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Atypical Child–Parent Neural Synchrony Is Linked to Negative Family Emotional Climate and Children′s Psychopathological Symptoms

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Family emotional climate is fundamental to children′s well-being and mental health. Family environments filled with negative emotions may lead to increased psychopathological symptoms in the child through dysfunctional child–parent interactions. Single-brain paradigms have uncovered changes in brain systems and networks related to negative family environments, but how the neurobiological reciprocity between child and parent brains is associated with children′s psychopathological symptoms remains unknown. Here, we first investigated the relation between family emotional climate and children′s psychopathological symptoms in 395 child–parent dyads. Using a naturalistic movie-watching functional magnetic resonance imaging technique in a subsample of 50 child–parent dyads, we further investigated the neurobiological underpinnings of how family emotional climates are associated with children′s psychopathological symptoms through child–parent neural synchrony. Children from negative family emotional climate experienced significantly more severe psychopathological symptoms. In comparison to child–stranger dyads, child–parent dyads exhibited higher intersubject correlations in the dorsal and ventral portions of the medial prefrontal cortex (mPFC), and greater concordance of activity with widespread regions critical for socioemotional skills. Critically, negative family emotional climate was associated with decreased intersubject functional correlation between the ventral-mPFC and the hippocampus during movie watching in child–parent dyads, which further accounted for higher children′s internalizing symptoms. Together, our findings provide insights into the neurobiological mechanisms that negative family environments can cause and maintain psychopathological symptoms in children through atypical child–parent neural synchrony. This has important implications for a better understanding of how child–parent connections may mediate the relation between environmental risks and developmental outcomes.

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All the necessary data and codes are available at https://osf.io/c2gjk/?view_only=ca36371395c14902b0842a34664f53fd. The raw data of this study are available from the corresponding author on request.

Haowen Su played a lead role in conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing–original draft, and writing–review and editing. Christina B. Young played a supporting role in

continued

Public Significance Statement
Our study provides a neurobiological account of how negative family emotional climate influences children′s internalizing symptoms through atypical brain-to-brain concordance in child–parent dyads. This work can inform dyad-based prevention and intervention strategies to improve children′s psychological well-being.

Keywords: family emotional climate, psychopathological symptoms, neural synchrony, naturalistic functional magnetic resonance imaging

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Children learn how to express and regulate their emotions through observing and modeling their parents′ emotional behaviors (Eisenberg, 2020; McCoy & Raver, 2011), highlighting the importance of family during early socialization. Family emotional climate, including how negative and positive emotions are expressed as well as how emotions impact parenting behaviors, has a large effect in shaping the emotional well-being and mental health of children (Speidel et al., 2020). Research in psychology has recognized that family emotional climate, especially its negative aspects, can cause and maintain various psychopathological symptoms in children (Gong et al., 2021).

Psychosocial views suggest that negative family emotional climate may lead to psychopathological symptoms in children by derailing the reciprocal coordination of psychosocial behaviors between child–parent dyads (Feldman, 2020; Morris et al., 2018). Indeed, previous studies have demonstrated that negative family environments compromise the effectiveness of reciprocal interactions in child–parent dyads (Hoyniak et al., 2021; Tarullo et al., 2017). Children who experience dysfunctional family interactions with parents are prone to develop psychopathological symptoms later in life (Feldman, 2007; Quiñones-Camacho et al., 2021). According to the biobehavioral synchrony model (Feldman, 2012), the reciprocal coordination of child–parent interactions involves various components, including psychosocial behaviors, autonomic responses, internal hormones, and brain functioning. These components work in a coodinated manner, reflecting shared representations and/or schema related to socioemotional experiences, which are important for child developmental outcomes. Although well documented in behavioral (Thomassin & Suveg, 2014) and physiological studies (Davis et al., 2018), the underlying neurobiological mechanisms of how family emotional climates impact psychopathological symptoms in children through altered reciprocal responses across child–parent brains remain largely unknown.

With a focus on cross-brain associations, an Extended Parent–Child Emotion Regulation Dynamics Model (Morris et al., 2018; Ratliff et al., 2022) proposes that parent–child brain-to-brain concordance is a key mechanism linking family systems (e.g., family emotional climate) to children′s mental health. Although no research has directly examined whether parent–child interbrain concordance mediates the relation between family environment and child psychopathological symptoms, several studies have provided preliminary evidence. Using functional near-infrared spectroscopy hyperscanning techniques, recent studies have demonstrated neural synchrony in the prefrontal cortex (PFC) across child–parent brains, which is critical for reciprocal interactions including cooperation (Reindl et al., 2018), joint attention (Quiñones-Camacho et al., 2020), and smiling (Piazza et al., 2020). Family risk factors including parenting stress (Azhari et al., 2019), maternal stress (Nguyen et al., 2020), anxious attachment (Azhari et al., 2020), and sociodemographic risks (Hoyniak et al., 2021) could diminish child–parent shared neural response in the PFC. Moreover, disrupted child–parent prefrontal synchrony was associated with poor emotion regulation (Reindl et al., 2018) and heightened irritability (Quiñones-Camacho et al., 2020) in typically developing children, as well as autistic symptoms in children with autism spectrum disorders (Wang et al., 2020). These findings provide initial evidence suggesting that family risk factors may alter child–parent brain-to-brain concordance, which may then impede the development of socioemotional skills in children.

writing–original draft and writing–review and editing. Zhuo Rachel Han played a supporting role in writing–original draft and writing–review and editing and an equal role in conceptualization. Jianjie Xu played a supporting role in writing–review and editing. Bingsen Xiong played a supporting role in visualization. Zisen Zhou played a supporting role in methodology. Jingyi Wang played a supporting role in data curation. Lei Hao played a supporting role in visualization. Zhi Yang played a supporting role in methodology. Gang Chen played a supporting role in methodology. Shaozheng Qin played a lead role in conceptualization, resources, supervision, and writing–review and editing and a supporting role in methodology.

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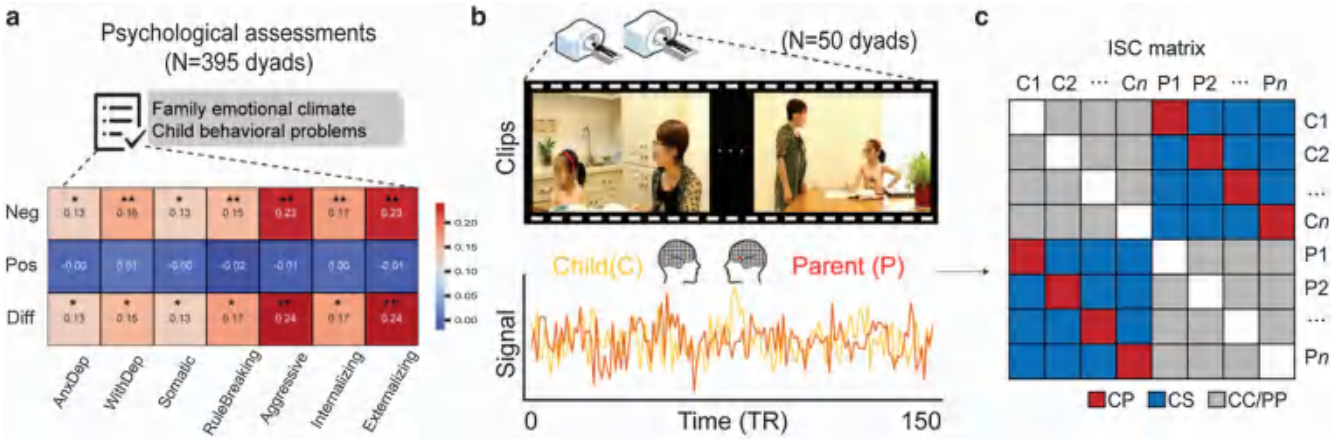
The transmission of shared mental representations of socioemotional experiences may also affect intersubject concordance between child and parent brains even in the absence of real-time interactions. Children learn social and emotional skills through dyadic interactions with their parents, which can help form and maintain shared meanings or narratives of socioemotional experiences and knowledge in long-term memory (Feldman, 2007; Fiske & Taylor, 2013). These processes require multiple brain regions and systems to interact and exchange information (Babiloni & Astolfi, 2014). Empirically, researchers have applied a dual-brain functional magnetic resonance imaging (fMRI) paradigm to examine the psychological function of shared neural responses (Lee et al., 2017, 2018). Lee et al. (2018) found that mother–child dyads with lower levels of family connectedness showed less similar neural response patterns in the anterior insular and dorsal anterior cingulate cortex (dACC), which then accounted for adolescent′s perceived stress level. In addition, lower levels of whole-brain intrinsic functional connectome similarity were associated with poorer emotional competence in children, which might increase psychopathological symptoms (Lee et al., 2017). Although previous studies with functional near-infrared spectroscopy or electroencephalogram techniques on shared neural responses identified the role of PFC, they were unable to examine deep brain regions such as the hippocampus due to spatial resolution limits.

