Parenting stress is associated with greater stimulus-oriented brain synchrony in father-child dyads

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ABSTRACT

Parenting stress that protracts beyond the psychological resources of the parent may lead to adverse caregiving responses that undermine the quality of the parent-child relationship. In developmental psychology, synchrony reflects the biobehavioural entrainment of parent and child to each other's emotional states, where greater synchrony is generally posited to be associated with an enhanced quality of parent-child relationship. We have previously investigated mother-child prefrontal cortical (PFC) synchrony using functional Near-infrared Spectroscopy (fNIRS) and showed that greater maternal stress was linked to reduced synchrony in PFC areas involved in mentalisation processes. However, fathers and mothers differ in regard to how they experience and respond to parenting stress. As such, the present study aims to examine how fathers' parenting stress affects father-child brain-to-brain synchrony. Hyperscanning fNIRS was used to record the PFC activities of 29 father-child dyads as they engaged in a typical activity of watching animation shows together. Three 1-min video clips were presented to each pair and synchrony between dyadic members was quantified algorithmically afterwards. Fathers' parenting stress was evaluated using a self-reported Parenting Stress Index-Short Form questionnaire. Findings show that greater parenting stress that stems from a perceived dysfunction in parent-child interaction is associated with higher synchrony in the medial rostral Brodmann Area 10 (BA10). This area is known to be implicated in stimulus-oriented attending, and is rendered less active during stimulus-independent processes such as mentalisation. This result suggests that dyads in which the father reports greater parenting stress are more likely to attend to sensory aspects of a joint activity, rather than engage in mentalisation processes which may help the father-child pair attune to each other's emotions.

Keywords: synchrony, parent-child, NIRS, prefrontal cortex

INTRODUCTION

Parenting stress is a multidimensional construct that poses an indubitable barrier to optimal parenting behaviours [1]. Caregiving demands that tax the parent beyond his/her psychological resources frequently lead to elevated stress levels which precipitate parental hostility and reduce dyadic reciprocity in parent-child relationships (e.g., [2][3][4]). The prevailing theoretical model, as evidenced by several empirical studies, posits parenting stress to be composed of two core structures that include parental and child domains [5]–[7]. This model lends support to the notion of two different yet related dimensions of parenting stress. However, to render these complex dimensions quantifiable, operational definitions of parenting stress are aligned to the subscales in instruments such as the Parenting Stress Index - Short Form (PSI-SF; [8]. The PSI-SF comprises a three-factor solution, namely the parental distress scale (PD), difficult child (DC) scale and the parent–child dysfunctional interaction (PCDI) scale. While PD mirrors the parental domain of parenting stress and focuses on the distress that the parent undergoes due to inhabiting the role of a parent, DC and PCDI reflects the child domain that chiefly quantifies the parent's impression of whether the child is difficult to rear and the degree to which the parent is content with the interactions that he/she has with the child, respectively [9]. Differentiating between these sources of stress may clarify the mechanisms by which parenting stress undermines the development of parent-child relationships.

Synchrony, the reciprocal matching of signals between two individuals [10], is postulated to be central to the formation of healthy dyadic bonds. Matched responses between a parent and child that manifest behaviourally in the form of reciprocal gazes and turn-taking often indicate that dyadic partners are sensitive to each other's emotional responses [11]. Over time, these overt reciprocal behaviours may become entrained into underlying neurophysiological patterns of synchrony that is unique to the dyad. However, the quality of synchrony in a parent-child relationship is not immune to adverse psychological factors, the primary of which is parenting stress. At the behavioural level, copious amounts of parenting stress hinder sensitive parental responses that impede synchronous interactional exchanges [12][13]. Recently, we have shown that parenting stress impairs synchrony at the neurophysiological level [14]. In a study on mother-child dyads, greater overall parenting stress was found to lead to diminished brain-to-brain synchrony in the medial left cluster of the prefrontal cortex (PFC) when the pair engaged in a typical passive activity of watching animation shows together [14]. We postulated that parenting stress undermined the mother's ability to discern and infer the emotional experiences of her child which subsequently underpinned the lack of synchrony amongst highly stressed mothers.

However, we have yet to investigate whether a similar mechanism of diminished brain-to-brain synchrony would be observed amongst stressed fathers in the same context of passive dyadic engagement. Mothers and fathers differ in regard to the stresses involved in parenting [15][16]. Several studies have demonstrated that child domains, namely negative child temperament, have a sizable effect on mother's parenting stress [16][17][18]. This association has been attributed to the fact that, compared to fathers, mothers are more sensitive to their child's emotional state. Conversely, sources of stress in the parental domain seem to have a larger influence on fathers. Fathers are more prone to viewing parenthood as an experience that limits their personal freedom, which is purported to stem from how parenthood is often viewed as a sphere that is independent of fathers' personal identity [8]. Given that the experience of parenting stress differs across mothers and fathers, the notion that it exerts disparate mechanisms on father-child and mother-child neurophysiological synchrony is plausible.

The present study sought to examine how brain-to-brain synchrony of father-child dyads varies as a function of father's self-reported parenting stress on the PSI-SF questionnaire. Brain activities of the prefrontal cortex (PFC), recognised for its socio-cognitive functions [19], would be recorded using tandem functional Near-infrared Spectroscopy (fNIRS) when dyads engaged in the same empirical paradigm as that of [14], where they watched animation shows together. We embarked on this study with two hypotheses. First, similar to [14], we expected parenting stress to manifest as reduced synchrony in brain regions that are encompassed within the medial left cluster of the PFC, an area responsible for mentalising processes. Second, rather than the total parenting stress being associated with synchrony, we expected the parental distress (PD) subscale to significantly influence synchrony instead due to greater perceived lack of freedom commonly experienced by fathers compared to mothers.

