Neuroscience

Mother-child dyadic interactions shape children's social brain and theory of mind

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eLife Assessment

This **important** study reports **solid** evidence for the significant role of mother-child neural synchronization and relationship quality in the development of Theory of Mind (ToM) and social cognition. The findings effectively bridge brain development with children's behavior and parenting practices, and will be of interest to researchers studying brain development and social cognition, as well as the general public.

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Abstract

Social cognition develops through a complex interplay between neural maturation and environmental factors, yet the neurobehavioral mechanisms underlying this process remain unclear. Using a naturalistic fMRI paradigm, we investigated the effects of age and parental caregiving on social brain development and Theory of Mind (ToM) in 34 mother-child dyads. The functional maturity of social brain networks was positively associated with age, while mother-child neural synchronization during movie viewing was related to dyadic relationship quality. Crucially, parenting and child factors interactively shaped social cognition outcomes, mediated by ToM abilities. Our findings demonstrate the dynamic interplay of neurocognitive development and interpersonal synchrony in early childhood social cognition, and provide novel evidence for neurodevelopmental plasticity and reciprocal determinism. This integrative approach, bridging brain, behavior, and parenting environment, advances our understanding of the complex mechanisms shaping social cognition. The insights gained can inform personalized interventions promoting social competence, emphasizing the critical importance of nurturing parental relationships in facilitating healthy social development.

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Introduction

Social cognition, defined as the ability to interpret and predict others' behavior based on their beliefs and intentions and to interact in complex social environments and relationships is a crucial aspect of human development [1,2]. Children's social cognitive abilities have far-reaching implications for their social competence, peer acceptance, and success in school [3,4]. A key component of social cognition is the ability to understand and reason about others' mental states, known as "Theory of Mind" (ToM) [5]. ToM enables children to predict and interpret others' actions based on an understanding of their unobservable mental states, such as beliefs, desires, and emotions [6]. The development of ToM follows a predictable sequence throughout childhood, with major milestones occurring between the ages of 3 and 5 years [6]. During this period, children show a marked improvement in their ability to appreciate that others can hold beliefs and knowledge states that differ from their own [7]. This understanding is typically assessed using false belief tasks, which require children to reason about what another person might mistakenly think or believe [8]. Success on these tasks indicates a more adult-like understanding of the mind and is considered a hallmark of ToM development [9].

Advances in neuroimaging techniques have allowed researchers to investigate the neural basis of social cognition and its development [10]. Studies in adults have consistently identified a network of brain regions involved in ToM reasoning, including the medial prefrontal cortex, temporoparietal junction, precuneus, temporal lobes, and inferior frontal gyri [11]. Additionally, a distinct network, known as the social pain matrix (SPM), has been implicated in processing others' physical sensations and pain. This network comprises regions such as the bilateral insula, medial frontal gyrus, secondary somatosensory cortex, and anterior middle cingulate cortex [12]. ToM and SPM networks are often jointly recruited to reason about different kinds of internal states: the internal states of others' minds, including beliefs and desires [13], and emotions [14], and the internal states of others' bodies, including pain [15]. Developmental studies have begun to chart the trajectory of these social brain networks in children, revealing that they become increasingly specialized and differentiated throughout childhood [16–18]. For example, a recent study by Richardson et al. found that the ToM and SPM networks are functionally distinct by age 3 and show increasing within-network correlations and anti-correlations between networks from ages 3 to 12 [17]. These findings suggest that the development of specialized brain regions for reasoning about others' mental states and physical sensations is a gradual process that continues throughout childhood.

Crucially, the development of social cognition is thought to be influenced not only by the maturation of neural circuits with age, but, just as importantly, by social-environmental factors such as parental caregiving and parent-child relationship quality. Family is considered the primary socialization context for children, and parenting plays a crucial role in shaping a child's experiences and social development [19,20]. Theories of bio-behavioral synchrony [21] and social learning [22] emphasize the importance of parent-child interactions and shared experiences in the development of social skills. Bio-behavioral synchrony refers to the matching of behavioral, physiological, and neural responses between mother and child during social interactions [21]. This synchronization is thought to facilitate emotional sharing and social understanding and has been linked to positive developmental outcomes [23,24]. Bandura's model of reciprocal determinism, which highlights the bidirectional interactions between individuals and their environment, provides a framework for understanding how children acquire social skills through observation, imitation, and reinforcement [25]. Repeated experiences of social synchrony during parent-child interactions are believed to shape the developing brain and have long-lasting effects on children's social competencies [26,27]. This dynamic interplay shapes their ability to understand and predict the behavior of others, which is crucial for the development of ToM and other social competencies.

