



ORIGINAL ARTICLE

Constructing the “Family Personality”: Can Family Functioning Be Linked to Parent–Child Interpersonal Neural Synchronization?

Khalil I. Thompson¹  | Clayton J. Schneider¹ | Joscelin Rocha-Hidalgo² | Shri Jeyaram¹ | Bedilia Mata-Centeno¹ | Emily Furtado¹  | Shreeja Vachhani¹ | Koraly Pérez-Edgar² | Susan B. Perlman¹

¹Department of Psychiatry, Washington University in St. Louis School of Medicine, St. Louis, Missouri, USA | ²Department of Psychology, Pennsylvania State University, State College, University Park, Pennsylvania, USA

Correspondence: Khalil I. Thompson (khalilt@wustl.edu)

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ABSTRACT

Introduction: Early child development occurs within an interactive environment, initially dominated by parents or caregivers, and is heavily influenced by the dynamics of this social context. The current study probed the neurobiology of “family personality”, or family functioning, in the context of parent–child dyadic interaction using a two-person neuroimaging modality.

Methods: One hundred and five parent–child dyads (child mean age 5 years 4 months) were recruited. Functional near-infrared spectroscopy (fNIRS) hyperscanning was employed to measure neural synchrony while dyads completed a mildly stressful interactive task. Family functioning was measured through the Family Adaptability and Cohesion Scale IV (FACES-IV).

Results: Synchrony during stress was significantly greater than synchrony during both baseline and recovery conditions for all dyads. A significant interaction between neural synchrony in each task condition and familial balanced flexibility was found, such that higher levels of balanced flexibility were associated with greater changes in frontal cortex neural synchrony as dyads progressed through the three task conditions.

Discussion: Parent–child dyads from families who display heightened levels of balanced flexibility are also more flexible in their engagement of neural synchrony when shifting between social conditions. This is one of the first studies to utilize a two-person imaging modality to explore the links between family functioning and interbrain synchrony between parents and their children.

1 | Introduction

Sullivan’s influential Interpersonal Theory of Psychiatry defined personality as “the relatively enduring pattern of recurrent interpersonal situations which characterize a human life” (Sullivan 1940, 2000). Indeed, many prominent theories in personality, or its developmental precursor temperament, characterize the development and presentation of one’s internal dispositions at the individual level within an interpersonal context

(Pincus, Hopwood, and Wright 2020). From birth, the development of the child’s temperament occurs in an interactive environment with their caretakers and within the context of familial attachment (Ainsworth 1982; Bowlby 1979). Thus, an important advancement to the personality/temperament literature would be to consider the development of a child within the backdrop of the broader family unit and its interactive patterns, or “family personality,” at both the behavioral and biological levels. Our study was designed to explore and characterize the underlying

neurobiological mechanisms tied to family personality via a hyperscanning (two person) neuroimaging modality (Czeszumski et al. 2020).

A prominent organizing framework for the exploration of family personality, or family functioning as it is called by the authors, is the Circumplex Model of Marital and Family Systems (Olson, Sprenkle, and Russell 1979), which measures the construct through the widely-used Family Adaptability & Cohesion Evaluation Scales (FACES; Olson, Waldvogel, and Schlieff 2019). This circumplex model, now commonly known as the FACES-Circumplex Model, shares some similarities to the original Interpersonal Circumplex (IPC; Leary 1958), which empirically operationalized Sullivan's core inferences into two geometrically oriented meta-concepts used to describe interpersonal disposition at the individual level: agency (power or differentiation from others) and communion (intimacy or union with others). The FACES-Circumplex model, in contrast, was designed to capture variation in family functioning along two curvilinear dimensions: *flexibility* (ability to change and negotiate roles in relationships and relationship rules) and *cohesion* (ability to facilitate emotional bonding between family members).

The FACES-Circumplex Model posits three major hypotheses: (1) balanced families (centered in the flexibility and cohesion dimensions), in contrast to unbalanced families (very high or very low scores of either dimension) are most conducive to positive well-being and success; (2) balanced families exhibit more positive communication styles than unbalanced families; and (3) balanced families display a greater capacity to adjust their levels of flexibility and cohesion to adapt to stress and developmental change, compared to unbalanced families. Over 1200 articles using the FACES-Circumplex Model have been published; however, few studies have focused on child development within this framework (Olson 2000; Olson, Waldvogel, and Schlieff 2019). While a limited number of studies have applied the most recent version of FACES (FACES-IV; Olson 2011) to early childhood, children with autism spectrum disorder (ASD) and other neurodevelopmental disabilities have been primary target population (Di Nuovo et al. 2011; Rieger and McGrail 2015; Sekulowicz et al. 2022). Few studies to date have examined family functioning through the FACES-Circumplex framework with neurotypical children in early or middle childhood.

Delineating individual and family personality dynamics at the self-report and/or behavioral level provides limited insight into the multiple mechanisms contributing to their expression. A number of studies have examined the neural correlates of adult personality at the individual level. For the purposes of the current project, we focused on the prefrontal cortex (PFC) as the region of interest, as it has emerged as a common hub of personality differentiation in the adult literature (Kennis, Rademaker, and Geuze 2013; Nostro et al. 2018; Sari and Erbaş 2022). Complementing adult personality research, the literature investigating the neural underpinnings of temperament from infancy through adolescence has also centered on PFC recruitment, particularly in relation to the development of domain-specific neural networks characterized by PFC hub integration (Kagan 2013; Posner and Rothbart 2019; Victor et al. 2016). Considerable attention has been directed toward the neural basis of personality and temperament at the individual level. Uncovering the neurobiological underpinnings driving family

functioning in interactive contexts would provide an additional layer of critical information that could illuminate key facets of early childhood neurodevelopment. Exposure to dysfunctional family environments during childhood has been explored as an impactful predictor and/or moderator of adverse psychosocial and neurodevelopmental outcomes, including changes to PFC structural integrity and functional adaptability (Bick and Nelson 2017; Gong et al. 2021; Hodel 2018; Sato et al. 2019). However, there is a dearth of research elucidating how family personality may manifest in interactive contexts and be associated with neural and behavioral trajectories. Thus, our goal is to explore and identify the potential neural correlates of family personality during parent-child interaction.