Brain systems involving the PFC and deep brain regions support our ability to learn from socioemotional interactions (Carpendale & Lewis, 2004). The mPFC, a core node of socioemotional networks, plays a critical role in transmitting shared socioemotional schema involving knowledge, values, and beliefs across individuals (Krueger et al., 2009; Roy et al., 2012). The dorsomedial prefrontal cortex (dmPFC) and vmPFC, two key portions of the human mPFC, are responsible for maintaining social and emotional knowledge (Krueger et al., 2009). The dmPFC enables individuals to extract the goals and intentions from others during social interactions (Wagner et al., 2016), and the vmPFC contributes to social inference as well as self-related emotional experience and knowledge (Benoit et al., 2014). The disruptions of the mPFC systems have been linked to social and emotional dysfunctions in various psychiatric disorders such as anxiety and depression (Hiser & Koenigs, 2018). Beyond the mPFC systems, recent studies have demonstrated that the hippocampus works in concert with distinct portions of the mPFC allowing individuals to learn socioemotional knowledge and experience through social interactions (Hiser & Koenigs, 2018; Yeshurun et al., 2021). It has been suggested that the mPFC and hippocampus allow individuals to integrate internal information (e.g., memory, experience, and beliefs) in order to respond to the external stimulus. Because they live in the same family environment, child–parent dyads often have reciprocal interactions during various social and emotional scenarios. Therefore, they tend to form shared internal representations to understand and respond to each other.

Methodologically, mapping brain-to-brain concordance has the potential to advance our understanding of how dyadic interactions between children and parents lead to shared socioemotional representations across brains (e.g., Reindl et al., 2018). Recent studies have used naturalistic movie-watching fMRI to examine how individuals process and understand the complex socioemotional world based on our internal mental schema including long-term memory, emotion, and prior belief. This paradigm lends itself to intersubject correlation (ISC) and intersubject functional connectivity (ISFC), which quantifies functional brain activity concordance in cortical and subcortical regions across participants during movie watching (Hasson et al., 2004; Simony et al., 2016). These approaches have emerged as a powerful tool for exploring brain function and its neural synchrony across individuals. As such, this approach allows us to identify: (a) shared neural responses across child–parent brains during movie watching and (b) child–parent dyadic brain predictors underlying the effects of family emotional climate on children′s psychopathological symptoms. Based on the extended parent–child emotion regulation dynamics model (Ratliff et al., 2022), we hypothesized that child–parent dyads would exhibit higher brain-to-brain concordance in the mPFC and related functional circuits when compared to control child–stranger dyads, and that the amount of concordance would mediate the association between negative family emotional climate and children′s psychopathological symptoms. Notably, recent neurocognitive models posit that the hippocampus and vmPFC support the segmentation of boundaries among continuous events unfolding over time in a movie and integration of discrete events into meaningfully structured representations, namely schema (Baldassano et al., 2017; Ben-Yakov & Henson, 2018; Ezzyat & Davachi, 2021). Our perception and process of such events are actively shaped by existing memories and schematic scripts about experiences in the world (Baldassano et al., 2018). Thus, we hypothesized that children would exhibit a similar pattern of hippocampal responses during transitions between meaningful events (boundary time points) as their parents.

To test the above hypotheses, we conducted two separate studies integrating behavioral assessments of family emotional climate and children′s psychopathological symptoms, as well as dyad-based analysis of movie-watching fMRI data in child–parent and child–stranger dyads. In Study 1, we investigated how family emotional climate related to children′s psychopathological symptoms including internalizing and externalizing symptoms in 395 child–parent dyads (Figure 1a). We assessed family emotional climate using a well-validated scale that characterizes how often positive and negative emotions are expressed in a family (Familly Expressiveness Questionnaire; Halberstadt et al., 1995). Internalizing and externalizing

Figure 1
An Illustration of Experimental Design and Intersubject Correlation Analysis (ISC)



Note. (a) Correlations of negative ("Neg") and positive ("Pos") family emotional climate with children′s internalizing and externalizing symptoms, respectively. The difference between the negative (top row) and positive (middle row) family emotional climate is shown with strong statistical evidence. (b) Representative frames of a 6-min movie depicting a 7-year-old girl and her mother having an arguement used as the movie-watching fMRI paradigm. An illustration of voxelwise ISC between two time series of a child–parent dyad for each voxel of the gray-matter mask. (c) A matrix represents pairwise correlations among child and parent participants, resulting in child–parent dyads (CP, red), child–stranger controls (CS, blue), child–child, and parent–parent pairs (CC/PP, gray). Each cell represents an ISC value. fMRI = functional magnetic resonance imaging; ISC = intersubject correlation; TR = repetition time. * $q < .05$. ** $q < .01$.

symptoms were measured by a widely used child behavior checklist (CBCL; Achenbach, 1991). In Study 2, we used a child-friendly naturalistic movie-watching paradigm in an fMRI experiment known for its ecological validity (Vanderwal et al., 2019) to measure child–parent shared brain responses in a subsample of 50 child–parent dyads (Figure 1b). Brain-to-brain concordance metrics during movie watching were assessed through ISC and ISFC methods. Given the correlational nature of dyad-based brain concordance, we used an optimized linear mixed effect model with crossed random effects to account for the complex data hierarchical structure (Chen et al., 2017; Figure 1c). Mediation analyses were used to examine if child–parent shared brain response accounts for the direct and/or indirect effects of negative family emotional climate on children′s internalizing and externalizing symptoms. Event segmentation analysis was implemented to explore whether children′s neural responses evoked by event boundaries were associated with their parents.

Method and Materials

Transparency and Openness

In the following, we report how we determined our sample size, all data exclusions, all manipulations, and all measures used in this study. All data and research materials are available upon request to the corresponding author. Analysis scripts are available at https://osf.io/c2gjk/?view_only=ca36371395c14902b0842a34664f53fd. Data were analyzed using spm, brainiak, AFNI, and MediationToolbox. The study design and its analysis were not preregistered.