One promising avenue for studying the neural underpinnings of parent-child interactions is the investigation of neural synchronization between parent and child during shared experiences. Naturalistic paradigms, such as movie viewing, offer several advantages over traditional fMRI tasks in studying social brain development[28,29]. They require minimal instruction, are easily replicable across research sites and social contexts, and can be tailored in length to engage young children and reduce the confounding effects of head motion during fMRI scanning [30–32]. Moreover, they allow for the investigation of social processing in a more ecologically valid context, as movies often depict complex social interactions and relationships that closely resemble real-life experiences[33,34]. Previous studies have successfully used movie-viewing paradigms to investigate ToM and social pain processing in children [17,18], demonstrating the feasibility and reliability of this approach in developmental populations.

Previous studies have suggested that in parent-child dyads neural similarity varied depending on family connectedness, such that only dyads reporting high family connectedness showed similar neural profiles [35], and that atypical child-parent neural synchrony in medial prefrontal-hippocampus circuitry is associated with psychopathology in children [36]. However, the neural basis of parent-child behavioral synchrony and its relation to social cognitive outcomes remains largely unexplored. Moreover, few studies have taken an integrative approach to examine the interplay between intrinsic and environmental factors in shaping social brain development.

Here we aim to address these gaps in the literature by investigating the neurobehavioral implications of intrinsic development and parental caregiving for children's social cognition. Understanding how these networks differentiate with age is essential not only for mapping typical brain development, but also for contextualizing the role of environmental influences. By establishing normative patterns of neural maturity and differentiation, we can better interpret how relational experiences—such as caregiver-child synchrony and parenting quality—modulate these trajectories. Thus, our first goal provides a developmental anchor that grounds our investigation of interpersonal and environmental contributions to social brain function. We examine developmental changes in the functional neural maturity of social brain networks and its relation to children's physiological age. We hypothesized that the neural maturity of the ToM and SPM networks, as measured by the similarity of children's brain responses to those of adults, would be positively associated with age. Our second goal was to investigate neural synchronization between child-mother dyads during a naturalistic movie-viewing paradigm and its association with parent-child relationship quality. We predicted that child-mother dyads would exhibit higher levels of inter-subject neural synchronization compared to child-stranger dyads and that the degree of synchronization would be positively related to the quality of the parent-child relationship. Our third goal was to explore the interaction between neurobehavioral factors of parenting and personal growth in predicting children's social cognition outcomes. We hypothesized that parenting factors, such as parent-child relationship quality and parental rearing behavior, would interact with personal growth factors, such as age and neural maturity, to predict children's ToM performance and social cognition deficits, with ToM serving as a mediator between these factors and social outcomes.

To test these hypotheses, we initially collected fMRI data from 50 child-mother dyads while they viewed an animated movie that depicted characters' mental states and physical sensations. 16 were excluded based on predefined data quality criteria, including excessive head motion and incomplete scans. The remaining 34 dyads constituted the final sample used for all analyses. We used reverse correlation analysis to identify movie events that drove activity in ToM and SPM brain networks, inter-region correlation analysis to assess the functional neural maturity of these networks, and inter-subject correlation analysis to measure neural synchronization between child-mother and child-stranger dyads. Structural equation modeling (SEM) was employed to examine the relationships among neurobehavioral factors of parenting and personal growth, ToM performance, and social cognition outcomes.