METHOD

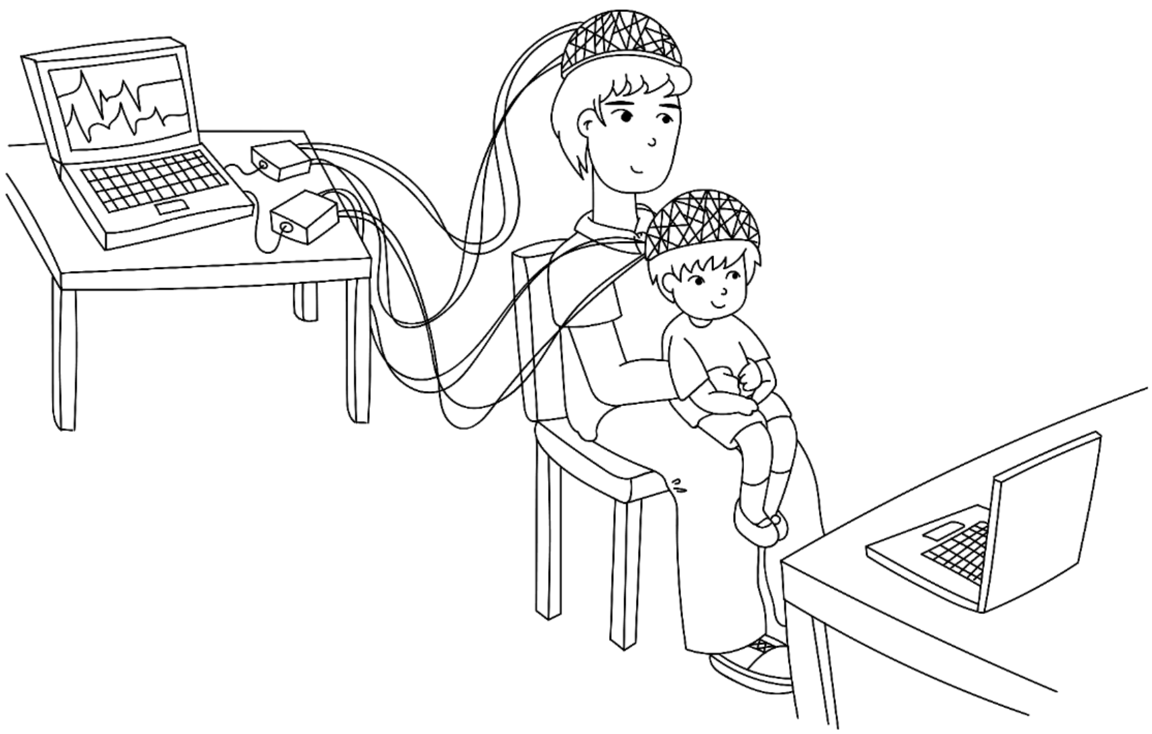
Participants

29 father-child dyads (11 girls, 18 boys) were recruited for this study through online platforms such as Facebook groups and forums (Mean age of fathers = 38.1 years, ± 3.67 years; Mean age of children = 42.2 months, ± 5.25 months). To be eligible for this study, fathers had to be at least 21 years old with a child aged between 36 and 48 months at recruitment. Both father and child were screened for any cognitive deficits as well as visual and hearing impairments so as to ensure that they were able to respond to the empirical tasks. Before the study commenced, informed consent was obtained from all participants (fathers signed on behalf of their child). Remuneration was provided at the end of the study to compensate for their gracious participation. All procedures were abided by relevant guidelines and were approved by the Institutional Review Board of Nanyang Technological University (IRB NTU-IRB-2018-06-016). All data are available at this URL: https://doi.org/10.21979/N9/PFHB88

Experimental procedure

This two-part study consisted of a home-based questionnaire and an experimental laboratory session. Prior to attending the laboratory session, fathers completed an online questionnaire consisting of a 36-item Parenting Stress Index-Short Form (PSI-SF)[8] and a brief demographic survey. After completing the questionnaire, both father and child were invited to the laboratory where they watched three video clips while their PFC activities were being recorded with functional Near-infrared Spectroscopy (fNIRS) in hyperscanning mode. The child sat on the father's lap throughout the duration of the study (Fig. 1). NIRS caps of suitable sizes were fitted on the head of both the father and child. Optodes were adjusted and the signal quality was calibrated on the laptop prior to commencing with the study. As the devices were being set up, the child was distracted by a short 1-min video clip from the movie 'Moana' which was screened on a second laptop. This second laptop was placed approximately 40cm from the dyad and was also used to present the three video clip stimuli. When the session was concluded, fathers were debriefed and remuneration was provided to the participants.

Figure 1. Schematic diagram and experimental set-up and seating arrangement of father and child. Figure illustrated by Farouq Azizan.



Parenting stress index - short form (PSI-SF)

The Parenting Stress Index - Fourth Edition (PSI-4) [20] is a 36-item instrument that measures perceived parenting stress in parents who have children between the ages of 1 to 12 years old. The PSI-SF is a condensed version of the original PSI and is composed of three subscales: Parental Distress (PD), Difficult Child (DC) and Parent-Child Dysfunctional Interaction (PCDI). The PD subscale consists of 12 items that quantifies personal factors that are related to the stress that the parent experiences, including perceived lack of freedom due to inhabiting the role of a parent (e.g. ‘Since having my child I have been unable to try new and different things.’). The DC subscale is composed of 12 items that measures the extent to which the parent perceives the characteristics of the child to be challenging (e.g. ‘My child generally wakes up in a bad mood.’). The PCDI subscale consists of 12 items that evaluates the degree to which the parent derives satisfaction from interacting with the child and whether the child is perceived to meet his expectations. For each item, the parent rates his response on a sale from 1 (strongly disagree) to 5 (strongly agree). Finally, the sum of the three subscales amounts to the total parenting stress that the parent experiences. Previous studies have found the PSI-SF to be reliable (alpha coefficient of 0.98) [14] [21]–[23] and has also been used with fathers [24]. The PSI index was also used as a self-report measure of parenting stress in our previous study on mother-child dyads [14]. However, [14] only examined the total parenting stress score, whereas the present study would investigate the three individual subscales of the PSI index (i.e. PD, PCDI and DC) to ascertain the sources of parenting stress that affect father-child brain-to-brain synchrony.

Video stimuli

The video stimuli used in this study are the same as that from our previous study on mother-child dyads [14]. Father-child pairs were instructed to watch three 1-min excerpts of Brave, Peppa Pig and The Incredibles. To generalise the task of watching animation shows together, these clips were specifically chosen due to their different emotional valences and audiovisual qualities, which later served as control variables. The clips were edited to ensure they were of similar volume and brightness. Prior to the onset of the first video clip, a 5-sec fixation cross was added. Between subsequent video clips, a 10-sec fixation cross was included (Fig. 2). The videos were presented in a pseudo-random order, where six different sequences of clips were first created before dyads were randomly assigned to one of the six sequences. The videos were screened on a 15-inch Acer Laptop in a dimly lit room. Both brightness and volume on the laptop were set to 60%.

Three aspects of the video clips were analysed and included as controls: i) video complexity, ii) audio intensity and fundamentals, and iii) emotional valence (i.e. positivity rating). The values of these parameters are reported in Table 1. Video complexity of each clip was analysed using Python and the FFmpeg software (v. 3.4.4) at a rate of 12 frames per second (FPS). To evaluate audio-related information, the video files were first converted into audio files using FFmpeg. Then, Praat software (v. 6.0.46) was used to measure audio intensity and audio fundamentals of the clips. To quantify emotional valence, each second of the clip was given a positivity rating by two independent coders. The sum of the second by second ratings throughout the 1-min clip was used as the final positivity rating of that clip.