Participants and Procedure

In Study 1, we recruited 446 families (children ages 6–12 years old) to participate in behavioral measurements of family emotional climate and children′s psychopathological symptoms. Of them, a subsample of Study 1 (50 child–parent dyads, N = 100 participants) underwent magnetic resonance imaging scanning in Study 2. After removing participants with missing values (missing > 20%) in behavioral measures including CBCL and Familly Expressiveness Questionnaire, data of 395 child–parent dyads (children: M ± SD = 9.35 ± 1.64 years old, range = 6.28–12.51, 22 boys; parents: M ± SD = 37.42 ± 4.62 years old, range = 27–57, 12 fathers) were analyzed in the correlation between family emotional climate and child′s psychopathological symptoms. All participants had normal or corrected-to-normal vision, and no one reported a history of psychiatric or neurobiological disorders and developmental delays (e.g., language comprehension difficulties, attention difficulties) that would impact their ability to follow the instructions of tasks and the content of videos.

A subset of 50 child–parent dyads completed fMRI scanning while watching a movie clip in Study 2. Nine child–parent dyads were excluded due to children′s head motion with mean framewise displacement larger than 0.5 mm during movie-watching scanning. The final sample consists of 41 child–parent dyads (children: M ± SD = 10.15 ± 1.41 years old, range = 7–12 years old, 46.3% boys; parents: M ± SD = 38.91 ± 5.34 years old, range = 29–49 years old, 24.4% father). Six child–parent dyads were further excluded for the mediation analyses due to the incomplete family

emotional expressiveness questionnaires, and 35 child–parent dyads were included in the mediation analysis. Control analysis was also conducted for resting-state fMRI data to examine whether the observed shared responses in child–parent dyads are specific to the naturalistic paradigm. After excluding participants with mean framewise displacement larger than 0.5 mm, data of 25 pairs of children and parents were analyzed in the ISC and ISFC (children: $M \pm SD = 7.80 \pm 1.33$ years old, range = 7.80–2.26 years old, 40% boys; parents: $M \pm SD = 39.31 \pm 5.51$ years old, range = 29–49 years old, 16% father). All participants provided written informed consent before their participation and received monetary compensation. The study was approved by the institutional review board of the local institute. The schematic view of participants selection is provided in Supplemental Figure S1.

Materials

Movie Watching

A 6-min video unfamiliar to all participants was shot for this study, which showed a 7-year-old girl arguing with her mother (Figure 1b). Critical moments are provided in Table S1. Children and their parents underwent fMRI when separately viewing the video. This video was played with no sound/subtitles to mitigate potential confounds in auditory perception and language comprehension.

Psychopathological Symptoms Assessment

Children′s psychopathological symptoms were assessed by the parent-reported CBCL scores based on parent surveys (Achenbach, 1991), including anxious/depressed syndrome, withdrawn/depressed syndrome, somatic complaints, rule-breaking behaviors, and aggressive behaviors. Internalzing symptoms were quantified by items from anxious/depressed syndrome, withdrawn/depressed syndrome, and somatic complaints. Externalizing symptoms were quantified by items from rule-breaking and aggressive behaviors. The Chinese version of the CBCL has been widely used (Crijnen et al., 1999). The internal consistency of the parent-reported CBCL scales in the present study was $\alpha = 0.81$ for internalizing symptoms and $\alpha = 0.84$ for externalizing symptoms. The raw scores of subscales were used in all analyses.

Family Emotional Climate Assessment

Family emotion climate was measured by the Family Expressiveness Questionnaire (Halberstadt et al., 1995). Parents reported how often positive and negative emotions were expressed in their family on a 9-point Likert scale. Coefficient αs in the present sample were 0.89 and 0.85 for the positive and negative subscales, respectively.

Family SES Assessment

Family SES was measured by a self-report family background questionnaire that used 10- and 6-point scales to assess the education and monthly income of each parent, respectively. To form a composite SES score for each parent, the income and education scores were first divided into individual z scores for each parent, which were then averaged.

Brain Imaging Data Acquisition

Whole-brain images were acquired from Siemens 3.0 T scanner (Siemens Magnetom Trio TIM, Erlangen, Germany), using a 12-channel head coil with a $T2^*$-sensitive echo-planar imaging sequence based on blood oxygenation level-dependent contrast. Thirty-three axial slices (4 mm thickness, 0.6 mm skip) parallel to the anterior and posterior commissure line and covering the whole brain. Each participant′s high-resolution anatomical images were acquired through three-dimensional sagittal T1-weighted magnetization-prepared rapid gradient echo with a total of 192 slices (repetition time 2,530 ms, echo time 3.45 ms, flip angle 9°, inversion time 1,100 ms, voxel size $1.0 \times 1.0 \times 1.0$ mm^3, acquisition matrix 256×256, field of view 256×256 mm^2, bandwidth 190 Hz/Px, slice thickness 1 mm). Seventeen child–parent dyads were scanned at Site 1, and the remaining 24 child–parent dyads were scanned at Site 2, and sites were included into statistical analyses as a covariate of no interest. Both scanners were 3.0T Trio TIM with the same types of head coils and sequence parameters.

Brain Imaging Data Analysis

Preprocessing

Based on previous studies on ISC preprocessing pipelines (Nastase et al., 2019), brain images were preprocessed using statistical parametric mapping (SPM12). Images were corrected for slice acquisition timing and realigned for head motion correction. Subsequently, functional images were coregistered to each participant′s gray-matter image segmented from corresponding T1-weighted image, then spatially normalized into a common stereotactic Montreal Neurological Institute (MNI) space and resampled into 2-mm isotropic voxels. Images were smoothed by an isotropic 3D Gaussian kernel with 6-mm full-width half-maximum. The preprocessed images were regressed on a set of nuisance covariates (i.e., motion parameters, the average signal of white matter, and cerebrospinal fluid) and 140-s high-pass filtered using toolbox Nilearn Version 0.6.2. Finally, the first five volumes and the last five ones were removed to minimize stimulus onset and offset effects, and the data were z-scored over time.

ISC and Statistical Analysis

Whole-brain ISC maps during movie watching were computed for all possible pairs of 41 participants in a gray-matter mask using BrainIAK′s ISC function (Kumar et al., 2020; Figure 1b). The ISC maps were submitted to further statistical analyses to identify brain regions that show synchronous (shared) neural response across the whole sample. We adopted a linear mixed-effects (LME) model using a crossed random-effects formulation that can accurately interpret the ISC data′s correlation structure (Chen et al., 2017). Participants′ gender, age, and two scanning sites were treated as covariates of no interest in the LME model. False discovery rate (FDR) correction was used to correct multiple comparisons (Benjamini & Hochberg, 1995). Next, we used a two-group formulation of the LME model with three covariates (age, gender, and site) to identify whether brain systems were more synchronous in child–parent dyads than child–stranger pairs. Child–parent dyads were defined by pairing a child and their own parent, and child–stranger dyads were generated by pairing a child with all parents except their own parent. 3dClustSim module of Analysis of Functional NeuroImages was used to correct multiple comparisons, with a voxelwise $p < .001$, clusterwise < 0.05. We also performed a parallel control analysis of resting fMRI data set to detect child–parent shared neural responses.

ISFC Analysis

The ISFC analysis was implemented to identify movie-evoked functional connectivity (FC) across participants. We used a seed-based ISFC approach by computing the correlation of a given seed′s, that is, 6-mm sphere of the peak voxel at MNI coordinate (2, 38, −18) in the vmPFC and (0, 56, 12) in the dmPFC, time series in one participant with every other voxel′s time series in another participant. The computation of ISFC produced two asymmetric matrices for $r(\text{vmPFC}_{\text{participant1}}, Y_{\text{participant2}})$ and $r(\text{vmPFC}_{\text{participant2}}, Y_{\text{participant1}})$. We then computed the average correlation, which was treated as the ISFC value between each participant pair, where r represents Pearson′s correlation and Y represents the time series of each given voxel from participants. Likewise, the LME was used to determine which brain regions showed higher coordination with vmPFC and dmPFC in child–parent pairs than child–stranger pairs. FDR was used to correct multiple comparisons.