Our findings revealed that the functional neural maturity of social brain networks was positively associated with children's physiological age, providing evidence for the continued development and refinement of these networks throughout childhood. Moreover, we found that child-mother dyads exhibited higher levels of neural synchronization compared to child-stranger dyads and that the degree of synchronization was negatively associated with parent-child conflict. These results suggest that shared neural responses during naturalistic viewing may reflect the quality of the parent-child relationship and highlight the importance of considering dyadic factors in studying social brain development. Finally, SEM revealed that parenting and personal growth factors interacted to predict children's social cognition outcomes, with ToM performance serving as a mediator. Specifically, we found that parenting factors had an indirect effect on social cognition deficits through their influence on children's personal growth and ToM abilities. These findings provide novel insights into the neurobehavioral mechanisms underlying social cognition development and highlight the importance of considering both intrinsic and environmental factors in shaping social brain function.

Results

The association between ToM behavior and individual behavioral characteristics

A total of 100 participants (50 mother-child dyads, with children between the ages of 3-8 years) participated in the study. Sixteen dyads were excluded due to high levels of head motion during fMRI scanning. Data from the remaining 34 mother-child dyads were used in further neuroimaging analysis.

All children completed a behavioral battery after the fMRI scan, which included a custom-made explicit ToM task (see Methods). Multiple regression and correlation analyses were used to evaluate the relationship between performance on the ToM task (i.e., proportion correct, referred to as ToM behavior) and general demographic and behavioral measures. Comparison between included and excluded dyads revealed no significant differences in child age ($t = 0.78$, $p = 0.44$), ToM scores ($t = 0.92$, $p = 0.36$), or gender distribution ($\chi^2 = 0.48$, $p = 0.49$), indicating that data exclusion did not bias the sample in a systematic way. Significantly associations between ToM behavior and age ($r = 0.434$, $p = 0.027$, false discovery rate [FDR]-corrected), conflict on Child–Parent Relationship Scale (CPRS) ($r = -0.377$, $p = 0.048$, FDR-corrected), rejection on the EMBU ($r = 0.388$, $p = 0.048$, FDR-corrected) (Egna Minnen Betriiffande Uppfostran, a self-report questionnaire to obtain ratings from parents about their own rearing behavior with their children), standard score on Peabody Picture Vocabulary Test, Fourth Edition (PPVT-4) ($r = 0.434$, $p = 0.027$, FDR-corrected) and total scores on social responsiveness scale (SRS) ($r = -0.598$, $p < 0.008$, FDR-corrected) were detected. No significant relationships were observed between ToM behavior and other behavioral characteristics (**Table 1**).

Reverse correlation analysis

We used reverse correlation analyses to identify events lasting more than four seconds in the continuous naturalistic stimulus that evoked reliable positive hemodynamic responses in the same brain region across subjects [37]. Reverse correlation analyses were performed on the average response time-courses in each network to identify events that drive activity in ToM and SPM brain regions (**Fig. 1A**). The regions of interest (ROIs) for the ToM and SPM networks were based on a previously published study (**Table 3**) [17].

	Coefficient *β*	SE	*P*_Regress	*R*_Pearson	*P*_Pearson
Receptive Vocabulary (PPVT)	0.203	0.030	0.206	**0.434**	**0.010**
Social Responsiveness (SRS Total)	-0.295	0.040	0.074	**-0.598**	**<0.001**
Parent–Child Conflict (CPRS)	-0.191	0.103	0.189	**-0.377**	**0.028**
Parent–Child Closeness (CPRS)	0.164	0.061	0.264	0.265	0.130
Parental Rejection (EMBU)	0.296	0.151	0.075	**0.388**	**0.023**
Parental Emotional Warmth (EMBU)	0.258	0.100	0.184	0.056	0.753
Parental Control Attempts (EMBU)	0.170	0.104	0.210	0.148	0.405
Child Age	0.348	0.577	0.073	**0.434**	**0.010**

Note: β is the standard regression coefficient from multiple regression analysis. *P*_Regress is the P value from multiple regression analysis. *R*_Pearson is the Pearson correlation coefficient from correlation between the individual behavioral characteristics and ToM behavior. *P*_Pearson is the P value from correlation between the individual behavioral characteristics and ToM behavior. SRS = Social Responsiveness Scale; CPRS = Child–Parent Relationship Scale; EMBU = Egna Minnen av Barndoms Uppfostran; PPVT = Peabody Picture Vocabulary Test. Bold font indicates the significance level at $p < 0.05$.

Table 1.

Relationship between individual behavioral characteristics and ToM behavior.