Second-person neuroscience can significantly improve our understanding of the neural mechanisms underlying interpersonal interaction and family functioning (Redcay and Schilbach 2019). The concept is based on the premise that the sociocognitive processes employed during social interaction fundamentally differ from the sociocognitive processes underlying social observation, a phenomenon that is conducive to the use of traditional, first-person approaches applied to individual participants. Second-person approaches attempt to simulate the natural social environment by using dynamic, interactive, ecologically valid experimental paradigms that require engagement with a human social partner and, therefore, expand beyond the constraints of first-person neuroscience (Schilbach et al. 2013). One construct captured under the umbrella of second-person neuroscience is dyadic synchrony, defined as an interaction between two individuals that is reciprocal, cooperative, mutually regulated, and responsive (Harrist and Waugh 2002). Within the developmental literature, caregiver-child dyadic synchrony has frequently been examined at the neurobiological level with "hyperscanning" techniques that specifically examine the neural concordance of two interacting brains (Czeszumski et al. 2020; Nam et al. 2020). This synchronization of brain activation (neural synchrony) has been hypothesized to facilitate communication, bond formation, and shared mental states among social partners (Redcay and Schilbach 2019; Wheatley et al. 2012). Through this ecologically valid approach, neural synchrony between a parent and child during naturalistic interaction may provide a window into the neural architecture supporting the real-time expression of family personality.

Our study was designed to be a "proof-of-principle" study exploring the neural underpinnings of family personality. We used functional near-infrared spectroscopy (fNIRS), a neuroimaging technique that leverages near-infrared light to measure changes in oxygenated and deoxygenated hemoglobin concentrations in the cortex region of the brain (Gervain et al. 2011). fNIRS is particularly useful for the implementation of naturalistic, interactive, hyperscanning paradigms due to its relative tolerance of motion artifacts, low measurement error due to split optodes on the same system, and ability to measure the brain in a range of scenarios that do not physically constrain participants (Hoyniak et al. 2021; Nguyen, Hoehl, and Vrtička 2021; Quiñones-Camacho et al. 2020). Furthermore, the preponderance of fNIRS literature has demonstrated that inter-brain synchrony in the PFC is a mechanism for social interaction, including cooperative or reciprocal exchange (Cui, Bryant, and Reiss 2012; Li et al. 2021; Zhang, Jia, and Zheng 2020), phenomena that are of interest for the current study. Previous fMRI research has also provided extensive evidence of enhanced PFC activation in

social decision-making and cooperative scenarios, particularly when heightened cognitive demands are placed upon the dyad (Emonds et al. 2012; Grossmann 2013; Lee et al. 2017).

We used the Disruptive Behavior Diagnostic Observation Schedule-Biological Synchrony (DB-DOS: BioSync; Quiñones-Camacho et al. 2020), developed originally to elicit variations in affect and behavior in children and their parents during a mildly stressful collaborative social task (Wakschlag et al. 2007). We examined neural synchrony between parents and their preschool-age children while they engaged in a mildly stressful, interactive task versus neural synchrony during a preceding baseline condition and subsequent recovery condition. We hypothesized that heightened levels of balanced flexibility and balanced cohesion would be associated with enhanced neural synchrony during the stress conditions compared to the baseline and recovery conditions of the DB-DOS.

2 | Methods

2.1 | Participants

A total of 122 children and a caregiver were recruited from the St. Louis, MO, and State College, PA regions. Participants were recruited as part of a multi-site, cross-sectional study (R56 MH126349; PI: Pérez-Edgar/Perlman) designed to investigate parent-child interaction in the context of broader family functioning. While data were collected from 122 dyads (parent-child pairs), dyads with computer or data storage errors ($n = 14$) or who had greater than 5 out of 10 bad quality optode channels as defined by our scalp-coupling preprocessing algorithm ($n = 3$), were systematically removed from the dataset. This procedure generated a final sample of 105 dyads (86% dyads retained). Of the 105 children (mean age 5 years 4 months; range 46–95 months), 50.5% were female. Of the 105 caregivers, 61% were female. The sample was 79% White, 8.6% Black or African-American, 6.7% Asian-American, 11.4% mixed/biracial, 1% other, and 1% refused to disclose. Subjects self-reported to be 5.7% Hispanic or Latinx. Additionally, the sample contained a broad range of socioeconomic diversity. Annual household income distribution was as follows: 3.8% less than \$20k; 5.7% \$20–40k; 15.2% \$40–60k; 18.1% \$60–80k; 8.6% \$80–100k; 7.6% \$100–120k; 31.4% \$120–250k; and 7.6% more than \$250k.

2.2 | Measures

Parent/guardians of the participants who engaged in the dyadic task completed the Family Adaptability and Cohesion Evaluation Scale Version IV (FACES-IV; Olson 2011), which applies a unique interpretation of the historical circumplex model (Gurtman and Pincus 2003) to family and marital systems (Olson 2000), without the application of trigonometric principles to inform the construction of family types. The FACES-circumplex model postulates that a functional, curvilinear spectrum characterizes family functioning, with balanced family systems tending to be more healthy and adaptive, occupying the center of the FACES dimensions of cohesion and flexibility, while unbalanced family systems tend to be maladaptive and dysfunctional, and occupy the positive and negative poles of the dimensions (see Figure 1). The self-report questionnaire contains 42 items assessing the two

balanced subscales of *balanced cohesion* and *balanced flexibility* (center of both dimensions) and the four unbalanced subscales of *disengagement* and *enmeshment* (positive and negative extremes of cohesion) and *rigid* and *chaotic* (positive and negative extremes of flexibility). Each subscale contains 7 items which are scored on a 5-point Likert scale ranging from 1 = *strongly disagree* to 5 = *strongly agree*. Example items from each subscale include: balanced cohesion—“Family members feel very close to each other”; balanced flexibility—“We shift household responsibilities from person to person”; Disengaged—“Family members seem to avoid contact with each other when at home”; Enmeshed—“We resent family members doing things outside the family”; Rigid—“There are strict consequences for breaking the rules in our family”; Chaotic—“It is unclear who is responsible for things (chores, activities) in our family”.

