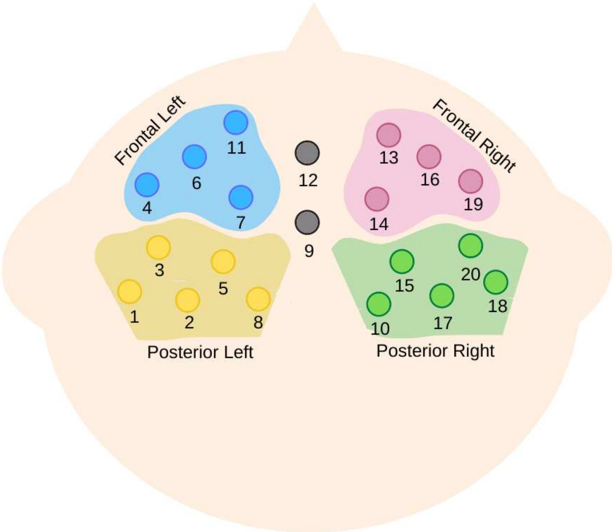

Fig. 3 Schematic spatial representation of the 20 fNIRS channels and four prefrontal clusters.

Computation of Synchrony

To compute synchrony between the signals of each channel for each parent-child dyad, a cross-correlations approach with a maximum 2-second lag was used on the `physynch` Python package [54, 67, 68]. Based on the findings of [69], which compared the reliability of computational approaches, cross-correlations was demonstrated to be the most reliable metric amongst other commonly used synchrony metrics such as Wavelet Transform Coherence [70]).

In a methodical paper that used data from the mother-child sample of this study to assess optimal computational strategies, [48] found that fixed length windows of 25, 30 and 35 seconds 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 s, 20 s, 25 s, 30 s and 35 s. We did not compute synchrony at 40 s and 45 s as selecting for these longer window durations would have reduced the sample size significantly [48]. 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 [48], average synchrony for each dyad was computed across each fixed-length portion, for joint and non-joint segments of shared play.

The procedure was replicated on surrogate signals, 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 [71]. The member of the dyad was randomly selected. The 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

Two types of Analyses of Covariance (ANCOVA) models were conducted. First, for each fixed-length window (i.e., 15 s, 20 s, 25 s, 30 s, 35 s), synchrony was incorporated as the dependent variable, with cluster as a factor and total parenting stress score as the continuous variable (i.e., Synchrony Cluster * Total Stress). Post-hoc Spearman's correlations tests between parenting stress score and synchrony were conducted for each cluster.

From the clusters which showed a significant correlation between synchrony and total stress, ANCOVA analyses were performed to investigate the effect of the type of parent. Here, synchrony was the dependent variable, dyad type (i.e., mother-child or father-child) was a factor and total parenting stress score was the continuous variable (i.e., Synchrony Dyad Type * Total Stress). Post-hoc pairwise analyses and Spearman's correlations tests were used to compare between dyad types.

These analyses were conducted for the joint portions and once again for the non-joint portions. Only dyads with at least one joint and non-joint segment were included in the analyses. All ANCOVA analyses were conducted on R software.

4 Discussion

The present study demonstrates a positive relationship between inter-brain synchrony during parent-child play and parenting stress, thereby positing synchrony as a potential dyadic neural pathway by which shared play improves parent-child bonding and alleviates parenting stress. The first hypothesis, that the association between inter-brain synchrony and parenting stress would be observed during parent-child joint behaviours, was fulfilled. Synchrony was associated with parenting stress during joint segments of shared play only, but not in non-joint segments. The second hypothesis, that the relationship between parenting stress and inter-brain synchrony would surface during continuous periods of joint behaviours was also met. The association between parenting stress and synchrony was significant during a 35 s fixed-length window of joint behaviours, but not for shorter periods. The third hypothesis that we would observe a positive relationship between synchrony and parenting stress, was partially fulfilled. The positive correlation between synchrony and parenting stress emerged only in the frontal left cluster corresponding to the left anterior, inferior and middle frontal gyrus of the PFC. Our fourth and final hypothesis, that there would be a significant difference between inter-brain synchrony observed in mother-child compared to father-child dyads was likewise satisfied. Mother-child dyads exhibited greater inter-brain synchrony compared to father-child counterparts in the frontal left cluster during joint segments of shared play.