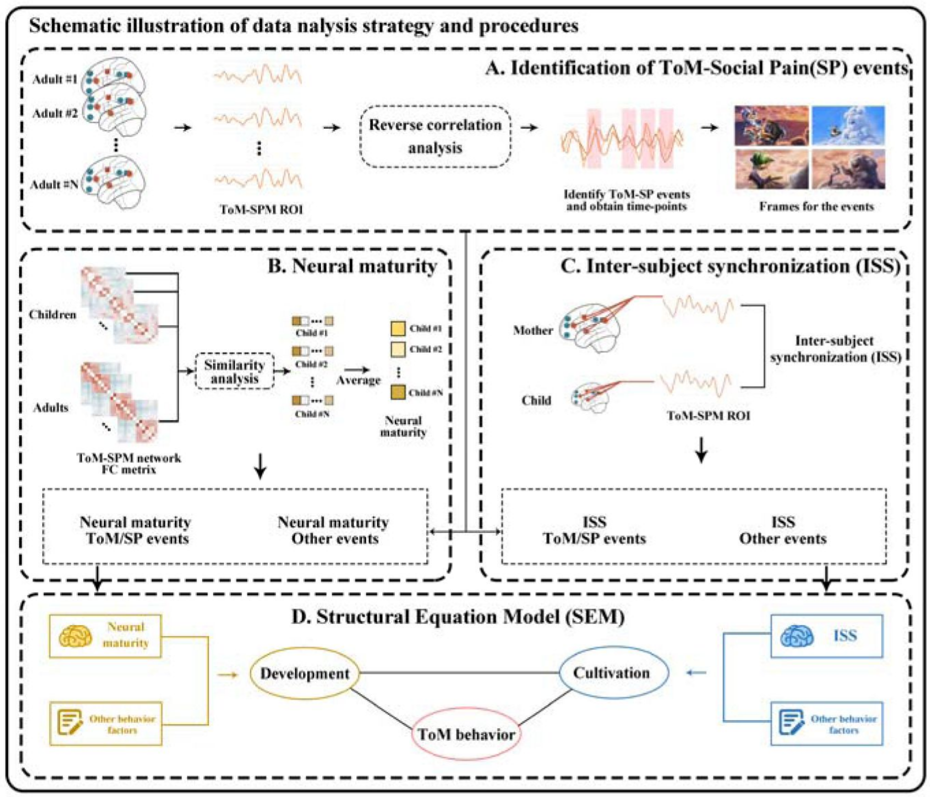


Fig 1.

Overview of analysis pipeline.

(A) Reverse correlation analysis was conducted on the average response network time-courses to identify ToM and Social Pain events driving activity in Theory of Mind (ToM) and Social Pain Matrix (SPM) related brain regions. **(B)** First, inter-region correlations were computed across all ToM and SPM brain regions of interest for each participant. Neural maturity of a child was then assessed by averaging the similarity between the child's correlation matrices and those of each adult. **(C)** Inter-subject synchronization (ISS) was determined by calculating the correlation of neural response time series between child-mother and child-stranger dyads. **(D)** A structural equation model was employed to explore the relationships among neurobehavioral factors of parenting and personal growth, ToM performance, and social cognition outcomes.

In adults, reverse correlation analysis identified seven ToM events (60 s total, length 8.3±6.18s) and eight social pain events (52 s total, length 6.5±2.60 s). All seven peak 'mind' events depicted the characters' beliefs, desires, and/or emotions (e.g., Peck finds other clouds and cranes are happy, Baby cries and then is made to laugh) (**Fig. 2A**). All eight peak 'social pain' events depicted characters experiencing social pain (e.g., Peck being bitten by a hedgehog) or events such as thunder and lightning (**Fig. 2B**). The five events that had the highest response magnitude in each network in adults are shown in **Fig. 2C**; see **Supplementary Table S1** for full descriptions of these events, including timing and duration information. The timepoints that exceeded baseline for ToM and SPM networks were almost entirely non-overlapping, with the exception of a single timepoint (2 s). Timepoints corresponding to ToM and Social Pain events were defined as ToM/SP events (132 TRs), while other timepoints were defined as other events (168 TRs) for further analysis.