The degree of overall balance within the family unit is subsequently evaluated along two core dimensions (cohesion and flexibility) that are orthogonally related to each other. Cohesion (a mathematical product of the balanced cohesion, disengagement, and enmeshment subscales) is defined as the strength of emotional bonding between family members within the unit. Flexibility (a mathematical product of the balanced flexibility, rigid, and chaotic subscales) is defined as the expression, quality, and organization of role relationships and relationship rules within the family unit. The calculations used to convert raw scores to dimension scores can be found below. These dimension scores are primarily used to plot the location of the family on a grid-based circumplex model, which contains five levels of cohesion and flexibility and 25 total types of family systems (see Figure 1). The subscale scores (e.g., balanced flexibility and balanced cohesion) are used for statistical analyses.

$$\text{Cohesion Dimension Score} = \text{Balanced Cohesion} + \left(\frac{[\text{Enmeshed} - \text{Disengaged}]}{2} \right)$$

$$\text{Flexibility Dimension Score} = \text{Balanced Flexibility} + \left(\frac{[\text{Chaotic} - \text{Rigid}]}{2} \right)$$

FACES-IV was developed in response to the limitations of the original FACES scales, which lacked the ability to measure the extreme ends of the cohesion and flexibility and capture the curvilinear nature of the full dimensions (Olson 2011). A confirmatory factor analysis of the 42 items selected to represent the six FACES subscales supported a curvilinear factor structure, with balanced cohesion having a strong negative correlation with the disengaged scale ($r = -0.90$) but had a low negative correlation with the enmeshed scale ($r = -0.15$) and balanced flexibility having a strong negative correlation with the chaotic scale ($r = -0.70$) but a low negative correlation with the rigid scale ($r = -0.12$). The extreme scales are also moderately correlated for the unbalanced cohesion scales and for the unbalanced flexibility scales, providing justification for the independence and separation of unbalanced scales to capture extreme familial dysfunction.

2.3 | Task Description/Procedure

The DB-DOS Biological Synchrony (DB-DOS: BioSync; Quiñones-Camacho et al. 2020, 2022) is a neurobiological adaptation of the

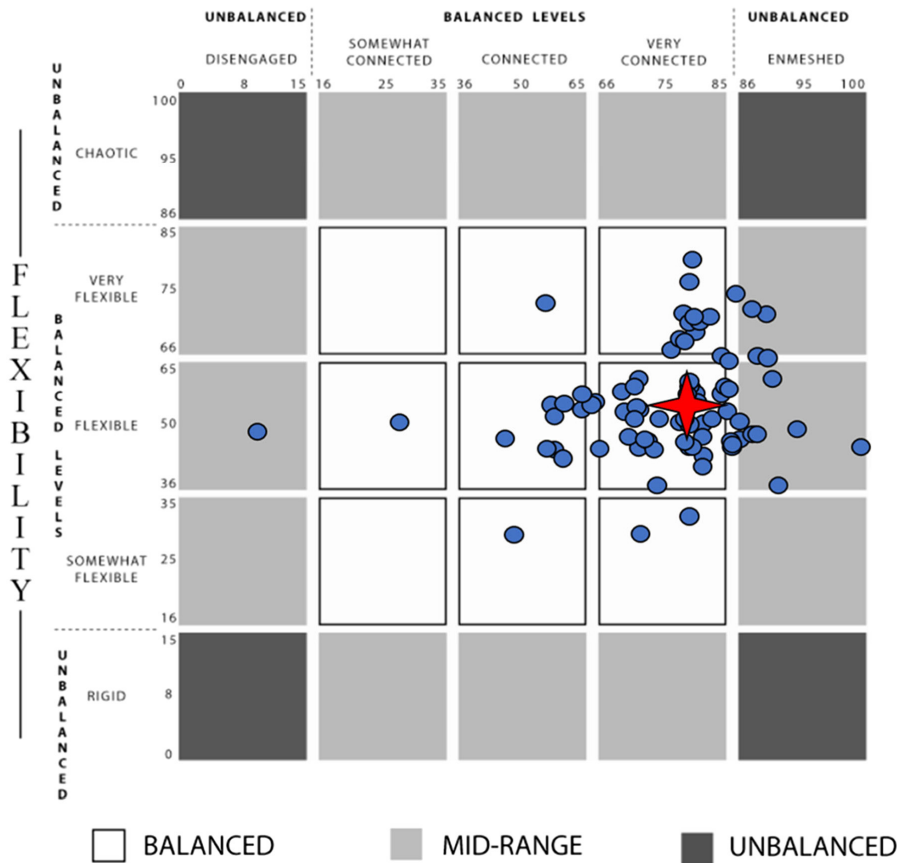


FIGURE 1 | A scatterplot illustration of cohesion and flexibility dimension scores of the present sample. The blue dots represent the individually reported dimensional scores of cohesion and flexibility for each dyad in the sample. The red star represents the average dimensional cohesion and flexibility across the entire sample.

Disruptive Behavior Diagnostic Observation Schedule (DB-DOS; Wakschlag et al. 2008), which was originally designed as a cooperative behavioral task, structured to evoke observable expressions of children’s behavioral problems. This interactive paradigm measures dyadic, interdependent responses from parents and children across social contexts with varying cognitive and behavioral demands. The DB-DOS: Biosynch has been modified to fit the structural necessities of biological imaging modalities (e.g., repeated trials to maximize signal strength).