Figure 2. Schematic flow of stimuli presentation. The order in which the three video clips were screened to participants was pseudo-randomised.

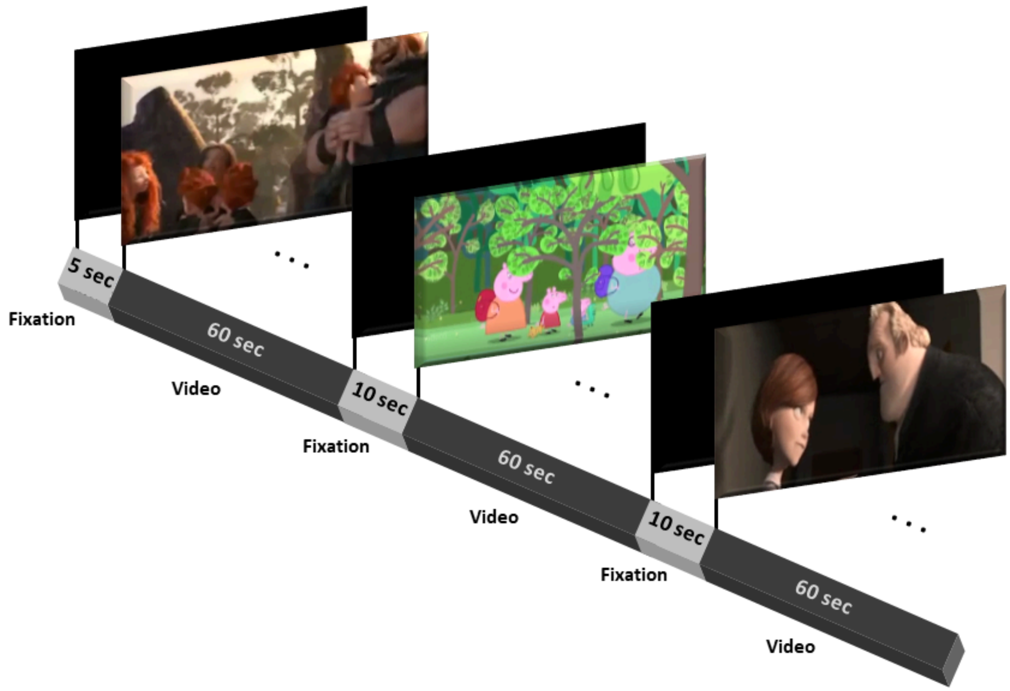


Table 1. Table reporting the video complexity, audio fundamentals, audio intensity, and positivity ratings of the three video clips.

Video Stimulus	Video Complexity (bytes)	Audio Fundamentals (Hz)	Audio Intensity (W/m^2)	Positivity Ratings
Brave	658119.31	245.26	59.89	45
Peppa Pig	468369.81	218.37	62.50	59
The Incredibles	423005.66	271.64	56.30	-54

Functional near-infrared spectroscopy (fNIRS) data acquisition

fNIRS experimental set-up and pre-processing

fNIRS was used to measure changes in concentration of oxygenated haemoglobin which served as a proxy of brain activation [25]. An fNIRS neuroimaging system (NIRSport, NIRx Medical Technologies LLC) with a 20-channel prefrontal cortex montage (NIRStar v.205 software), consisting of 8 sources and 7 detectors, was used in this study. LED sources of 760 nm and 850 nm wavelengths were applied at a scan rate of 7.81 Hz.

NIRSLab (nirsLAB v.2017.06) was used to preprocess the collected data. The preprocessing stream began with the setting of onset markers of the three video stimuli. Following that, motion correction of discontinuities and spike artefacts were conducted. Channels were then inspected for background noise, where those with Gain > 8 and CV > 7.5 were rejected and omitted from downstream preprocessing steps. To remove physiological and slow signals, a 0.01Hz to 0.2Hz bandpass filter was applied. The resulting signals were further inspected for undetected artifacts by two independent coders. Finally, the preprocessed optical signals were converted into changes in oxygenated (HbO) and deoxygenated (HbR) haemodynamic signals using the modified Beer-Lambert Law.

Analytical Plan: Synchrony Analyses

Dynamic Time Warping (DTW)

Similarities in brain activation patterns between father and child pairs were measured with a Dynamic Time Warping (DTW) algorithm. DTW[26] in R studio (version 1.0.153, R-core 3.4.2) was applied to pre-processed time-series signals of father and child. This algorithm allows for optimal arrangement and alignment of all sequence points between the two signals [27]. DTW calculates a distance index which reflects the cost function of matching any two sequences. Dissimilar signals would incur a greater cost which translates to a distance index of a bigger magnitude. The greater the distance index, the lesser the synchrony between the two members of the father-child dyad [26]. The DTW settings in the present study replicate the ones used in our previous study on mother-child pairs [14]. The distance indexes that were obtained were normalised so that they ranged between 0 and 1.

Descriptive analyses

The means and standard deviations of the distance indices for all channels would be reported.

Preliminary analysis

Preliminary analyses would be conducted on the distance index of each channel to examine the influence of demographic variables (i.e. child's sex, child's age) and stimuli variables (i.e. video positivity ratings) on PFC responses. For each channel, three separate models with child's sex, child's age, and video positivity ratings as the independent variables were run. For each model, video complexity and audio fundamentals were incorporated as covariates.

Inferential analyses

Multiple linear regression analysis were conducted for each channel. Similar to the beta-coefficient analyses, distance index was incorporated as the independent variable, parenting stress score was the independent variable, while video complexity and audio fundamentals were the controls. Each scale from the PSI questionnaire was fitted independently in separate models. (i.e., Distance Index = Parenting Distress + (Video Complexity + Audio Fundamentals)).

Analytical Plan: Beta-Coefficient Analyses

General linear model (GLM)
Using NIRSLab (nirsLAB v.2017.06), a within-subject GLM was performed so as to extract beta-coefficients for each of the three video stimuli, from each child and parent. The same GLM settings as [14] were used. Similarly, pre-whitening was omitted and a haemodynamic response function (HRF) was specified. A Discrete Cosine Transformation (DCT) temporal parameter with a 128 sec high-pass period cut-off and a Gaussian Full Width at Half Maximum (FWHM) 4 model were applied to the GLM. Beta-coefficients from each of the 20 channels were extracted from all participants. Within each participant, beta-coefficients were aggregated across the three video stimuli.

Descriptive analyses
Descriptive statistics of the averaged beta values in each of the 20 channels would be reported for both fathers and children.

Preliminary analyses
R studio (version 1.0.153, R-core 3.4.2) was used to analyse all data in this study. Preliminary analyses were conducted to investigate whether demographic variables (i.e. child's sex, child's age) and stimuli variables (i.e. video positivity ratings) were associated with either child's or father's beta-coefficient values for each channel. Therefore, three separate preliminary statistical models, with child's sex, child's age, and video positivity ratings as the independent variables, were run for each channel. This set of preliminary analyses was conducted for both child's and father's beta-coefficient values. To account for differences in video complexity and audio fundamentals across the three videos, these variables were fitted as covariates in all models.