Additionally, reverse correlation analysis conducted on the children alone identified 6 of the 8 social pain events and 4 of the 7 ToM events discovered in the adult sample (**Fig. 2A-B**). This indicates some overlap in the neural processing of social pain and ToM events between children and adults, highlighting the potential developmental continuity in these neural networks.

Neural maturity reflects the development of social brain

Children were divided equally into three groups according to their age (**Table 2**): Pre-junior group (3.3~4.8y), Junior group (5.0~5.8y) and Senior group (6.0~8.0y). Average correlation matrices were computed for different age groups to reveal the extent to which a group of brain regions operate as a network with synchronized responses. In adults, each network exhibited strong positive correlations within-network and negative correlations across networks (within-ToM correlation M(s.e.) = 0.51(0.04); within-SPM correlation M(s.e.) = 0.39(0.05); across-network M(s.e.) = −0.11(0.01). In children, each network also exhibited positive correlations within-network and negative correlations across networks (within-ToM correlation M(s.e.) = 0.31(0.04); within-SPM correlation M(s.e.) = 0.29(0.04); across-network M(s.e.) = −0.09 (0.02). The pattern of network correlations exhibited substantial strengthening between the ages of 3 and 8 years (**Fig. 3A**). Among children, average correlations within-ToM (r = 0.40, p = 0.02, FDR-corrected) and within-SPM network (r = 0.32, p = 0.05, FDR-corrected) increased significantly with age (**Fig. 3B**). Nevertheless, the two networks were already functionally distinct in the youngest group of children we tested. In the Pre-junior group only (3-4 years old children, n = 12), both ToM and SPM networks had positive within-network correlations (within-ToM correlation M (s.e.) = 0.29(0.06); within-SPM correlation M(s.e.) = 0.23(0.05), across-network M(s.e.) = −0.05(0.02)).

Next, we tested whether the functional neural maturity (i.e., similarity of correlation matrices to adults) of a child was related to their physiological age or parent-child relationship quality. The neural maturity of each child was quantified by averaging the similarity between their correlation matrices and those of each adult within the ToM/SPM networks (**Fig. 1B**). Our findings revealed a significant correlation between neural maturity and age (r = 0.42, p = 0.01, FDR-corrected), while no significant correlation was observed with parent-child relationship quality (r = −0.13, p = 0.47) (**Fig. 3C-D**). Furthermore, we observed a significant correlation between neural maturity and age during ToM/SP events (r = 0.46, p = 0.01, FDR-corrected), while no such correlation was found during other events (r = −0.04, p = 0.84) (**Fig. 3E**). A paired t-test revealed that the neural maturity of children during ToM/SP events was lower than that during other events (T = −6.29, p < 0.01). A direct comparison revealed a significant difference in neural maturity between ToM/SP events and age for ToM/SP versus other events (F = 3.48, p = 0.046, **Fig. 3F**).