The DB-DOS: BioSync consists of three conditions—(1) a pre-play “Baseline” condition; (2) a “Stress” condition in which mild stress or frustration is induced; and (3) a post-play “Recovery” condition. During the Baseline condition, parents and children created an interactive art project. During the Stress condition (10 min), dyads were left alone, seated at a table with desirable toys, and parents were instructed to prevent the child from touching them. Dyads were then tasked to complete challenging tangram puzzles together. These puzzles consisted of seven flat geometric shapes that could be combined to form larger shapes, such as an object or animal. To enhance the mild stress elicited by the task, dyads were told they would receive a prize only by completing an unspecified number of puzzles; puzzles were selected that were too difficult for the child’s developmental stage;

time to complete the task was cut short (1:45 instead of the promised 2:00 min per trial); and a countdown clock was displayed, indicating the amount of time left in the task. After the Stress condition ended, the Recovery condition (10 min) allowed the dyad to play with the attractive toys that they were prevented from touching during the “Puzzle”. This condition served as an opportunity for stress recovery during a low-demand but interactive activity that mimicked elements of the Baseline condition. The baseline and recovery conditions consisted of four recurring trials of 2 min followed by a 15-s intertrial interval.

2.4 | fNIRS Data Acquisition

A NIRScout fNIRS system (NIRx Medical Technologies LLC, Glen Head, NY, USA) was used to collect noninvasive optical imaging (i.e., fNIRS) data using a continuous-wave system. Light was emitted at 760 nm and 850 nm from eight LED light sources and measured by four photodiode light detectors, resulting in 10 measurement channels (source-detector pairs) per wavelength (see Figure 2). Optical signals were collected at a frequency of 7.31 Hz. Sensors were mounted on a neoprene head cap with a source–detector distance of 3 cm. The head caps were placed on the scalp following the international 10–20 coordinate system for

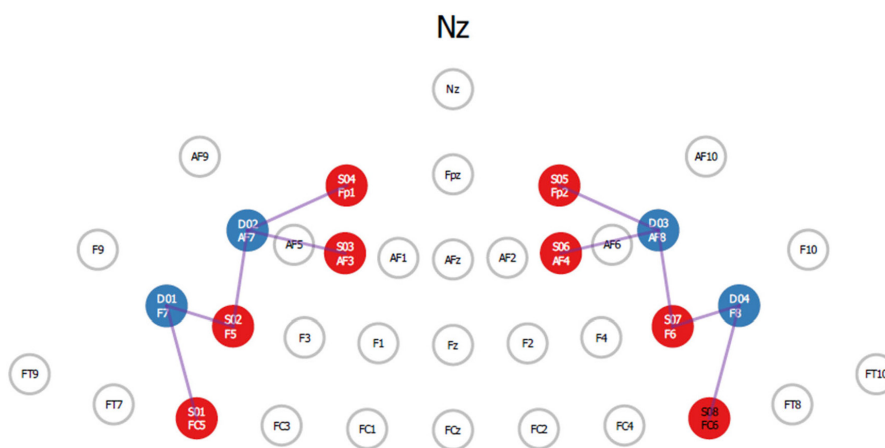


FIGURE 2 | Each fNIRS head cap collected optical density and hemodynamic activity information across 10 channels (source-detector pairs) while dyads completed the DB-DOS task. Four channels covered the dorsolateral PFC (dlPFC) region, and six covered the ventrolateral PFC (vlPFC) region.

both the parent and the child, with the sources located in Fp1, Fp2, AF3, AF4, F5, F5, FC5, and FC6. This placement extended the probe over sections of the frontopolar, dorsolateral, and ventrolateral PFCs based on registration to the Brodmann area brain atlas (Garey 1999). The Brodmann areas were identified using the fNIRS Optodes Location Decider toolbox (Zimeo Morais, Balardin, and Sato 2018), which also informed probe placement. When necessary, hair was manually separated under the optodes to improve scalp coupling and overall signal detection.

2.5 | fNIRS Preprocessing

Parent-child neural synchrony was defined as the average of cross-wavelet transform coherence (WTC) between the dyad during a particular context and was approximated using task-based frequencies of interest (between 0.0095 and 0.2 Hz; Nguyen, Hoehl, and Vrtička 2021). WTC is calculated separately for the three conditions of the task: baseline, stress, and recovery.

The fNIRS data were preprocessed using the MNE-Python package (Gramfort et al. 2013). First, whole-trial raw fNIRS data were converted to raw optical density format, after which each channel was evaluated using a scalp-coupling index (SCI; Hernandez and Pollonini 2020; Pollonini et al. 2014). Channels with an SCI < 0.5 (scale between 0 and 1) were marked as invalid and removed from subsequent analyses. Taking a conservative approach, if either the parent or the child in any dyad had 10 or more (of their 20) channels marked as invalid due to low SCI, the dyad was dropped from the analysis (3 dyads). Most fNIRS hyperscanning studies include dyads in the study even if only one channel per participant meets threshold (Nguyen, Hoehl, and Vrtička 2021; Reindl et al. 2019). Thus, our inclusion threshold was more stringent than the norm. Following the channel-pruning step, the temporal-derivative distribution repair (TDDR) algorithm was administered on a channel-wise basis to correct head motion artifacts. The TDDR-corrected data was then bandpass-filtered with low- and high-pass frequency thresholds of 0.01 and 0.5 Hz to target the natural frequency-based oscillatory dynamics of task-related hemoglobin changes in the brain (Reindl et al. 2019). Via the Beer-Lambert Law

(related to the extinction or attenuation of light to the properties of the material through which the light is traveling), the modified optical density data was converted to hemoglobin concentration values using a partial-pathlength factor (PPF) set at 0.1.