Inferential analyses
To account for different brain activation patterns between groups of fathers and that of children, multiple linear regression analysis was performed on each channel, for fathers and children, separately. For each model, beta values were fitted as the dependent variable, parenting stress score was included as the independent variable while video complexity and audio fundamentals served as controls. Only one scale of the PSI constituted a factor in the model at any one time (i.e., Beta = Parenting Distress + (Video Complexity + Audio Fundamentals)). As these analyses do not address our main research questions, results from these analyses would be reported in the *Supplementary Materials*.

Results

Synchrony Analyses

Descriptive results

The means and standard deviations of distance indices are reported along with data on demographic variables in Table 2 (see *Supplementary Materials*).

Preliminary results

Three different preliminary analyses were conducted on each channel to investigate the effects of video positivity, child’s age and child’s sex on distance index. Variables which were found to be significant were included as a control in the inferential analyses. Child's age had a significant association with distance index in channel 15 (CH15; $R2=0.0673$, $F(3,29)=1.769$, $p=0.049$) and was subsequently incorporated as a control in the inferential models of CH15. Neither video positivity nor child’s sex had a significant associaiton in any channel.

Inferential Results

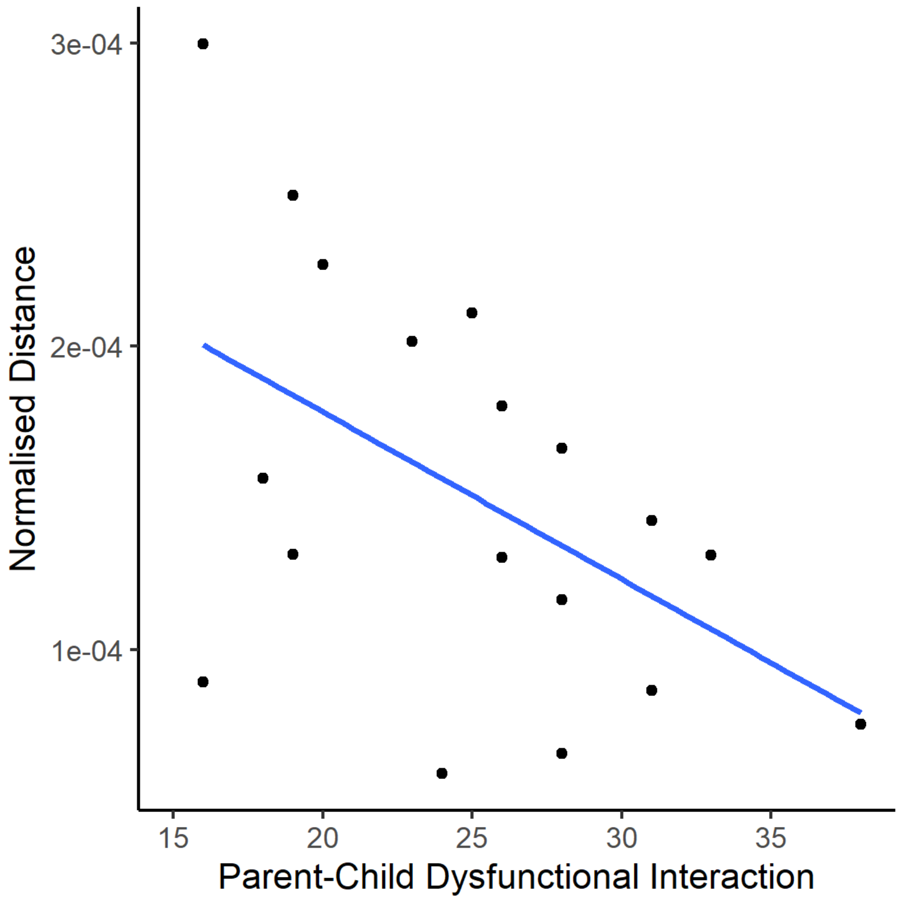
To test whether parenting stress influenced father-child brain-to-brain synchrony, multiple linear regression was conducted for each subscale (Parenting Distress, Parent-child Dysfunctional Interaction, Difficult Child) and total parenting stress score. Across all regression models, distance index was the dependent variable, and video complexity and audio fundamentals were held constant.

Parenting Distress was associated with distance index in Channel 14 (CH14) only ($R2=0.0384$, $F(3,58)=1.811$, $p=0.0429$). This channel maps to the right middle frontal gyrus. However, a follow-up Pearson’s product moment correlation test did not elicit significant results ($r= -0.256$, $p=0.2741$).

Parent-Child Dysfunctional Interaction was significantly associated with distance index in CH12 ($R2=0.0348$, $F(3,50)=1.637$, $p=0.0489$) and CH13 ($R2= 0.0977$, $F(3,56)=3.128$, $p=0.0216$). The former channel corresponds to the medial rostral area of Brodmann Area 10 (BA10) while the latter corresponds to the right rostral area of BA10. In CH12, Pearson’s product moment correlation test ascertained that parent-child dysfunctional interaction had a significant negative correlation with distance index ($r=-0.506$, $p=0.0321$) (Fig. 3). Since distance score is inversely related to synchrony, higher parent-child dysfunctional interaction was associated with higher synchrony in the medial rostral area of BA10. In CH13, Pearson’s product moment correlation test did not generate a significant association between parent-child dysfunctional interaction and distance index ($r=-0.395$, $p= 0.085$).

There was no significant effect of Difficult Child subscale or total parenting stress score on distance index in any of the channels.

Figure 3. Scatterplot depicting correlation between parent-child dysfunctional interaction score and distance index in Ch12 ($r=-0.506$, $p=0.0321$), which corresponds to the medial rostral area of BA10.



Beta-coefficient Analyses

To evaluate the effects of parenting stress on father and child brain responses separately, multiple linear regression was conducted for each subscale (Parenting Distress, Parent-child Dysfunctional Interaction, Difficult Child) and total parenting stress score (see *Supplementary Materials* for results).