Shared play is known to exert powerful positive effects on the dyadic relationship by providing opportunities for mutual interactions that allay caregiver stress and enhance the emotional bond between parent and child [28–32]. Despite its well-established history, the mechanism by which shared play leads to beneficial dyadic outcomes remains unknown. The present study postulated that inter-brain synchrony could serve as a dyadic neural pathway by which play improves the quality of parent-child relationships. In this study, joint segments were characterised 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-brain synchrony during play, we found synchrony to emerge only during joint behaviours during shared play [42–47]. Contributing to this body of work, the present study likewise demonstrated that instances of positive simultaneous joint interaction in particular drives inter-brain synchrony in parent-child dyads during play.

For a significant association between inter-brain synchrony and parenting stress to emerge, we demonstrated that shared play had to be mutual and positive, bearing instances of joint attention, joint action and joint positive affect, as well as sustained for a continuous duration. Parents who experience excessive parenting stress often display diminished emotional sensitivity and struggle to interact with their child [17–20]. Drawing upon this literature alone, one might expect more stressed dyads to exhibit less inter-brain synchrony during joint segments of shared play. However, the benefits of shared play especially to caregivers who experience high levels of parenting stress is likewise recorded [25–27]. In the present study, a strong positive association between synchrony and parenting stress was evident only after a continuous period of uninterrupted positive joint behaviours of approximately 35 s. This observation suggests that, for parents who experience greater stress where enjoyable parent-child interactions are infrequent and difficult to achieve, prolonged positive joint behaviours during play could have exerted beneficial and reparative effects that entrained dyadic brain signals and are reflected as inter-brain synchrony. When arriving at this conclusion, it is important to rule out confounding factors such as differences in parenting and child behaviours across dyads with greater compared to lesser parenting stress that could have driven the positive association between inter-brain synchrony and parenting stress. In our previous behavioural analyses study that examined parental and child aspects of emotional availability during play using this same dataset [23], we showed that there was no significant relationship between total parenting stress and parental sensitivity, structuring, intrusiveness, hostility as well as child responsiveness and involvement during play. As such, differences in parenting and child behaviours across high- and low-stressed dyads were not driving the positive correlation between synchrony and parenting stress. The most plausible explanation remains that positive continuous play elicits inter-brain synchrony to a greater extent in dyads with higher levels of parenting stress as such quality play is disproportionately more beneficial to these dyads.

Whereas a positive correlation between stress and synchrony unfolded in the frontal left cluster during shared play in this study, the opposite effect, where parents with greater stress exhibited less synchrony with their child in the posterior left region of the PFC when engaged in a passive shared activity of co-viewing animation shows together, was observed in one of our previous studies [53]. We posited two potential reasons that could explain these different observations. First, the stark contrast in findings between these two studies could lie in the nature of the dyadic activity being investigated. Prevailing theories of synchrony in parent-child relationships posited that matching dyadic behaviours are critical in eliciting synchrony [9, 13, 14]. In [53], mother-child dyads participated in a passive activity which did not provide opportunities for mothers to engage in such reparative interactions with their children. As such, the negative association between parenting stress and synchrony in the passive co-viewing paradigm could have reflected the lack of attunement that exists in dyads with greater parenting stress in the absence of any of the beneficial effects of play. Conversely, in the present shared play paradigm, continuous positive joint behaviours during shared play could have lent important restorative attunement to dyads with greater parenting stress in particular, thus driving inter-brain synchrony to a greater extent in those dyads.