Epoch-related timings were then standardized across participants, yielding trial lengths of 120, 105, and 120 s, for the baseline, stress, and recovery conditions, respectively. Four repeated trials constituted one of the three conditions of the task, and the preprocessed fNIRS data was divided into epochs covering the entire fNIRS time series. Once converted to epoch form, HbR (deoxygenated hemoglobin) channels were dropped, as HbO is considered more relevant to task-based imaging studies (Blockley et al. 2013; Hare et al. 1998). An additional channel-pruning step was then performed, where if the peak-to-peak differences across an epoch for any given HbO channel (max value of epoch minus min value of epoch) was greater than $200e-6$, it was removed to minimize the presence of spike signal artifacts. The channels of each epoch were then standardized such that the mean average of the first 5 s of the epoch was considered a baseline HbO value, and this amount was subtracted from the entire signal. As a final preprocessing step, a linear detrend to reduce overall signal variation was applied for each epoch when loaded for analysis in our MNE protocol.

Once preprocessing was complete, neural synchrony values were estimated for each parent and child (i.e., child of Dyad A paired with parent of Dyad A; a “real dyad”) in a task condition by fNIRS channel analysis. Prior to calculating synchrony values, a random set of children’s data was selected as the comparator for each parent’s data so that in addition to real dyadic synchrony, “false dyadic” synchrony values (i.e., child of Dyad B paired with parent of Dyad A) would also be produced for further evaluation in later analyses. For this randomly permuted dataset, 999 samples were taken from the children’s data to match with the parent’s data. This process does result in duplicate samples. However, for these samples, synchrony values were only calculated once for computational efficiency.

Neural synchrony was evaluated using the PyCWT Python package (Nedorubova, Kadyrova, and Khlyupin 2021). The

continuous wavelet transform (CWT) can be used to investigate the changes in HbO at various channels and ROIs as a function of time and frequency. Here, the cross-WTC is used to investigate the coherence in these HbO changes between a parent–child dyad at task-related time points and expected frequency signatures (see Figure 3). The WTC was performed using the parameters described in the PyCWT documentation, on normalized epochs of data, and on a channel-wise basis for each dyad. A singular value was obtained for each channel in a dyad by averaging the WTC over the length of the epoch, from task-related frequencies of ~0.0095–0.2 Hz (corresponding to periods of 5–105 s) and excluding the cone-of-influence (COI) artifactual regions at the peripheral areas of the WTC output. This frequency range was selected because it captures low-frequency, task-related signals of interest and provides the greatest magnitude of visibility of all areas of the WTC cone produced to visualize significant BOLD changes in fNIRS data (Nguyen, Hoehl, and Vrtička 2021).

The singular WTC value was calculated for each dyad contained in the randomly generated set (described above); furthermore, values were calculated across each of these dyad's like-channels (e.g., parent's S4_D2 to a child's S4_D2) and in each of the 3 task conditions, unless the channel for either parent or child did not pass the HbO peak-to-peak validation, in which case that channel was excluded from analysis. We reduced this dataset by averaging the singular WTC values for the different task iterations so that, for the free-play context for example, we have only one value per sampled dyad per channel, and further reduced the data by averaging channel-wise for the four identified regions-of-interest (ROIs). These ROIs were the left and right dorsolateral PFC (dlPFC) and the left and right ventrolateral PFC (vlPFC).

2.6 | Parent–Child Neural Synchrony Analyses

A validation check for the neural synchrony construct was calculated using permutation testing with real dyads tested against false dyads. This approach allowed us to confirm that the observed synchrony was driven by a dyad's active interaction over and above the fundamental elements of shared experience between two non-partner participants (i.e., neural synchrony based on hearing the same sounds and seeing the same stimuli at the same time). Neural synchrony was calculated between all possible participant pairs to determine the suitable null distribution of neural synchrony values. There were neural synchrony values for 105 real dyads and 32,448 false (null) dyads. Permutation testing was then conducted to calculate the p value associated with each real dyad's neural synchrony value by estimating the number of values from false pairings that were equal to or greater than the observed value. Constant terms were chosen to ensure that the resulting p values would be between zero and one. The occurrence of neural synchrony was assessed for each condition using a one-sample t -test. Lastly, the corresponding p values were corrected for multiple comparisons by calculating the Benjamini–Hochberg false discovery rate-corrected p value (Thissen, Steinberg, and Kuang 2002) across all unique channel pairs (10 channels).

Following the implementation of these t -tests, neural synchrony values were extracted from the Python-based programming environment and transferred to standard statistics software programs [Jamovi (Şahin and Aybek 2020) and SPSS (Argyrous 2011)]. Pearson's correlation tests were first conducted to determine whether any significant associations existed between the six FACES subscale scores and the three primary regions of interest (ROIs): (1) the dlPFC, (2) the vlPFC,