Intrasubject Functional Connectivity Analysis

To verify that child–parent vmPFC–hippocampal intrasubject functional connectivity played a unique role in the relationship between negative family emotional climate and children′s internalizing problem, we also examined whether the single-brain′s vmPFC-seeded FC is associated with negative family emotional climate and children′s internalizing symptoms. We examined single-brain FC in children′s and parent′s brains and ran multiple regressions with negative family emotional climate and children′s internalizing symptoms as separate regressors, predicting vmPFC-seeded FC. Other settings are identical for above ISFC.

Meta-Analytic Decoding With Neurosynth

The Neurosynth allows us infer the psychological domains involved in brain map of the shared vmPFC circuits in child–parent dyads. Specifically, we correlated the thresholded child–parent vmPFC- and dmPFC-based ISFC map (FDR $q < 0.05$) to the topics map of 15 general psychological domains involving a range of possible brain processes during movie viewing using the Neurosynth′s Python notebook (https://github.com/neurosynth/neurosynth; commit Version 948ce7).

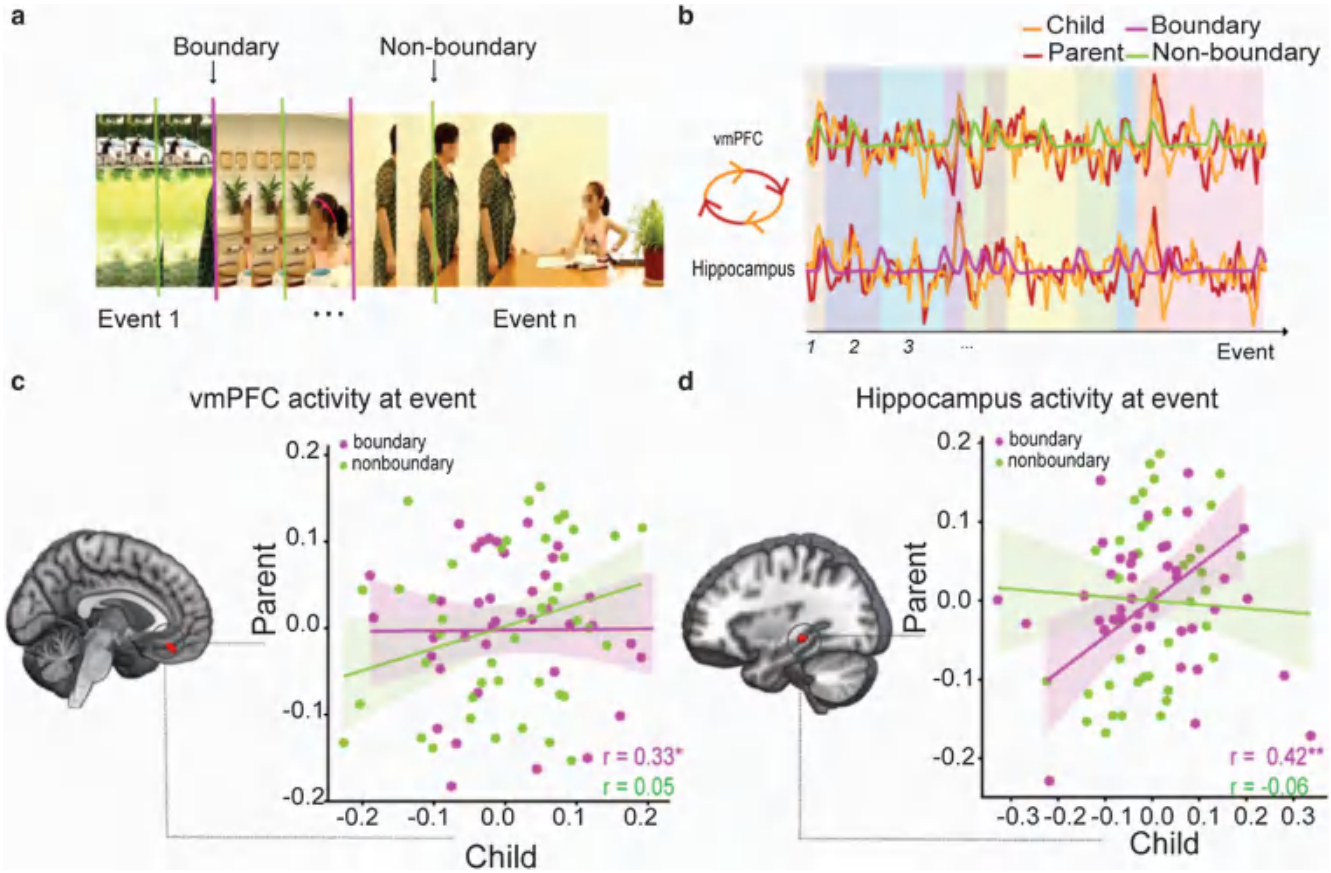
Mediation Analysis

Mediation analysis was performed using the Mediation Toolbox developed by Tor Wager′s group (https://github.com/canlab/MediationToolbox). Prior to the mediation analysis, average values representing ISFC strength with the vmPFC and dmPFC were extracted from significant clusters identified in the above linear mixed model to examine the correlation with negative family emotional climate using FDR corrections to control the false positives. Next, a mediation model was constructed to investigate the mediating pathways between negative family emotional climate, shared vmPFC–hippocampus ISFC strength, and children′s internalizing symptoms, especially anxiety/depressed aspects. The indirect or mediated effect was tested by a bias-corrected bootstrapping method ($n = 10{,}000$ resamples). All statistical tests here are two-tailed and pass the FDR correction. More details are provided in the Supplemental Materials.

Event Boundary Analysis

Event boundaries were collected by an independent group of 20 adult raters (10 males) who watched the same 6-min silent video. The raters were asked to press a key at the end of one meaningful event and the beginning of another. In line with one previous study (Reagh et al., 2020), we included the boundary and nonboundary time points of this video (Figure 2a). Boundaries time points were agreed upon in at least half of the samples, and we found a total of 10 event boundaries of the time series. We also added the same number of nonboundary time points compared to the event boundaries. The onset times of boundary and nonboundary events were next convolved with a canonical hemodynamic response function to obtain the boundary and nonboundary time series. Then, we correlated each participant′s hippocampal and vmPFC time series with the event boundary and nonboundary time series. Finally, we examined whether

Figure 2
Child–Parent Hippocampal and vmPFC Activity Concordance in Response to Boundary and Nonboundary Events



Note. (a) An illustration of boundary and nonboundary events for major episodic events during movie watching. (b) Child–parent dyads showed higher vmPFC–hippocampus functional coupling during movie watching, and their vmPFC and hippocampal activity concordance were modulated by segmentation of event boundaries. The magenta and green lines represent expected signals of event boundaries and nonboundaries respectively. The yellow and red lines represent neural signals in children and parents separately. (c) Child–parent hippocampal activity concordance was significantly higher for boundary than nonboundary event time series ($Z = 2.30$, $p = .01$). (d) Child–parent vmPFC activity concordance was marginally significantly higher for boundary than nonboundary time series ($Z = -1.39$, $p = .08$). vmPFC = ventromedial prefrontal cortex.
* $p < .05$. ** $p < .01$.

children′s hippocampal and vmPFC response to the boundary and nonboundary time series were correlated with their parent′s response while controlling children′s age, gender, and sites of no interest.