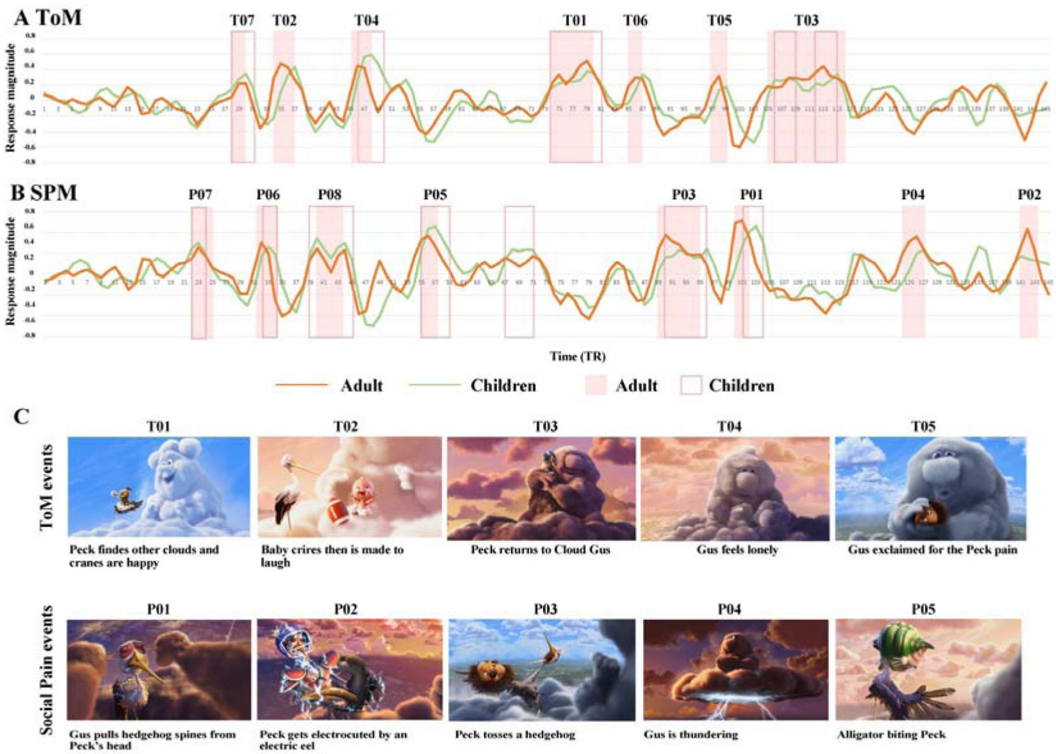


Fig 2.

Reverse Correlation Analysis.

The average time courses of child (green) and adult (red) groups for the **(A)** Theory of Mind (ToM) and **(B)** Social Pain Matrix (SPM) networks during movie viewing are presented. Each time point along the x-axis corresponds to a single TR (2 seconds). Shaded blocks represent time points identified as ToM and Social Pain events in a reverse correlation analysis conducted on adults, while dark borders indicate time points identified as ToM and Social Pain events in children. Event labels (e.g., T01, P01) denote the ranking of average response magnitude in adults. **(C)** Example frames and descriptions for the five events with the highest response magnitude in adults are provided.

Fig 3.

Inter-region correlation analysis and neural maturity.

(A) Average z-scored correlation matrices were computed across all Theory of Mind (ToM) and Social Pain Matrix (SPM) regions of interest for each age group (Pre-junior: n = 12; Junior: n = 11; Senior: n = 11; Adults: n = 34). The nomenclature of brain regions is shown in **Table 3**. **(B)** Correlation between the average inter-regional correlation within ToM/SPM networks and age. **(C)** Correlation between neural maturity and age. **(D)** Correlation between neural maturity and conflict score of CPRS. **(E)** Correlation between neural maturity and age during ToM/SP and other events, as defined by reverse correlation analysis. Group differences in neural maturity during ToM/SP and other events are shown on the right. *** $p < 0.001$. **(F)** Group differences in neural maturity during ToM/SP and other events for each age group. * $p < 0.05$.