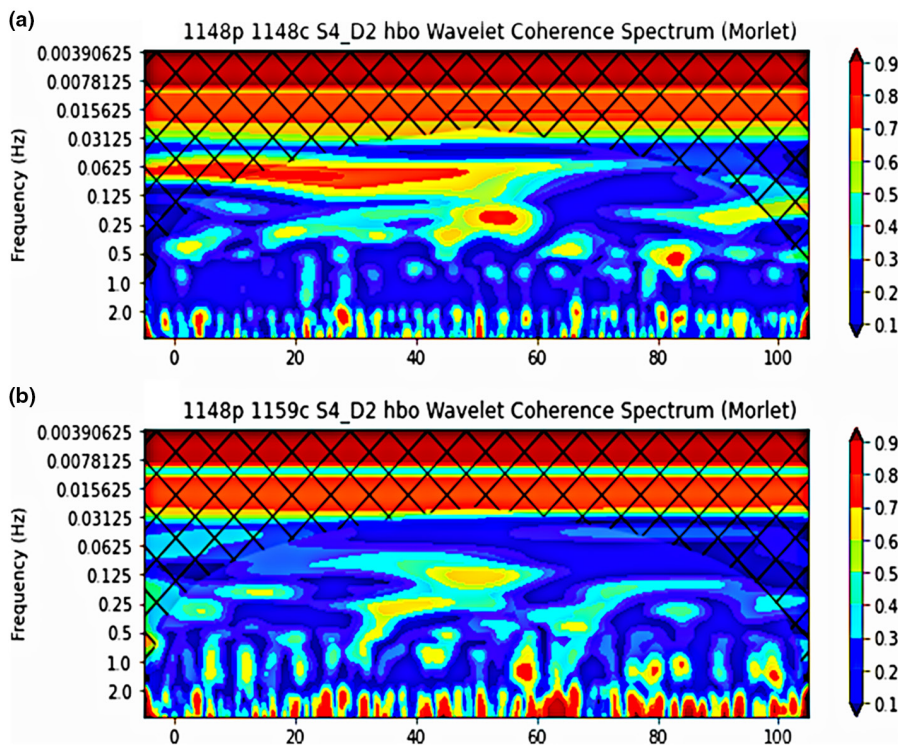


FIGURE 3 | A wavelet coherence map displaying the magnitude of synchrony in Hz between both real (top graph) and false (bottom graph) dyads during the task. Time is plotted on the x-axis, and frequency on the y-axis. Low-frequency densities (dark red spots) related to the task of interest can be detected in plot (a) only. Plot (b) only displays high frequency densities associated with physiological noise at the bottom of the graph.

and (3) both subregions combined (frontal cortex). Correlations were calculated for each experimental condition of the DBDOS: Biosynch (baseline, stress, and recovery).

Following the Pearson's correlation tests, repeated measures ANCOVAs were conducted to examine patterns of change in synchrony between conditions as a function of subscale scores. The framework for each repeated measures ANCOVA proceeded as follows: Task condition was entered as a repeated measures factor with three sub-levels (baseline, puzzle, and recovery). Experiment site, child sex, parent sex, and child's age in years were entered as a between-subjects factors. Continuous variables of interest were extracted from FACES questionnaire responses. Six subscale scores were included: balanced flexibility, balanced cohesion, disengaged, enmeshed, chaotic, and rigid. Once a continuous variable was designated for analyses, repeated measures cells were selected based on the brain region of interest for the analysis. Three cell arrangements accounting for neural synchrony in each task condition were tested for the analysis: (1) full frontal cortex, (2) dlPFC, and (3) vlPFC synchrony.

The predictive value of the FACES subscale scores was then tested to determine whether synchrony values associated with each task condition varied as a function of a subscale score. Within-subjects and between-subjects effects were evaluated; however, the expectation was that there would be no between-subjects effects that predicted change in synchrony values across conditions. Investigating the within-subjects effects, if an interaction between task condition and subscale score was statistically significant, a qualitative illustration of the relationship was produced in lieu of a formal exploratory post hoc test, which could not be conducted due to the inclusion of subscale scores as continuous variables. The qualitative illustration allowed for the exploration of the pattern of change across task conditions as subscale score increased or decreased, further elaborating upon our initial expectations of interactions identified with the confirmatory omnibus F test.

3 | Results

3.1 | Descriptive Statistics

Means and standard deviations for FACES dimensional and subscale scores for the participants were as follows: Cohesion (Dimension) ($M=76$, $SD=13.8$), Flexibility (Dimension) ($M=55$, $SD=11.4$), Balanced Cohesion ($M=31$, $SD=3.51$), Balanced Flexibility ($M=27$, $SD=3.49$), Disengaged ($M=12$, $SD=3.79$) Enmeshed ($M=14$, $SD=4.27$), Rigid ($M=21$, $SD=3.61$), and Chaotic ($M=14$, $SD=4.48$). A scatterplot circumplex model plotting both individual and average FACES dimension scores is presented in Figure 1.

Exploring significant associations among our FACES subscale scores and covariates for the current study, we found that child age (years) was negatively correlated with the rigid subscale ($r=-0.254$, $p=0.016$). Additionally, parent sex was negatively associated with the enmeshed ($r=-0.249$, $p=0.019$), rigid ($r=-0.272$, $p=0.010$), and chaotic ($r=-0.240$, $p=0.024$) subscales, indicating that fathers were more likely to report

heightened levels of these family dynamics. There were no significant associations between child sex and FACES scores. Finally, experimental site was positively associated with the cohesion dimension ($r=0.218$, $p=0.040$), indicating that family cohesion was significantly stronger at the PSU site versus the WUSTL site.

3.2 | Neural Synchrony Validation

First, baseline one-sample *t*-tests were conducted on the permuted parent-child synchrony output. Real dyad synchrony during the baseline ($t(957)=322.29$, $p<0.001$), stress ($t(951)=322.67$, $p<0.001$), and recovery ($t(958)=332.94$, $p<0.001$) conditions all significantly differed from a baseline of zero. False dyad synchrony during the baseline ($t(100893)=3495.69$, $p<0.001$), stress ($t(99850)=3327.28$, $p<0.001$), and recovery ($t(100362)=3577.87$, $p<0.001$) epochs also significantly differed from a baseline of zero. Paired samples *t*-tests indicated that real dyad synchrony was significantly greater than false dyad synchrony during the baseline ($t(957)=5.41$, $p<0.001$), stress ($t(951)=5.06$, $p<0.001$), and recovery ($t(958)=5.53$, $p<0.001$) epochs.

3.3 | Neural Synchrony Between Conditions

When comparing synchrony in the frontal cortex between conditions for the real dyads, synchrony during the stress condition was significantly greater than synchrony during both the baseline ($t(951)=7.94$, $p<0.001$) and recovery ($t(951)=7.69$, $p<0.001$) epochs. However, there was no significant difference in real dyadic synchrony between the baseline and recovery conditions ($t(957)=0.452$, $p=0.452$).