Results

Negative Family Emotional Climate Linked to Children′s Psychopathological Symptoms

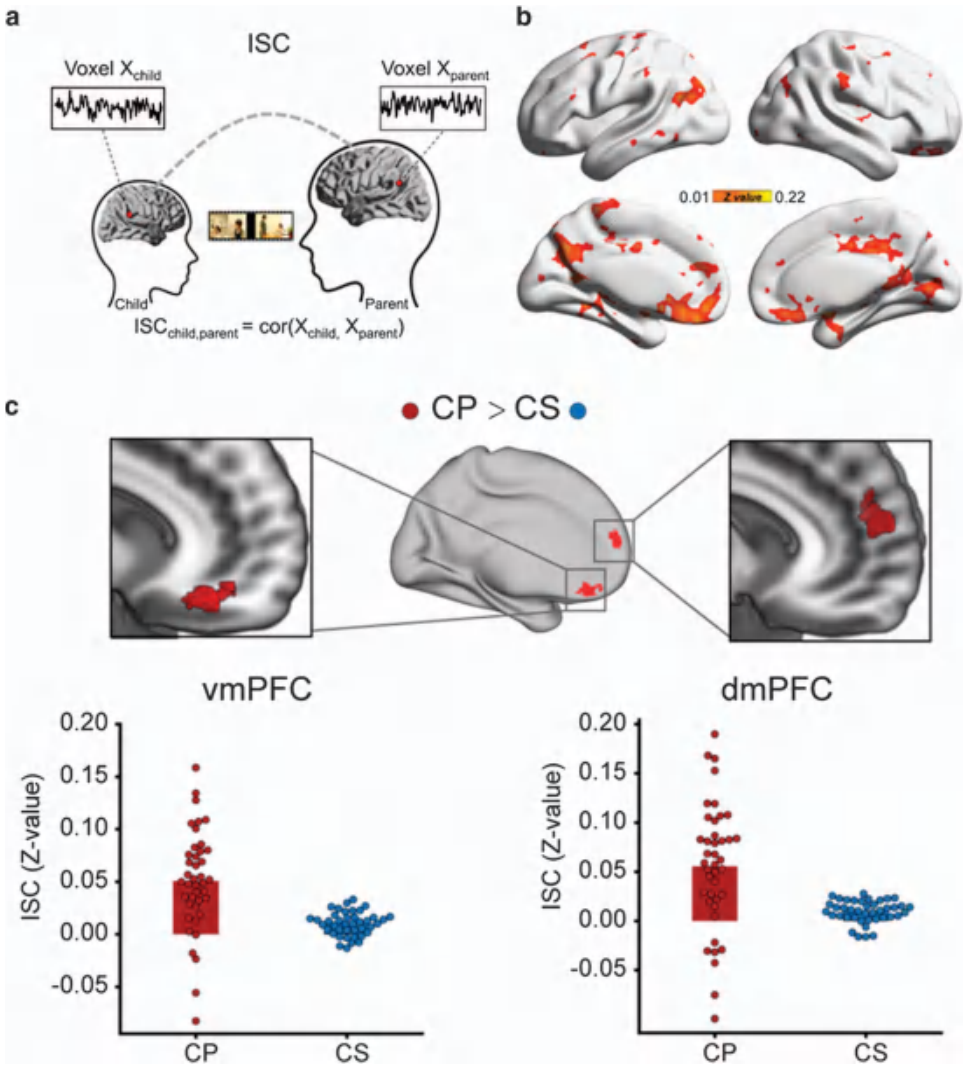
First, we examined how family emotional climate, including positive and negative components, was associated with children′s psychopathological (i.e., internalizing, externalizing) symptoms in Study 1. Pearson′s correlation analyses revealed that negative family emotional climate was associated with more severe children′s internalizing symptoms ($r = 0.17$, $q < 0.001$, 95% CI [0.08, 0.26]), including anxious/depressed ($r = 0.13$, $q = 0.024$, 95% CI [0.03, 0.22]), withdrawn/depressed ($r = 0.16$, $q = 0.005$, 95% CI [0.07, 0.25]), and somatic symptoms ($r = 0.13$, $q < 0.001$, 95% CI [0.04, 0.22]), as well as externalizing symptoms ($r = 0.23$, $q < 0.001$, 95% CI [0.14, 0.32]), including aggressive ($r = 0.24$, $q < 0.001$, 95% CI [0.07, 0.24]) and rule-breaking behaviors ($r = 0.15$, $q = 0$ .001, 95% CI [0.14, 0.32]; all q values were FDR corrected; Figure 1a). There were no reliable associations of positive family emotional climate with children′s internalizing and externalizing symptoms (all $rs < 0.01$, $qs > 0.70$). Further tests for Fisher′s z-transformed correlation coefficients revealed statistically stronger correlations with negative than positive family emotional climate (all $Zs > 1.95$, $qs < 0.05$, FDR corrected). Notably, the positive associations of negative family emotional climate with children′s internalizing and externalizing symptoms remained significant even after controlling for child′s and parent′s age, gender, and socioeconomic status (SES;

Supplemental Figure S2). These results indicate that children from negative family environments exhibit more severe internalizing and externalizing symptoms.

Increased Child–Parent Neural Synchrony in the mPFC During Movie Watching

Next, we identified intersubject shared patterns of temporal neural activity in response to viewing a movie across brains. The ISC maps were computed to represent shared brain activity by correlating time series of the same voxel across participants (Figure 3a). A LME model was conducted for ISC maps collapsing across children and parents to identify brain regions showing ISC during movie watching. This analysis revealed significant clusters in unimodal and transmodal association areas (Figure 3b, $q < 0.05$ FDR-corrected). This pattern of results is consistent with ISC data from previous fMRI studies (Finn et al., 2018; Hasson et al., 2004).

Figure 3
Primary Results From Intersubject Correlation (ISC) Analysis



Note. (a) An illustration of intersubject correlation (ISC) between time series of a given voxel in each child and his/her parent′s brain. (b) Brain regions show statistically significant ISC during movie watching in general, with prominent effect in the posterior visual cortex followed by frontal, temporal, and parietal cortices. Statistically significant clusters were thresholded using $q < 0.05$ FDR corrected. The color bar represents Fisher′s Z value. (c) Representative views of the vmPFC and dmPFC showing stronger intersubject synchronized activity (ISC) in child–parent dyads as compared to child–stranger controls. Significant clusters were derived from a contrast between child–parent (CP) dyads and child–stranger (CS) controls, with a voxelwise threshold $p < .001$ (two-tailed) combined with cluster-level threshold significance level α of 0.05 corrected for multiple comparisons. FDR = false discovery rate; vmPFC = ventromedial prefrontal cortex; dmPFC = dorsomedial prefrontal cortex.