Discussion

Given the extensive demands of caregiving, most mothers and fathers inevitably experience some parenting stress in the course of parenthood [28]. The present study aimed to examine how different sources of parenting stress influence father-child brain-to-brain synchrony in the prefrontal cortical (PFC) region when they engaged in a passive everyday activity of watching animation shows together. Parenting stress was evaluated using a self-reported Parenting Stress Index (PSI) inventory which consisted of three subscales, namely

Parenting Distress, Parent-Child Dysfunctional Interaction and Difficult Child. Drawing from our previous findings on mother-child dyads [14], we postulated two hypotheses for the present study. First, we expected parenting stress to undermine synchrony in the PFC region that is critical for mentalising the emotions of others, particularly the medial left areas. However, this hypothesis was not fulfilled. Instead, we observed an increase in synchrony in one specific area, that is the medial frontopolar/rostral PFC that falls within the domain of Brodmann Area 10 (BA10). Second, we hypothesised that father's self-reported parenting distress would influence synchrony the most compared to other sources of parenting stress. This second hypothesis was not fulfilled either as higher self-reported parent-child dysfunctional interaction (PCDI), instead of PD, was associated with increased synchrony in the medial frontopolar/rostral area of the PFC. This area of the brain is shown to be recruited for stimulus-oriented attention, which suggests that dyads with higher dysfunctional interaction tend to focus on the sensory input that they receive during the shared activity [29], [30].

Dyads in which the father reported higher dissatisfaction with the interactions he had with his child exhibited greater synchrony in the brain area responsible for stimulus-oriented (SO) processing, which may detract dyads from stimulus-independent (SI) attention that facilitates attunement to each other's emotional states. Tasks that demand vigilance and processing of sensory stimuli, which the activity of watching animation shows fall into, typically recruit SO attention. Conversely, self-engendered cognitions that are incited by the stimuli but goes beyond the available sensory input, such as memories and mentalisation processes, employ SI attention . However, it is essential to note that these distinctions are not definitive and tasks may elicit varying extents of either stimulus-oriented or -independent attention. provided the example of attending a lecture which is a task that primarily requires SO attention, although SI attention may be involved, such as when an individual ponders what he/she should have for lunch or how difficult his/her classmates perceive the lecture material to be. Similarly, when dyads in the present study watched animation shows together, they exhibited varying extents of brain-to-brain synchrony in an area implicated in SO attention. Supporting this explanation is a predominant "gateway hypothesis" in the extant literature regarding the rostral-caudal distinction of BA10 functions, which posits SO to be associated with the medial rostral regions, while SI is facilitated by the caudal domains during low-demand tasks [31]–[33]. For instance, in an fMRI study that required participants to switch between mentalising and non-mentalising tasks, [30] demonstrated that SO non-mentalising tasks demanded the recruitment of rostral regions of BA10 while mentalising tasks recruited caudal regions. Since enhanced synchrony among dysfunctionally interacting pairs was found in the medial rostral area, dyads with impaired interactions may be more preoccupied with SO processing of sensory input rather than SI cognition, such as mentalising the emotions of the other member of the dyad.

Fathers who reported impaired dyadic interactions are likely discontented with the affiliation they experience with their child. Such stress and dissatisfaction are often accompanied by less sensitive parent-child attunement [28][34][35]. The stimulus-driven synchrony observed in dyads with higher reported dysfunctional interaction potentially indicates reduced mentalisation in the fathers of these dyads [36]. "Mind-mindedness", a mentalisation process by which parents attend to and infer the emotional states of their child, is postulated to chiefly support sensitive parent-child attunement [36][37][38]. We posit that over-attending to sensory aspects (i.e. SO attention) of a dyadic activity might undermine fathers' cerebral "mind-mindedness" (i.e. SI attention) which manifest behaviourally as less attuned parent-child interactions. For instance, fathers who devote more attention to sensory aspects of an activity might simply engage in less mentalisation processes which reduces their ability to sensitively respond to their child, a limitation which compromises the quality of parent-child interactions over time. Conversely, over-attending to sensory input might instead reflect a coping mechanism in dyads with impaired parent-child interactions as an attempt to participate in joint activities without actively engaging with each other on an emotional level. These postulations remain largely theoretical and further research is required to explicate the mechanisms underpinning stimulus-driven synchrony with mentalisation and dysfunctional parent-child relationships.

Contrasting the present findings against that of our previous study [14], it is evident that parenting stress affects brain-to-brain synchrony in both father-child and mother-child dyads. In mother-child pairs, [14] found that parenting stress was associated with diminished brain-to-brain synchrony in the medial left cluster of the PFC which is largely recruited for mentalisation processes. This result suggests that mothers who experience greater parenting stress are less able to synchronise their emotional states to that of their child. In the present study on father-child dyads, we found that parenting stress that stemmed from dyadic dysfunctional interaction was accompanied by increased brain-to-brain synchrony in the medial rostral area of the brain that is responsible for stimulus-oriented attention. In line with the previous study on mother-child pairs, this finding suggests that stimulus-independent attention, such as mentalisation of the child's emotional state, occurred less in highly stressed fathers.

Several limitations ought to be assessed in this study. First, paternal parenting stress was evaluated using a self-report questionnaire which reduced the objectivity of the measure of stress. For instance, scores could have reflected fathers' social desirability bias or participants' tendency to report expected normative levels of stress. Despite this limitation, parenting stress is arguably a subjective experience that renders self-reported accounts of stress phenomenologically valid. Second, the area of the brain that was investigated was only restricted to the prefrontal cortex. Brain-to-brain synchrony could have spanned across other cortical and subcortical regions which belong to specific networks that are implicated in mentalisation processes. Some examples of brain areas involved in mentalisation include cortical structures such as the temporal cortex and subcortical areas like the amygdala [39]–[41]. Future studies may adopt more extensive brain montages when conducting neurophysiological synchrony studies. Third, this study did not include a manipulation to determine the effects of physical contact between the father and child. Having the child on the father's lap could have incurred a significant effect of touch on synchronous brain responses. Future studies should also examine synchrony in dyads when they are seated side-by-side to ensure that touch is controlled in the experimental design.

Conclusion

While childrearing is a joyous experience for most, parents are bound to encounter some amount of parenting stress in their lives. The current body of literature has ascertained that parenting stress reduces parent-child synchrony and impairs the quality of this relationship [12], [13]. However, the mechanisms underlying this association are poorly understood. In this study, we extended our previous investigation on mother-child pairs [14] to examine brain-to-brain synchrony in father-child pairs with the same empirical paradigm. Our findings suggest that dyads in which the father reports more parenting stress, stemming from dysfunctional interactions, exhibit greater synchrony in stimulus-oriented attention. Greater engagement with sensory aspects of a joint activity might render dyads with less opportunity for stimulus-independent attention that facilitates emotional attunement. This finding provides significant insight to our understanding of how parenting stress undermines sensitive responses in father-child dyads.

Supplementary Materials

Synchrony Analyses

Descriptive Results

The means and standard deviations of distance indexes are reported in Table 2.

Table 2. Table reporting the mean and standard deviation of distance index for each channel, along with sample size and demographic variables.