3.4 | FACES Correlation Findings

Correlation tests were conducted to explore associations between synchrony in the frontal cortex ROIs and FACES subscale scores. We found that balanced flexibility was negatively associated with frontal cortex ($r=-0.316$, $p=0.003$), dlPFC ($r=-0.257$, $p=0.015$), and vlPFC ($r=-0.238$, $p=0.025$) synchrony during the recovery condition. There was also a significant positive association between the enmeshed subscale and vlPFC synchrony during the baseline condition ($r=0.221$, $p=0.037$). No other significant associations were detected between FACES subscale scores and synchrony values across task conditions.

3.5 | FACES Repeated Measures ANCOVA Analyses

A sequence of repeated measures ANCOVA analyses were conducted to probe further the relationship between balanced flexibility and neural synchrony across task conditions. The model contained three repeated measures: baseline, stress, and recovery conditions. Between-subjects factors included experiment site, child sex, and parent sex. The continuous variables incorporated into the analyses included the six subscales scores

and child age (years). Based upon the significant correlations of interest, three sets of repeated measures dependent variables containing the neural synchrony values for the three neural ROIs were delineated. Interactions between task condition and FACES subscale scores were then evaluated for significance.

The first FACES subscale ANCOVA model revealed a significant interaction between balanced flexibility and synchrony in the frontal cortex across task conditions ($F=6.49, p=0.002$). However, there were no significant interactions between frontal cortex synchrony and balanced cohesion ($F=1.98, p=0.142$), disengaged ($F=0.471, p=0.625$), enmeshed ($F=0.418, p=0.659$), rigid ($F=0.214, p=0.808$), or chaotic ($F=0.221, p=0.802$) subscale scores (see Table S1 in the supplemental materials). Regarding the between-subjects factors, a significant interaction was detected between frontal cortex synchrony and experiment site ($F=3.60, p=0.030$). However, there were no significant interactions between frontal cortex synchrony and child age ($F=0.710, p=0.493$), child sex ($F=2.51, p=0.085$), or parent sex ($F=1.37, p=0.258$). To probe the significant interaction between frontal synchrony and balanced flexibility, a clustered bar graph was produced (see Figure 4), and balanced flexibility scores were artificially separated into low, mid, and high categories. A review of the graph revealed that as balanced flexibility increased, the variation in neural synchrony between task conditions also increased as well. Most notably, while all levels of balanced flexibility were associated with the stress condition eliciting the highest levels of synchrony, followed by a decline in synchrony during the recovery period, the decline became steeper as balanced flexibility increased. This same relationship between balanced flexibility and task condition was identified for both the dlPFC ($F=4.29, p=0.015$) and the vlPFC ($F=4.53, p=0.012$) (see Tables S2 and S3 in the supplemental materials). No significant relationships were identified between the rest of the FACES subscale scores and synchrony across the three ROIs.

4 | Discussion

The goal of the current study was to investigate how family personality may be related to brain-to-brain synchrony between parent-child dyads using a two-person neuroimaging modality while

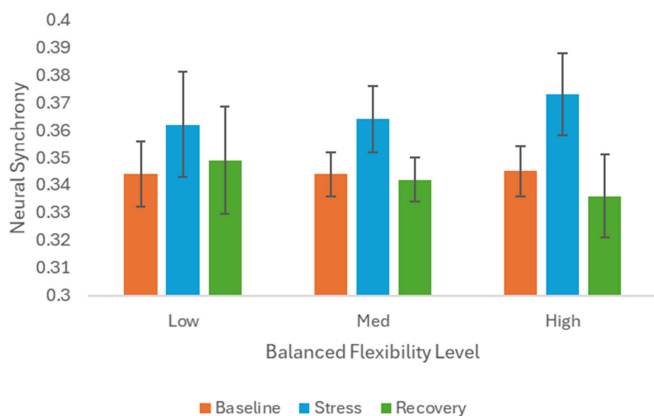


FIGURE 4 | The bar graph depicts the interaction between balanced flexibility and frontal cortex neural synchrony across each task condition of the DB-DOS. As balanced flexibility increases, the degree of variation in neural synchrony between task blocks also increases.

dyads engaged in a dynamic, ecologically valid social interaction task. Neural synchrony among all dyads was strongest during the mildly stressful problem-solving condition. Furthermore, we found that the sub-dimension of balanced flexibility significantly interacted with task conditions, such that families who report themselves as having a more flexible family structure were more flexible in their use of synchrony over the course of the three social conditions of the study. The unbalanced FACES subscales were not significantly associated with changes in neural synchrony across social conditions. Additionally, we did not detect any significant associations between balanced cohesion and neural synchrony across the ROIs for the study, contrary to initial expectations. By demonstrating psychobiological evidence of a relationship between family personality and interbrain synchrony among parents and their young children, we introduce a novel avenue of exploration in second-person neuroscience that expands beyond defining individual interpersonal profiles to encompassing the family unit and their shared experience.

Interbrain synchrony has been previously established as a neural indicator for social engagement, and the moment-to-moment interaction between the brains' of individuals can strengthen or diminish depending upon the degree of reciprocity of responses and mutual engagement between social partners (Czeszumski et al. 2020). Synchrony during the stress condition significantly exceeded the synchrony detected in the baseline and recovery conditions (which also incorporated collaborative tasks but without rigorous problem-solving components), suggesting that dyadic tasks that require substantial reasoning demands from both parents and children uniquely modulate the brain-to-brain network environment over and above the basic attachment-influenced relationship that characterizes parent-child interactions (Feldman 2017). Previous research has also detected differential neural synchrony patterns between parent-child dyads during problem-solving and cooperative contexts versus competitive contexts (Miller et al. 2019; Nguyen et al. 2021; Reindl et al. 2018, 2022), further reaffirming not only the co-regulatory nature of parent-child interaction, but the importance of shared intention and affect in a collaborative environment and how it may facilitate social neurodevelopment (Feldman 2015).