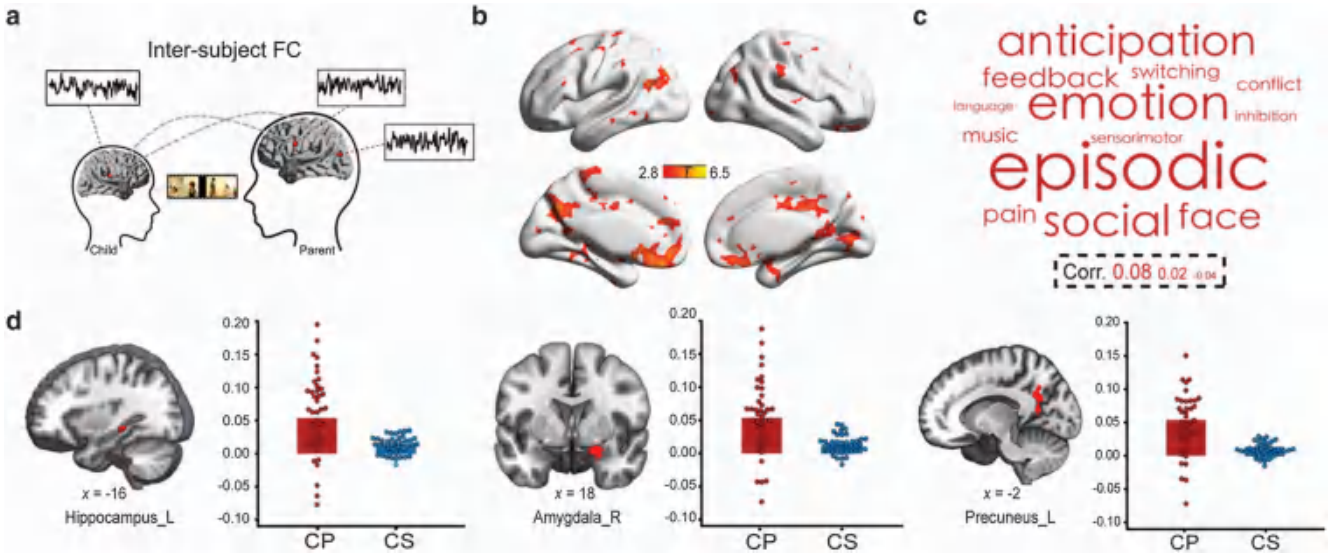
We then conducted dyad-based analysis using ISC maps between each child and their parent in comparison to each child and all stranger's parents as a control. We implemented an optimized LME model with crossed random effects (Chen et al., 2017) and examined brain systems showing shared temporal neural responses during movie watching unique to child–parent dyads relative to child–stranger controls. This analysis (Figure 3c, Supplemental Table S3) revealed significant clusters (voxelwise $p < .001$ two-tailed, clusterwise significance level < 0.05) in the ventral mPFC (vmPFC), peak MNI coordinate at (2,38, −18); cluster size $k = 116$ voxels, and the dorsal mPFC (dmPFC), peak at (0, 52, 12), $k = 122$ voxels. There were no significant clusters when examining greater activity in child–stranger versus child–parent dyads. To verify whether this effect is specific to movie stimulus, we also performed parallel analysis for resting-state fMRI data from 25 child–parent dyads, and there were no statistically reliable ISC effects in the vmPFC and dmPFC (Supplemental Table S5).

Increased Child–Parent vmPFC Connectivity With Social and Emotional Systems During Movie Watching

Given that mPFC-centric circuitry is implicated in human emotion and social cognition (Krueger et al., 2009; Lieberman et al., 2019), we used the vmPFC and dmPFC clusters identified above as separate seeds to perform ISFC analyses. The LME model for the vmPFC-seeded ISFC map was examined to identify functional circuits showing higher interbrain FC in child–parent versus child–stranger dyads (Figure 4a). This analysis revealed significant clusters in widespread regions in the frontal, temporal, and occipital lobes, including the hippocampus, peak MNI coordinates (−16, −30, −8); amygdala, peak MNI coordinates (18,2, −16); and fusiform gyrus, peak MNI coordinates (−32, −48, −8), FDR $q < 0.05$ (Figure 4b–d, Supplemental Table S4). Parallel analysis for dmPFC-seeded ISFC maps revealed that child–parent dyads exhibited higher connectivity with the angular gyrus, peak MNI coordinates (−46, −64, 24), and medial prefrontal gyrus, peak MNI coordinates (0, 54, 14), than child–stranger dyads (Supplemental Figure S3a, Table S4; FDR $q <$ 0.05). To verify whether this effect is specific to movie watching, we also performed parallel analysis for resting-state fMRI data, and there were no any reliable ISFC effects in child–parent dyads compared to child–stranger controls.

We then used a meta-analytic decoding approach based on a widely used Neurosynth platform (Yarkoni et al., 2011) to determine psychological functions of the above clusters that showed higher interbrain FC with the vmPFC and dmPFC in child–parent than child–stranger dyads. This analysis revealed that child–parent shared vmPFC-based connectivity patterns with widespread regions that are implicated in episodic memory, emotion, and social functions (Figure 4c), whereas the dmPFC-based connectivity did not exhibit a connectivity

Figure 4
Results From Intersubject Functional Connectivity (ISFC) Analysis and Metadecoding by the Neurosynth



Note. (a) An illustration of seed-based ISFC that involves computing the correlation between a seed's time series in a child's brain and all other voxels' time series of his/her parent brain. (b) Compared to child–stranger control dyads, child–parent dyads showed stronger ISFC of the vmPFC with the inferior frontal gyrus, middle cingulum gyrus, precuneus, fusiform, hippocampus, and middle occipital gyrus ($q < 0.05$ FDR corrected). (c) Word cloud depicting commonly used terminology associated with regions showing vmPFC connectivity. (d) Representative slices of significant clusters in the hippocampus, amygdala, and precuneus show stronger ISFC in child–parent dyads than child–stranger control dyads. ISFC = intersubject functional connectivity; CP = child–parent dyads; CS = child–stranger controls; FDR = false discovery rate; vmPFC = ventromedial prefrontal cortex; FC = functional connectivity.

pattern implicated in these functions (Supplemental Figure S3c). These results indicate higher vmPFC connectivity with social and emotional systems in child–parent dyads than child–stranger controls.

Reduced Child–Parent vmPFC Connectivity With the Hippocampus Links to Negative Family Emotional Climate and Children's Internalizing Symptoms

Given our central hypothesis at issue, we further investigated how negative family emotional climate was associated with ISC metrics of brain activity and connectivity during movie watching in child–parent dyads, and whether such alteration was linked to children's psychopathological symptoms. Brain–behavior association analyses were conducted for ISC and ISFC metrics of the vmPFC and dmPFC. With these metrics, we found that negative family emotional climate was significantly correlated with lower child–parent shared vmPFC connectivity with the left hippocampus (Figure 5b) and right precuneus ($q = 0.03$, FDR corrected; Supplemental Table S4). Next, we observed a negative correlation of child–parent vmPFC–hippocampal FC with children's internalizing symptoms ($r = -0.41$, $q = 0.04$, FDR correction). Further analyses indicate that the aforementioned association is mainly driven by the association between FC and anxious/depressed symptoms ($r = -0.43$, $q = 0.03$, FDR correction).

Because child–parent vmPFC–hippocampal connectivity was associated with both negative family emotional climate and children's internalizing symptoms, we then conducted a mediation analysis to examine whether this ISFC pathway accounts for the association between negative family emotional climate and children's internalizing symptoms. This analysis revealed an indirect pathway of reduced vmPFC connectivity with the hippocampus mediating the association between negative family emotional climate and higher children's internalizing symptoms (Figure 5c, $B = 0.17$, $SE = 0.10$, $p = .028$, bootstrapped 95% CI [0.01, 0.42], 56.7% of the total effect size) and children's anxious/depressed symptoms ($B = 0.19$, $SE = 0.12$, $p = .04$, bootstrapped 95% CI [0.00, 0.46], 59.4% of the total effect size). Notably, the mediation effect was significant even when regressing out child–parent's age and gender (Supplemental Figure S4b). Because children's emotional symptoms may also have the possibility of influencing family emotional climate (Rothenberg et al., 2020), we tested an alternative model with children's internalizing symptoms as input variable and negative family emotional climate as an outcome predictor. Although this model is also valid (Supplemental Figure S4c and d), model comparison with Bayesian information criterion (BIC) favors the initial model with family emotional climate affecting child internalizing symptoms (BIC = 113.89) over the reverse alternative model (BIC = 228.34; Raftery, 1995).