Channel	Brain Area	Mean Distance Index	Standard Deviation	*N*	Child's Sex	Child's Age (in months)	Father's Age (in years)
1	Left middle frontal gyrus, part of BA46	0.000211	0.000166	10	Male = 6, Female = 4	41.4 ± 5.441	36.6 ± 3.534
2	Left lateral PFC, part of BA46	0.000201	0.000190	13	Male = 8, Female = 5	41.769 ± 5.46	37.154 ± 3.412
3	Left inferior frontal cortex; part of BA45	0.000171	0.000140	19	Male = 12, Female = 7	42.579 ± 5.242	37.526 ± 3.717
4	Left inferior frontal cortex; part of BA47	0.000165	0.000140	21	Male = 12, Female = 9	42.810 ± 5.326	37.667± 3.624

5	Left lateral dorsolateral PFC; part of BA09	0.000239	0.000178	6	Male = 3, Female = 3	40.5 ± 3.564	36.5 ± 4.135
6	Left anterior PFC; part of BA10	0.000157	0.000143	17	Male = 9, Female = 8	42 ± 4.962	37.059 ± 3.288
7	Left middle frontal gyrus, part of BA46	0.000122	9.446 e-05	13	Male = 8, Female = 5	41.231 ± 5.052	38.077 ± 3.662
8	Left frontal eye fields; part of BA08	0.000217	0.000182	12	Male = 6, Female = 6	42.75 ± 4.731	37.917 ± 3.7774
9	Left medial PFC in superior frontal gyrus; part of BA09	0.000152 221	9.792925 e-05	8	Male = 4, Female = 4	41.125 ± 4.73399 6	37.375 ± 3.622844
10	Right frontal eye fields; part of BA08	0.000172	0.000115	13	Male = 9, Female = 4	40.385 ± 4.35	38.538 ± 3.573
11	Left rostrolateral PFC; part of BA10	0.000198	0.000184	21	Male = 14, Female = 7	42.333 ± 5.132	37.286 ± 3.58
12	Medial rostral PFC; part of BA10	0.000151	0.000122	16	Male = 11, Female = 1	40.688 ± 4.127	37.375 ± 3.344
13	Right rostrolateral PFC; part of BA10	0.000142	0.000120	19	Male = 11, Female = 8	41.895 ± 4.965	38.053 ± 3.719
14	Right middle frontal gyrus, part of BA46	0.000130	0.000129	21	Male = 12, Female = 9	42.048 ± 5.258	37.714 ± 3.797
15	Right lateral dorsolateral PFC; part of	0.000135	9.877 e-05	11	Male = 5, Female = 6	41.273 ± 5.515	37.455 ± 3.297

	BA09						
16	Right anterior PFC; part of BA10	0.000161	0.000119	19	Male = 10, Female = 9	41.632 ± 4.621	37.737 ± 3.798
17	Right lateral PFC, part of BA46	0.000163	0.000116	17	Male = 11, Female = 6	43 ± 5.948	37.529 ± 3.81
18	Right middle frontal gyrus, part of BA46	0.000170	0.000165	14	Male = 8, Female = 6	40.643 ± 4.765	36.286 ± 3.268
19	Right inferior frontal cortex; part of BA47	0.000188	0.000146	21	Male = 12, Female = 9	42.81 ± 5.326	37.667 ± 3.624
20	Right inferior frontal cortex; part of BA45	0.000165	0.000136	18	Male = 10, Female = 8	41.722 ± 4.663	37.333 ± 3.835

Beta-Coefficient Analyses

Descriptive Results
The means and standard deviations of the beta coefficients of fathers and children are reported in Tables 3 and 4, respectively.

Table 3. Table reporting the mean and standard deviation of fathers' beta coefficient values for each channel, along with sample size and demographic variables.

Channel	Brain Area	Mean Beta Coefficient	Standard Deviation	*N*	Child's Sex	Child's Age	Father's Age
1	Left middle frontal gyrus, part of BA46	-3.905 e-05	0.000221	17	Male = 10, Female = 7	42.412 ± 5.853	36.588 ± 3.337
2	Left lateral PFC, part of BA46	-2.409 e-05	0.000215	16	Male = 10, Female = 6	41.688 ± 5.056	36.563± 3.669

3	Left inferior frontal cortex; part of BA45	-5.622 e-06	0.000278	23	Male =13, Female =10	42.130 ± 5.057	37.087 ± 3.753
4	Left inferior frontal cortex; part of BA47	-2.117 e-05	0.000271	27	Male =16, Female =11	42.481 ± 5.345	37.185 ± 3.659
5	Left lateral dorsolateral PFC; part of BA09	5.373 e-06	0.000201	17	Male =10, Female =7	42.118 ± 5.84	37.588 ± 3.938
6	Left anterior PFC; part of BA10	1.572 e-05	0.000178	24	Male = 13, Female = 11	42.292 ± 5.505	37 ± 3.489
7	Left middle frontal gyrus, part of BA46	1.496 e-05	0.000165	21	Male =12, Female = 9	42.571 ± 5.591	37.571 ± 3.88
8	Left frontal eye fields; part of BA08	-2.054 e-05	0.000233	16	Male =10, Female =6	43.313 ± 5.437	37.938 ± 3.642
9	Left medial PFC in superior frontal gyrus; part of BA09	-4.788 e-05	0.000488	16	Male = 8, Female = 8	43.25 ± 5.495	37.813 ± 3.563
10	Right frontal eye fields; part of BA08	1.44 e-05	0.000161	21	Male = 14, Female = 7	42.667 ± 5.73	37.667 ± 3.367
11	Left rostrolateral PFC; part of BA10	2.663 e-05	0.000286	27	Male = 17, Female = 10	42.481 ± 5.345	37.222 ± 3.672
12	Medial rostral PFC;	6.228 e-06	0.000153	26	Male =15 , Female = 11	42.154 ± 5.289	36.808 ± 3.51

	part of BA10						
13	Right rostrolateral PFC; part of BA10	-5.339 e-05	0.000265	25	Male = 14, Female = 11	41.92 ± 4.949	37.36 ± 3.785
14	Right middle frontal gyrus, part of BA46	-1.427 e-05	0.000133	24	Male = 14, Female = 10	42.542 ± 5.672	37.583 ± 3.682
15	Right lateral dorsolateral PFC; part of BA09	-1.567 e-05	0.000185	18	Male = 11, Female = 7	42.222 ± 5.857	37 ± 3.343
16	Right anterior PFC; part of BA10	-7.714 e-06	0.000231	24	Male = 13, Female = 11	41.5 ± 4.77	37.167 ± 3.875
17	Right lateral PFC, part of BA46	-2.907 e-05	0.000208	18	Male = 12, Female = 6	43.111 ± 5.789	37.611 ± 3.712
18	Right middle frontal gyrus, part of BA46	-4.915 e-05	0.000191	19	Male = 11, Female = 8	41.89474 ± 5.065074	36.36842 ± 3.200877
19	Right inferior frontal cortex; part of BA47	-3.241 e-05	0.000252	26	Male = 15, Female = 11	42.692 ± 5.335	37.154 ± 3.728
20	Right inferior frontal cortex; part of BA45	5.982 e-06	0.000214	22	Male = 12, Female = 10	42.545 ± 5.484	36.955 ± 3.836

Table 4. Table reporting the mean and standard deviation of childrens' beta coefficient values for each channel, along with sample size and demographic variables.