Family balanced flexibility is the healthy, adaptive expression of dimensional flexibility, defined as the capacity to shift and negotiate roles and rules within the family unit. Balanced flexibility was significantly positively associated with larger, systematic, variations in neural synchrony across task conditions, with the most prominent changes detected between the stress and recovery conditions. That is, families who reported themselves to be more flexible were also more flexible in neural synchrony levels in their transition in and out of conditions with varying task demands. Maintaining fluidity and an openness to change during decision-making is suggested to support the overall stability and adaptability of the family unit (Olson, Waldvogel, and Schlieff 2019). This finding acts as a "proof-of-principle", establishing that dyadic neural substrates may be associated with self-report questionnaires evaluating dyadic or family-level relationships. Broader implications of this finding underscore existing evidence of the role flexibility, which has been linked to positive childhood outcomes (Dreman 2003; Everri, Mancini, and Fruggeri 2016; Zalewska-Lunkiewicz et al. 2016), plays in the developmental trajectory of young children.

Another observation warranting discussion was the lack of significant findings linking neural synchrony to family cohesion. Family cohesion reflects the degree of emotional bonding and perception of social support among family members (Olson 2011). Previous research has illustrated how family cohesion can foster family resilience by acting as a protective buffer to socioemotional conflict between parents and their children or experienced from external sources (Baer 2002; Benzies and Mychasiuk 2009). Moreover, two recent publications exploring the relationship between FACES-defined family functioning and parent-adolescent neural synchrony in response to watching emotional film clips detected heightened synchrony associated not only with higher cohesion, but also less observable negative affect and self-reported anxiety (Deng et al. 2022; Zhou et al. 2023). However, in the present study, there were no significant associations between balanced cohesion and synchrony in the frontal cortex regions of interest. It is possible that cohesion was not a significant factor for the current study because the DB-DOS paradigm is designed to probe problem-solving during mild stress and is free of overt emotional content like the studies described above. Increasing the magnitude of stress experienced by the dyad during the problem-solving task may serve as a suitable first step in addressing this deficiency in future studies. It may also be possible that the lack of findings in the cohesion domain is due to a sample skewed towards higher levels of cohesion in comparison to the flexibility dimension, which was more normally distributed. It may be the case that our participants perceive their families, and specifically their relationship with their child, as being closer than average. Indeed, a meta-analysis found children's age to be the most robust moderator of parent-child congruence in perception of family closeness and parenting practices, with a greater mean age being related to higher correspondence between parents and their children (Korelitz and Garber 2016). Children in our study were preschool age, which may be a time period in which parents perceive their cohesion to be high, likely due to heightened levels of parental involvement required to support day-to-day family activities. We also note that, although it was not a focus of the study, fathers reported lower levels of family functioning than mothers, which nods to inherent demand characteristics present in self-report of family life.

Our study has several strengths. Multi-site data collection enhances the generalizability of the study to different regions of the country, allowing us to diversify the sample by targeting families from variable socioeconomic, racial/ethnic, and urban/rural backgrounds. Fathers also comprised 39% of parents in the sample, which is a strength given that most of the child development literature overwhelmingly studies mothers (Mitchell et al. 2007). There are, however, limitations to our findings. First, while the sample for the current study exceeds what is commonly seen in the broader fNIRS hyperscanning literature, it is still limited in its overall scale as a cross-sectional study and issues with low statistical power remain. Taking a big data approach and integrating these findings with subsequent studies with larger samples using the same measure and analytic protocol will be critical to enhancing the validity of this proof of principle framework. Second, a condensed period of interaction between family members in a controlled setting does not necessarily reflect day-to-day interactions between parent-child dyads. Our paradigm only provides a snapshot of their interpersonal dynamics and does not capture information concerning

the frequency of interactions or willingness to engage in interaction. Finally, while characterizing the neurobiological presentation of the family personality and functioning was the primary focus of the study, it would be beneficial to apply existing, individually-focused circumplex questionnaires to this line of research to expand the comprehensiveness of family personality profiling. In the current study, only child temperament measures completed from the parent's perspective were included. No parent personality measures were utilized to compare with the children's profiles. Furthermore, the family profiles in the current study were drawn from self-report and are reliant on the perceptions and responses of the parent alone without input from the child who, in the current age range, is unable to respond to questionnaires. These limitations may be at least partially addressed with observer-based coding of this early-middle childhood age range in future studies.

Despite these limitations, the findings of the present study contribute to the literature by establishing a potential relationship between sub-dimensions of family functioning and neural synchrony between parents and their young children during a sensitive maturational period. This is among the first studies to highlight the importance of family personality as a group-based interpersonal profile while further connecting it to the inter-network functioning capacity of the human social brain. Future studies should probe family personality from a longitudinal perspective to better understand how interbrain neural substrates between parent-child dyads adjust to maladaptive contexts and impact the mental health and well-being of the family members individually and as a family unit (Perlman et al. 2022).

Author Contributions

Khalil I. Thompson—Writing, Study Design, Data Analysis, Data Interpretation; Clayton J. Schneider—Writing, Software Development; Joscelin Rocha-Hidalgo—Writing, Data Collection, Data Interpretation; Shri Jeyaram—Data Collection, Data Analysis; Bedilia Mata-Centeno—Data Collection, Data Analysis; Emily Furtado—Data Collection; Shreeja Vachhani—Data Collection; Koralý Pérez-Edgar—Writing, Study Design, Data Interpretation; Susan B. Perlman—Writing, Study Design, Data Interpretation.

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This research (study and analysis plan) was not preregistered in an independent institutional registry.

Ethics Statement

This study was approved by the Institutional Review Board (IRB) of the Pennsylvania State University, serving as the single IRB site. All parents provided written consent.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this study are openly available in the National Institutes of Health National Data Archive at <https://reporter.nih.gov/project-details/10414182>, reference number/collections ID 4005.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.