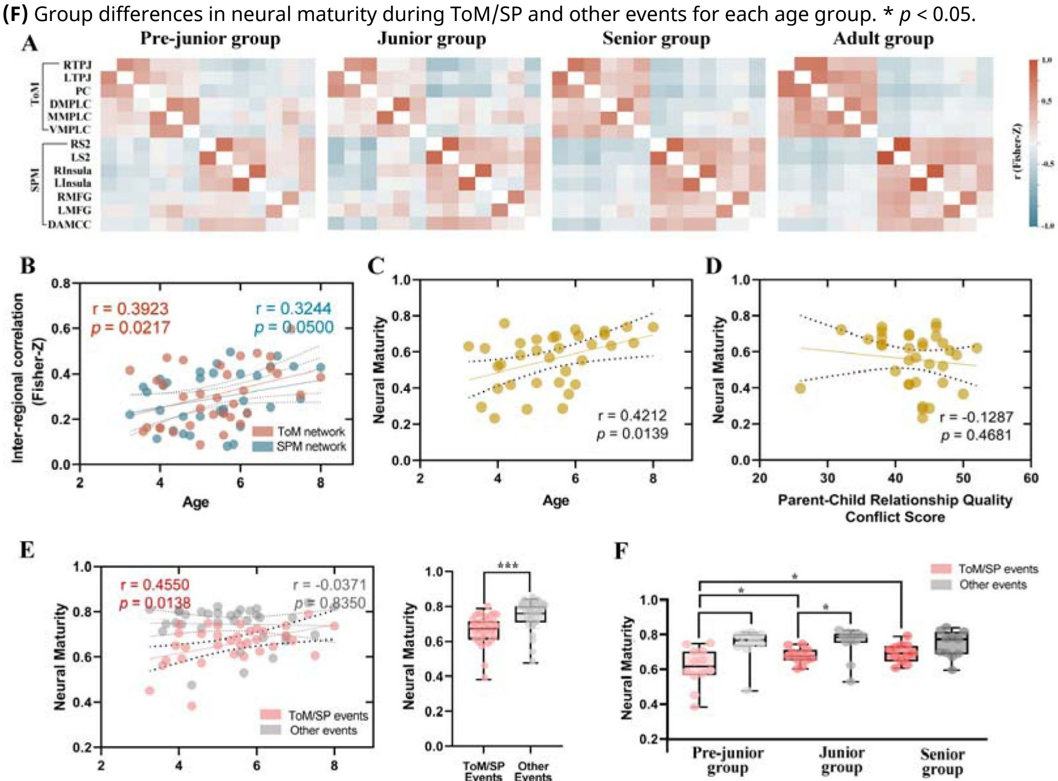


Table 2.

Demographic information and behavioral data by age group.

Group	N	Age (Mean ± SD Range)	Gender (Female/Male)	Handedness (Right/Left/Mix)	Theory of Mind behavior score	PPVT (Standard score)	Parents-children relationship (CPRS)		Parents' rearing behavior (EMBU)			Social Responsiveness (SRS) Total
							Conflict	Closeness	Rejection	Emotional warmth	Control attempts	
Pre-junior	12	4.1±0.4 (3.3~4.8)	6/6	11/0/1	7.4±4.7	139.2±18.8	43.3±5.5	27.3±9.7	16.2±2.4	58.3±7.0	43.8±4.1	40.0±18.0
Junior	11	5.5±0.3 (5.0~5.8)	4/7	10/0/1	10.6±2.3	152.3±10.8	44.4±2.3	28.1±7.6	18.8±3.0	58.1±7.2	41.0±4.8	35.1±16.0
Senior	11	6.7±0.7 (6.0~8.0)	6/5	9/1/1	11.8±1.9	151.5±19.0	40.2±3.5	25.9±7.0	18.8±3.4	57.2±4.6	41.1±3.7	26.0±13.7
Adult (Mother)	34	36.7±4.0 (30.7~48.8)	34/0/0	33/0/1	NA	NA	NA	NA	NA	NA	NA	NA

Note: PPVT, Peabody Picture Vocabulary Test, Fourth Edition; CPRS = Child–Parent Relationship Scale; EMBU = Egna Minnen av Barndoms Uppfostran (parenting style); SRS = Social Responsiveness Scale.

Network	ROI	Center Coordinate
ToM	RTPJ	[48 -60 30]
	LTPJ	[-48 -62 30]
	PC	[0 -54 34]
	DMPFC	[-6 54 36]
	MMPFC	[-4 58 16]
	VMPFC	[-4 56 -16]
Pain	RS2	[60 -28 38]
	LS2	[-62 -32 34]
	Rinsula	[42 6 -6]
	Linsula	[-42 -2 -4]
	RMFG	[50 42 12]
	LMFG	[-46 36 14]
	AMCC	[0 2 42]

Table 3.

Definition of ToM and SPM regions of interest.

Regions identified, center coordinate [x y z] for each region of interest in the Theory of Mind (ToM) and Social Pain Matrix (SPM) networks. RTPJ and LTPJ, right and left temporoparietal junction; PC, precuneus; DMPFC, MMPFC and VMPFC, dorsal, middle and ventral components of medical prefrontal cortex; RS2 and LS2, right and left secondary sensory; Rinsula and Linsula, right and left insula; RMFG and LMFG, right and left middle frontal gyrus; AMCC, anterior middle cingulate cortex.