Channel	Brain Area	Mean Beta Coefficient	Standard Deviation	*N*	Child's Sex	Child's Age	Father's Age

1	Brain Area	-9.316 e-06	0.000310	17	Male = 10, Female = 7	42.411 ± 5.853	36.588 ± 3.337
2	Left middle frontal gyrus, part of BA46	4.210 e-06	0.000258	16	Male = 10, Female = 6	41.688 ± 5.056	36.563± 3.669
3	Left lateral PFC, part of BA46	-5.095 e-05	0.000299	23	Male = 13, Female = 10	42.130 ± 5.057	37.087 ± 3.753
4	Left inferior frontal cortex; part of BA45	-4.4238 e-05	0.000382	27	Male = 16, Female = 11	42.481± 5.345	37.185 ± 3.659
5	Left inferior frontal cortex; part of BA47	4.545 e-06	0.000188	17	Male = 10, Female = 7	42.118 ± 5.840	37.588 ± 3.938
6	Left lateral dorsolateral PFC; part of BA09	2.827 e-06	0.000165	24	Male = 13, Female = 9	42.2927 ± 5.505	37 ± 3.489
7	Left anterior PFC; part of BA10	-2.0241 e-05	0.000151	21	Male = 12, Female = 9	42.571 ± 5.591	37.571 ± 3.880
8	Left middle frontal gyrus, part of BA46	-5.0816 e-08	0.000307	16	Male = 10, Female = 6	43.313 ± 5.437	37.938 ± 3.642
9	Left frontal eye fields; part of BA08	2.602 e-05	0.000218	16	Male = 8, Female = 8	43.25 ± 5.495	37.813 ± 3.563
10	Left medial PFC in superior frontal gyrus; part of BA09	-2.949 e-05	0.000246	21	Male = 14, Female = 7	42.667 ± 5.730	37.667 ± 3.367

11	Right frontal eye fields; part of BA08	-3.06 e-05	0.000261	27	Male = 17, Female = 10	42.481 ± 5.345	37.222 ± 3.672
12	Left rostrolateral PFC; part of BA10	4.281 e-05	0.000314	26	Male = 15, Female = 11	42.154 ± 5.289	36.808 ± 3.51
13	Medial rostral PFC; part of BA10	-7.207 e-05	0.000321	25	Male = 14, Female = 11	41.92 ± 4.949	37.36 ± 3.785
14	Right rostrolateral PFC; part of BA10	-8.422 e-06	0.000222	24	Male = 14, Female = 10	42.542 ± 5.672	37.583 ± 3.682
15	Right middle frontal gyrus, part of BA46	-4.214 e-05	0.000223	18	Male = 11, Female = 7	42.222 ± 5.857	37 ± 3.343
16	Right lateral dorsolateral PFC; part of BA09	-9.949 e-06	0.000260	24	Male = 13, Female = 11	41.5 ± 4.77	37.167 ± 3.875
17	Right anterior PFC; part of BA10	-2.413 e-05	0.000274	18	Male = 12, Female = 6	43.111 ± 5.789	37.611 ± 3.712
18	Right lateral PFC, part of BA46	2.078 e-06	0.000247	19	Male = 11, Female = 8	41.895 ± 5.066	36.368± 3.201
19	Right middle frontal gyrus, part of BA46	-7.152 e-05	0.000297	26	Male = 15, Female = 11	42.692 ± 5.336	37.154± 3.728
20	Right inferior	-2.584 e-05	0.000257	22	Male = 12, Female = 10	42.545 ± 5.484	36.955± 3.836

	frontal cortex; part of BA47						

Preliminary results

Three preliminary sets of analyses were conducted on each channel to investigate the effects of video positivity, child's age and child's sex on father's beta values. These preliminary analyses were conducted once again for child's beta values.

The preliminary analyses on father's beta coefficients revealed a significant effect of child's age in Channel 3 (CH3; $R2=0.0191$, $F(3,83)=1.557$, $p=0.0393$), CH5 ($R2=0.0596$, $F(3,83)=2.817$, $p=0.00745$), CH7 ($R2=0.0418$, $F(3,83)=2.25$, $p=0.0125$), CH9 ($R2=0.0264$, $F(3,83)=1.777$, $p=0.0372$), CH11 ($R2=0.0344$, $F(3,83)=2.022$, $p=0.0312$) and CH 14 ($R2=0.0363$, $F(3,83)=2.081$, $p=0.0159$). Therefore, child's age would be included as a control variable in these channels. Neither video positivity nor child's sex was associated with father's beta coefficients in any channel. Across all three models, video complexity emerged as a significant variable in CH8 ($R2=0.0287$, $F(3,83)=1.847$, $p=0.0472$). Video complexity was already included as a control in all inferential models.

Meanwhile, the preliminary analyses on child's beta coefficient showed a significant of video positivity ratings in CH3 ($R2=0.0472$, $F(2,84)=3.13$, $p=0.015$), CH10 ($R2=0.0659$, $F(2,84)=4.035$, $p=0.0134$), CH11 ($R2=0.041$, $F(2,84)=2.836$, $p=0.0429$), CH13 ($R2=3.511$, $F(2,84)=2.836$, $p=0.00963$) and CH14 ($R2=0.0435$, $F(2,84)=2.957$, $p=0.0179$). Child's age had a significant effect in CH14 ($R2=0.0783$, $F(3,83)=3.437$, $p=0.0443$) and CH17 ($R2=0.0435$, $F(3,83)=3.231$, $p=0.0184$), whereas child's sex had a significant effect in CH10 ($R2=0.211$, $F(3,83)=8.682$, $p=0.00011$. These variables were incorporated as controls in the inferential models for channels in which they emerged to be significant. Across child's age and child's sex preliminary models, the covariate audio fundamentals was found to be a significant variable in CH3 ($R2=0.0378$, $F(3,83)=2.127$, $p=0.0155$), CH10 ($R2=0.2113$, $F(3,83)=8.682$, $p=0.00734$), CH11 ($R2=0.0729$, $F(3,83)=3.256$, $p=0.0396$), CH13 ($R2=0.0629$, $F(3,83)=2.924$, $p=0.00937$), CH14 ($R2=0.0390$, $F(3,83)=2.163$, $p=0.0182$) and CH18 ($R2=0.0482$, $F(3,83)=2.451$, $p=0.0305$). However, audio fundamentals were already controlled for in all inferential models.