To verify whether negative family emotional climate is associated with children's internalizing symptoms through shared rather than each individual's vmPFC–hippocampus responses, we performed vmPFC-seeded FC within children's brains (Figure 5a). We did not find any reliable effects pertaining to intrabrain metrics (Figure 5b). In addition, we conducted a time-lagged analysis for vmPFC-based ISFC to determine when child–parent dyads exhibited the highest ISFC. This analysis revealed that child–parent dyads exhibited the highest vmPFC–hippocampal functional correlation at lag zero (Supplemental Figure S4). Together, these results indicate that reduced child–parent vmPFC connectivity with the hippocampus accounts for the adverse effects of negative family emotional climate on children's internalizing symptoms (see Figure 4).

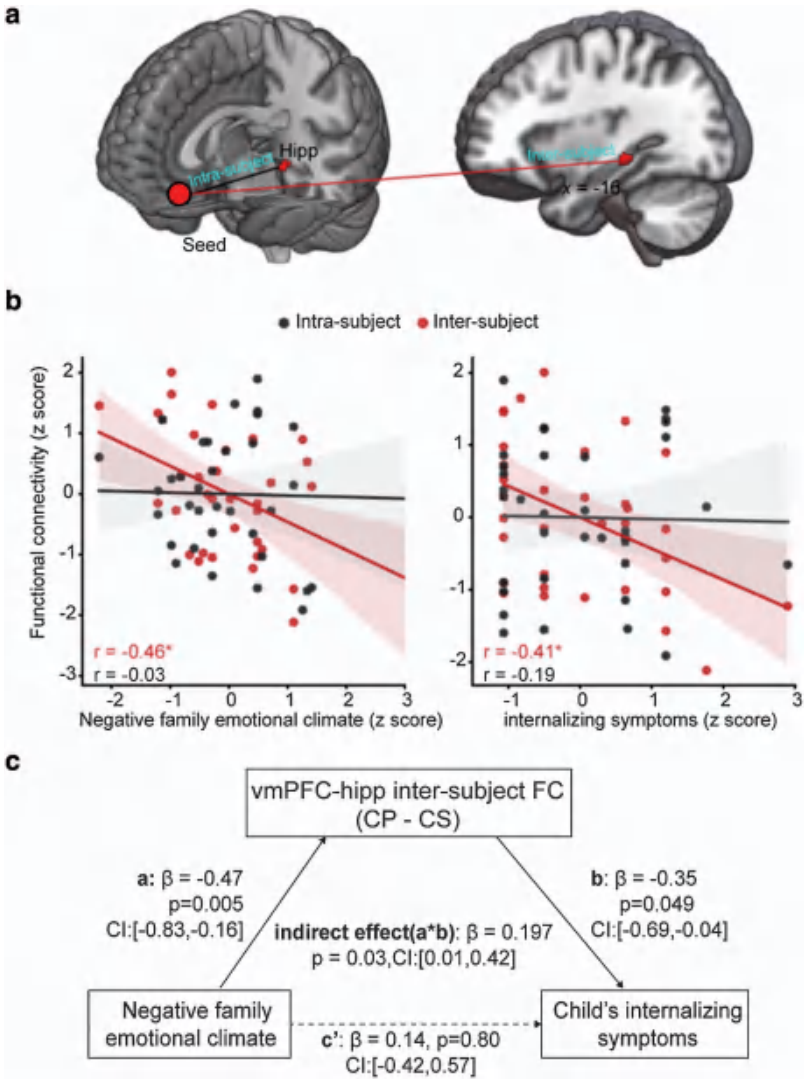
Child–Parent vmPFC and Hippocampal Activity Concordance in Event Boundaries During Movie Watching

To test our hypothesis on a shared pattern of neural responses to event boundaries in child–parental dyads, we investigated whether children's neural responses evoked by boundary versus nonboundary events are similar to their parents. We therefore implemented a dyad-based analysis of brain responses to event segmentation during movie watching to examine whether children's hippocampal and vmPFC responses to event boundary and nonboundary time points are correlated with their parents. As expected, this analysis revealed that children's hippocampal responses (Figure 2d) to event boundaries were indeed positively associated with their parent's responses ($r = 0.42$, $p = .008$, 95% CI [0.11, 0.65]). This concordance, however, did not emerge for nonboundary time points ($r = -0.06$ $p = .703$, 95% CI [−0.38, 0.26]). Further Z-test analysis for two correlation coefficients revealed a significant difference ($Z = 2.30$, $p = .01$). Interestingly, a parallel analysis revealed an opposite pattern of child–parent concordance for the vmPFC activity (Figure 2c). That is, children's vmPFC responses to nonboundary time points were positively correlated with their parents ($r = 0.33$, $p = .042$, 95% CI [0.01, 0.59]) but not with event boundaries ($r = 0.05$, $p = .75$, 95% CI [−0.27, 0.37]). Further tests revealed a marginally significant difference between the two correlations ($Z = -1.39$, $p = .08$). Taken together, these results indicate that the vmPFC and hippocampus exhibit interactive activity concordance in child–parent dyads in response to nonboundary and boundary events during movie watching.

Discussion

In this study, we investigated the neural reciprocity of how negative family emotional climate was associated with children's psychopathological symptoms by quantifying

Figure 5
Reduced Intersubject Neural Functional Connectivity in Child–Parent Dyads Links to Negative Family Emotional Climate and Internalizing Symptoms



Note. (a) Representative view of the vmPFC seed and its intra- and intersubject connectivity with the hippocampus. (b) Scatter plots depict the negative correlations (FDR corrected) of intersubject vmPFC–hippocampal connectivity (red) with negative family emotional climate and children′s anxious/depressed symptoms. This pattern is not observed using intrasubject vmPFC–hippocampal connectivity (gray). (c) A mediation model depicts the indirect pathway of negative family emotional climate on children′s internalizing symptoms via the shared vmPFC–hippocampal intersubject connectivity. Standardized coefficients are depicted. The solid lines represent statistically significant effects. CP = child–parent dyads; CS = child–stranger controls; FDR = false discovery rate; CI = confidence interval; vmPFC = ventromedial prefrontal cortex; FC = functional connectivity.
* $q < .05$. All statistical tests here are two-tailed and pass the FDR correction.

brain-to-brain concordance of activity and connectivity during naturalistic movie watching in child–parent dyads. Compared to child–stranger controls, child–parent dyads exhibited higher ISC in the vmPFC and dmPFC during movie watching, and higher ISFC of the vmPFC with widespread regions critical for socioemotional cognition. Critically, reduced child–parent vmPFC–hippocampal connectivity accounted for the association between negative family emotional climate and children′s internalizing symptoms, with the vmPFC and hippocampus exhibiting higher child–parent

activity concordance to nonboundary and boundary events, respectively. Our findings illustrate a neurobiological model of how negative family emotional climate is associated with children′s internalizing symptoms through reduced child–parent brain-to-brain concordance in the vmPFC–hippocampal circuitry.