Second, two different regions of the PFC were implicated across the co-viewing and play studies, with the former demonstrating a decrease in synchrony with greater parenting stress in the posterior left cluster whereas the latter evinced an increase in synchrony with greater parenting stress in the frontal left cluster. The posterior left cluster comprises the left Brodmann areas (BA) 8, 9 and 46 that correspond to the frontal eye field, middle frontal gyrus and the dorsolateral PFC. These areas are involved in higher-order cognitive functions, including executive functioning, mentalising the perspectives of others, working memory and selective attention [72–74]. According to [53], diminished synchrony in this cluster when co-viewing narrative scenes together could have reflected less similar emotional coordination and mentalisation processes between stressed mothers and their children. By comparison, the frontal left cluster consists of the left BA 47, 46 and 10 which maps to the inferior frontal cortex, anterior PFC and middle frontal gyrus. These regions primarily subserve task management and planning of self-initiated social behaviours, all of which are functions which a complex social task such as dyadic free play requires [75–77]. Dyads with greater parenting stress could have established a more coordinated rhythm of interaction after continuous positive joint behaviours that was reflected as enhanced synchrony in the region of the brain involved in social cognition and behavioural organisation. Further research is required to provide a more in-depth explanation underlying these observations.

It is well-known that parenting behaviours between mothers and fathers differ during play [49–52], which makes the greater synchrony shown by mother-child compared to father-child dyads in this study a noteworthy point of discussion. Whereas fathers engage in more physical play and interact with their child as equal playmates, mothers tend to occupy a caregiving role during play, exhibiting more sensitive and scaffolding behaviours towards their children. Mothers' didactic approach could have facilitated greater entrainment in mother-child dyads that emerged as enhanced inter-brain synchrony in the frontal left PFC which oversees complex social cognition and behavioural planning. Moreover, the trajectory of parenting stress development and response to play-based intervention differ between mothers and fathers as well, with focal play therapy found to alleviate stress in mothers but not in fathers [78]. These previous findings point to the differential effects of play in mothers and fathers, which was likewise revealed in this present study.

Findings from the present study should be taken 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 lent further evidence to support inter-brain synchrony as a dyadic neural pathway that alleviates parenting stress through play. Nonetheless, extensive research has already been conducted to establish the beneficial effects of shared play in reducing caregiver stress and improving the parent-child relationship [25–32], which allows the present study to focus on the dyadic neural mechanism that occurs during play. Third, the study did not consider anti-phase reciprocal interactions and defined joint instances of behaviours exclusively as in-phase dyadic behaviours that occur at the same time. However, in defining this narrow scope of joint behaviours, we were able to provide distinct comparisons between joint and non-joint segments of shared play. The decision to limit our scope to in-phase joint behaviours was also supported by previous studies which found neural synchrony to emerge most stably and prominently when dyadic behaviours occur simultaneously [38, 39]. Future studies could be conducted to discern the effect of reciprocal behaviours on inter-brain synchrony in relation to parenting stress. Finally, inter-brain 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.

5 Conclusion

The beneficial effects of shared play on the parent-child relationship has been recorded for decades. Our study is the first to present a potential dyadic neural mechanism, in the form of inter-brain synchrony, through which shared play may disproportionately benefit dyads with greater parenting stress. In uncovering that play has to be mutual, continuous and positive for synchrony to occur at a deeper brain-to-brain level, this study also demonstrates the promising use of inter-brain synchrony as a metric to identify specific features of shared play that might render it more efficacious to dyads.

Supplementary information. This article reports insignificant results in the supplementary section.

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- Conflict of interest/Competing interests The authors declare no conflict of interest.
- Availability of data and materials The data for this study is available at `https://doi.org/10.21979/N9/R7D1UP`.
- Code availability The code for this study is available at https://gitlab.com/abp-san-public/fnirs-synch-methods.
- Authors' contributions A.A. collected the data, analysed the data and wrote the manuscript. A.B. conducted data analyses and edited the manuscript. G.E. supervised the study and reviewed the manuscript.

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