Inferential Results

To test whether parenting stress influenced fathers' and childrens' brain responses, multiple linear regression was conducted for each subscale (Parenting Distress, Parent-child Dysfunctional Interaction, Difficult Child) and total parenting stress score. Across all regression models, beta coefficients were fitted as the dependent variable, and video complexity and audio fundamentals were held constant.

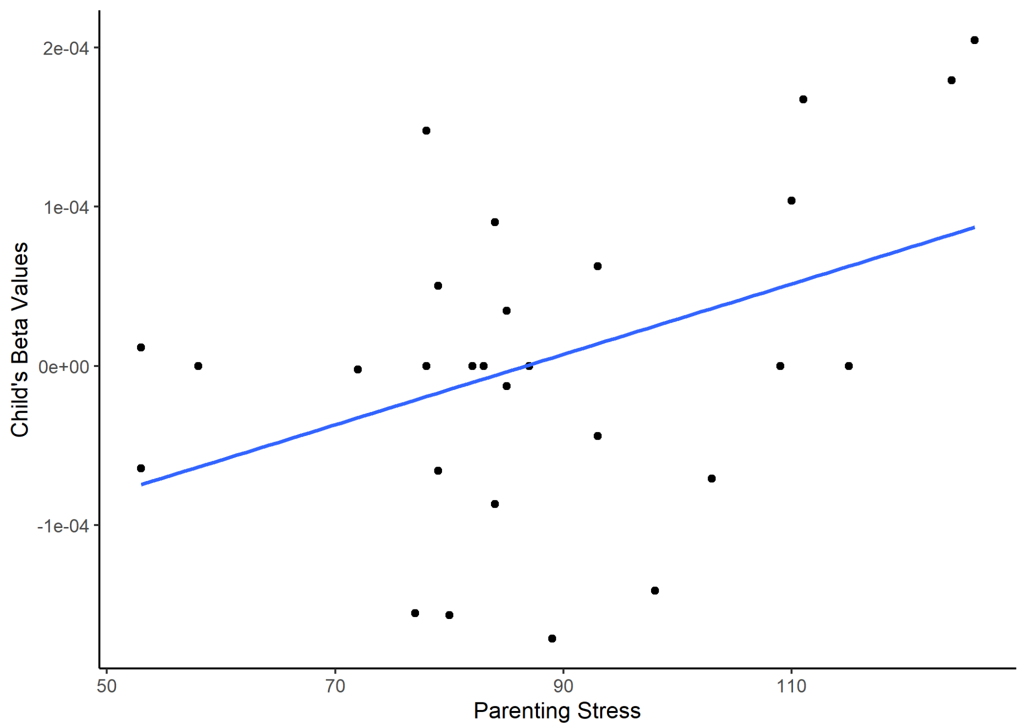
Amongst fathers, total parenting stress score was found to be significantly associated with beta coefficient values in CH16 ($R2=0.0448$, $F(3,83)=2.346$, $p=0.027$) which was mapped to the right anterior PFC. However, a follow-up Pearson's product Moment Correlation Coefficient did not elicit significant results ($r=0.333$, $p=0.077$). Similarly, parent-child dysfunctional interaction subscale was significantly associated with beta coefficient values in CH16 ($R2=0.0673$, $F(3,83)=3.067$, $p=0.00887$). However, an outlier was found to be influencing the result. Upon removal of the outlier, the follow-up Pearson's product Moment Correlation Coefficient did not elicit significant results either ($r=0.175$, $p=0.3718$). No significant association was found for beta coefficient values with parenting distress score and difficult child subscale in any of the channels.

Amongst children, total parenting stress score was significantly associated with beta coefficient values in CH5 ($R2=0.0461$, $F(3,83)=2.387$, $p=0.0319$), CH6 ($R2=0.0875$, $F(3,83)=3.749$, $p=0.0199$) and CH7 ($R2=0.0295$, $F(3,83)=1.871$, $p=0.0216$). These channels were mapped to the left lateral dorsolateral PFC, left anterior PFC and left middle frontal gyrus, respectively. Pearson's product-moment correlation test revealed significant positive associations between the Difficult Child score and child's beta-coefficients in CH5 ($r=0.373$, $p=0.0465$). However, inspection of the data in CH5 revealed the existence of outliers, which, upon removal, led to an insignificant correlation in CH5 ($r=0.143$, $p=0.495$). The correlation test was not significant for CH7 ($r=0.366$, $p=0.051$), and only generated a significant association between total parenting stress and beta coefficient in CH6 ($r=0.416$, $p=0.0247$) (Fig. 4). Since beta coefficient values reflect brain activity, higher scores of total parenting stress is associated with a higher brain response in the left anterior PFC of children.

Parent-child dysfunctional interaction subscale was also found to be associated with beta coefficient values in CH7 ($R2=0.07$, $F(3,83)=3.162$, $p=0.003$), which corresponded to the left middle frontal gyrus. A follow-up Pearson's product-moment correlation coefficients showed that higher reported dysfunctional interaction was positively correlated with child's beta values ($r=0.468$, $p=0.0106$). However, inspection of the data in CH7 showed the presence of outliers, which, upon removal, rendered the correlation insignificant ($r=0.324$, $p=0.1222$).

Difficult Child subscale was significantly associated with beta coefficient values in CH17 ($R2=0.0621$, $F(3,83)=2.898$, $p=0.0308$). This channel corresponded to the right middle frontal gyrus. However, Pearson's product moment correlation test did not reveal a significant association ($r=0.335$, $p=0.0759$). No significant association was found for parenting distress score with beta coefficient values in any of the channels.

Figure 4. Scatterplot depicting the correlation between total parenting stress score and childrens' beta value in CH6 ($r=0.416$, $p=0.0247$), which corresponds to the left anterior PFC.



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Acknowledgements
This work was supported by the NAP Start-up Grant M4081597 (G.E.) from Nanyang Technological University Singapore as well as the Ministry of Education Tier-1 Grant RG55/18 (NS) 2018-T1-001-172 (G.E.), and the Singapore’s Children Society (A.A.). The founding agencies had no role in the conceptualization, design, data collection, analysis, decision to publish, or preparation of the manuscript. We would like to extend our appreciation to Michelle Neoh and Lim Meng Yu for their assistance in the project, and Farouq Azizan for his illustration.

Contributions
A.Azhari and G.E. conceptualized the study; A.Azhari, J.C.S.C, W.T.W, J.P.M.B, J.R.D., S.S.B.A.H. and A. Ang. pre-processed and analyzed the data. A.A. wrote the original draft; G.E., A.Azhari, J.C.S.C, W.T.W, J.P.M.B, J.R.D., S.S.B.A.H. and A. Ang. reviewed and edited the submitted version of the article.

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