Behaviorally, children in negative family emotional climate experienced more severe internalizing and externalizing symptoms. This is in line with previous findings showing positive associations between family risk factors (e.g., maternal maltreatment, family conflicts) and internalizing and externalizing symptoms in children (Gong et al., 2021; Schleider & Weisz, 2017). According to the biobehavioral synchrony and social learning models (Feldman, 2020; Justyna, 2017), child–parent shared mental representations and experiences are indispensable for children to learn emotional skills as they socialize with their parents in daily life. Through child–parent reciprocal interactions such as affective synchrony and empathic dialogues, children regulate themselves to attune to each other′s minds. This helps them develop socioemotional skills such as emotion regulation and theory of mind, which then reduces the risk of suffering psychopathological symptoms (Feldman, 2020; Thomassin & Suveg, 2014).

Socioemotional interactions in a family have also been demonstrated to help child–parent dyads build a shared or synchronous pattern of brain responses (Piazza et al., 2020; Wass et al., 2020). Such shared neural responses can help children learn and form socioemotional skills through reciprocal interactions with their parents in daily life (Reindl et al., 2018), which in turn serves as a scaffold for socialization. Conversely, negative family emotional climate may impede child–parent brains from forming effective socioemotional skills, contributing to the risk of developing children′s psychopathological symptoms. As discussed below, this account is supported by three aspects of our observed concordance across child–parent brains.

First, our movie-watching fMRI results show that child–parent dyads exhibited higher ISC in the vmPFC and dmPFC during movie watching than control child–stranger dyads. This is reminiscent of previous findings showing that the mPFC plays a critical role in characterizing shared neurocognitive processes between children and their parents (Hoyniak et al., 2021; Itahashi et al., 2020; Piazza et al., 2020). The mPFC is thought to act as a simulator for socioemotional schema that allows us to integrate and summarize social, self, and emotional information as events unfold over time (Krueger et al., 2009). When processing socioemotional events, the dmPFC is important for inferring other′s goal-oriented actions, whereas the vmPFC is crucial for appraisal, evaluation, and regulation of values involved in self and affective processes (Bzdok et al., 2013). Such processes could serve as a neurocognitive basis for understanding the intentions and mental states of others (Fiske & Taylor, 2013). Thus, higher ISC in the dmPFC and vmPFC across child–parent dyads likely reflect that similar strategies might be employed to perceive and integrate external information with existing knowledge to construct meanings or narratives as continuous events unfold over time during movie watching.

Second, our results also show that child–parent dyads exhibited higher ISC of vmPFC- and dmPFC-based FC with widespread regions of social and emotional brain networks in comparison with child–stranger dyads. Specifically, child–parent dyads shared vmPFC coupling with distributed regions crucial for episodic memory, emotion, and social processing (Lieberman et al., 2019; Phillips et al., 2019), while shared dmPFC coupling had relatively uniform connectivity with regions such as temporal parietal junction during movie watching. These inferences were drawn from a widely used reverse inference database (Yarkoni et al., 2011). The vmPFC and its coordination with the hippocampus, precuneus, and amygdala are recognized to support the appraisal of perceived socioemotional events (Hiser & Koenigs, 2018) and the reinstatement of existing knowledge and strategies formed over the course of child–parent interactions (Feldman, 2015, 2017). These processes help children learn how to cope with negative emotions (Nawa & Ando, 2019; Roy et al., 2012). Our data suggest that vmPFC circuitry is critical for integration of disparate events shared by child–parent dyads when viewing emotional movies, likely by promoting transmission of affectivity and sociality across child–parent dyads.

Third and more importantly, our fMRI results showed that reduced child–parent brain-to-brain concordance in the vmPFC–hippocampal pathway mediated the association between negative family emotional climate and more severe child internalizing symptoms. This finding provides one of the first pieces of empirical evidence for the extended parent–child emotion regulation dynamics model (Ratliff et al., 2022), showing that cross-brain connectivity between child and parent serves as an important mechanism linking family environment with child emotional development. The vmPFC–hippocampal circuitry may be important for constructing the meaning of emotional events (Nawa & Ando, 2019; Roy et al., 2012). Both these regions are part of the default mode network, which is an active and dynamic "sense-making" network that integrates incoming information with existing memory and knowledge to form internal context-dependent models (namely schema) of events as they unfold over time (Hasson et al., 2012; Yeshurun et al., 2021). Child–parent concordance of vmPFC–hippocampal coupling during movie watching likely reflects their coconstruction of socioemotional events according to shared and/or embodied relationships. It is possible that children with higher parental concordance of vmPFC–hippocampal connectivity may develop better socioemotional skills and thus exhibit lower levels of internalizing symptoms. Our observed mediation effect suggests that child–parent vmPFC–hippocampal

concordance could serve as a potential biomarker for children in families with emotional disorders. Future work may use neurofeedback techniques to explore the impact of upregulating vmPFC–hippocampus coordination with parents on children′s emotional health.

The vmPFC–hippocampal circuitry is also crucial in updating and integrating new events into existing memory schemas (Gilboa & Marlatte, 2017; Zeithamova et al., 2012). Analysis of event boundary-evoked response revealed that children′s hippocampal responses to event boundaries were positively related to their parents′ responses. Given that segmenting continuous events into meaning units is driven by our experience and mental schemas (Baldassano et al., 2018), child–parent concordance on hippocampal activity during boundary-evoked responses suggests that child–parent dyads utilize their shared episodic memories and schemas to understand and interpret socioemotional events during movie watching. Together with stronger interbrain vmPFC–hippocampal connectivity observed in child–parent dyads, our results are among the first to suggest that the vmPFC may signal child–parent concordance of hippocampal activity in order to orchestrate long-term memory, emotional and social systems to support their understanding of events during movie watching. However, the event-boundary analysis is a preliminary result to characterize child–parent neural responses to boundary and nonboundary events. Further studies with optimal task designs are required to investigate the neurocognitive mechanisms involved in child–parent shared neural response.

Several limitations should be considered in our study. First, we assessed child–parent neural concordance at activity and connectivity levels when viewing a movie showing a girl arguing with her mother. Whether our findings can be generalized into other types of situations remains open for future studies. Second, although we leveraged a naturalistic movie-watching fMRI paradigm, dedicated task designs are needed to complement the interpretation of child–parent shared neural responses in vmPFC and related circuits. Specifically, we did not manipulate child–parent socioemotional events during movie watching. Future studies with optimal task design are required to assess shared neural representations during socioemotional experiences in child–parent dyads. Third, the indirect effect of child–parent shared brain responses is based on cross-sectional data. It is thus possible that such relationships are bidirectional (Gong et al., 2021; Nelemans et al., 2020). Longitudinal designs are required to disentangle the directionality effects. In addition, potential sex-related dyads (e.g., father-son dyads, mother-daughter-dyads) should be addressed in future studies. There may be important sex-specific associations between shared neural response and psychopathological symptoms in children given different parenting roles (Cabrera et al., 2018).

Conclusion

The present study demonstrates that atypical child–parent neural synchrony during movie watching is linked to negative family emotional climate and children′s psychopathological symptoms. Child-parent interbrain concordance in ventral mPFC–hippocampal circuitry, rather than intrabrain metrics, emerges as a key locus that mediates the adverse effect of negative family environment on children′s internalizing symptoms. Our study provides a neurobiological account of how negative family environment influences children′s internalizing symptoms through shared socioemotional representations across brains in child–parent dyads. This work can inform the development of dyad-based prevention and interventions designed to mitigate children′s internalizing symptoms.

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