Inter-subject neural synchronization and child-parent relationship quality

First, we examined whether the inter-subject synchronization (ISS) between child-mother dyads within the ToM/SPM network was associated with parent-child relationship quality. We averaged fMRI timeseries across all ToM and SPM ROIs to obtain a network-level timeseries. ISS was then defined as the temporal correlation between the mean fMRI time series of the child-mother dyads or child-stranger dyads, and a Fisher's r-to-z transform was applied to convert the correlation coefficient (r) value to a normally distributed variable z (**Fig. 1C**). Compared to child-stranger dyads, ISS was higher in child-mother dyads (Two-sample *t* tests, T= 2.48, $p = 0.016$) (**Fig. 4A**). Additionally, partial correlation analysis with the age of children as a covariate was performed to explore the relationship between ISS and child-parent relationship quality. A significant negative correlation between conflict scores on the CPRS and ISS was found within child-mother dyads ($r = -0.41$, $p = 0.02$, FDR-corrected), while such correlation was not found within child-stranger dyads ($r = 0.20$, $p = 0.24$) (**Fig. 4B**). Moreover, there was no significant correlation between age and either ISS within child-mother dyads or within child-stranger dyads (**Fig. 4C**).

Subsequently, we investigated whether the association between relationship quality and ISS was specific to ToM/SP events. ANOVA revealed a main effect of parent-child relationship (child-mother dyads vs. child-stranger dyads), with stronger ISS in child-mother dyads ($F = 8.84$, $p = 0.004$). ANOVA also revealed a main effect of events (ToM/SP vs. other events), with stronger ISS during ToM/SP events ($F = 10.05$, $p = 0.002$). No significant interaction effect was observed between events and parent-child relationship ($F = 0.10$, $p = 0.75$). Partial correlation indicated that ISS between child-mother dyads was marginally significantly correlated with conflict scores during ToM/SP events ($r = -0.34$, $p = 0.05$, FDR-corrected), while such a correlation was not present during other events ($r = 0.03$, $p = 0.86$) (**Fig. 4D**).

No such significant correlation was observed in child-stranger dyads (**Fig. 4E**). In comparison to other events, ISS was found to be higher during ToM/SP events for both child-mother and child-stranger dyads (Pair *t*-tests, $p < 0.05$, FDR-corrected).

Structural equation modeling of parenting, personal traits and ToM factors underlying children's social skills

We used SEM to examine the relation between neurobehavioral factors and parenting and personal traits, including conflict/closeness from the CPRS, warmth/rejection/control from the EMBU, sex, age, neural maturity and ISS between child-mother dyads. Additionally, verbal intelligence, measured by the PPVT-4 standard score, was also used in the model estimation, recognizing the indispensable role of language in the development of ToM [38]. The SEM involved confirmatory factor analysis to consolidate the neurobehavioral factors into latent variable constructs and serial mediation analysis to explore the relationships between these latent constructs, ToM behavior, and social cognition deficits (measured by total SRS scores). The model showed a strong fit to the data, $\chi2 = 14.16$, $\chi2/df = 1.09$, CFI = 0.957, RMSEA = 0.052 (**Fig 5**).

As expected, child-parent relationship quality, rearing behavior, and child-parent ISS contributed significantly to the latent construct of *parenting* (*ps* < 0.01), and individual child's neural maturity, verbal intelligence, age and sex contributed significantly to the latent construct of *personal trait* (*ps* < 0.001). *Parenting* had a significantly positive effect on ToM behavior and a negative effect on *personal trait*. *Personal trait* had a positive effect on ToM behavior, and ToM behavior had a negative effect on social cognition deficits. *Parenting* had a significant total effect on social cognition deficits ($\beta = -0.651$, $p < 0.05$). Additionally, a serial indirect mediating effect was found, where *parenting* and *personal trait* factors interacted to predict children's social cognition

Fig 4.

Inter-subject neural synchronization.

(A) Group differences in inter-subject synchronization (ISS) during movie viewing. **(B)** Partial correlation between conflict scores of CPRS and ISS within child-mother and child-stranger dyads. **(C)** Correlation between age and ISS within child-mother and child-stranger dyads. **(D-E)** Partial correlation between conflict scores on the CPRS and ISS within child-mother and child-stranger dyads during ToM/SP events and other events. Group differences in ISS during ToM/SP and other events are displayed on the right. * $p < 0.05$.

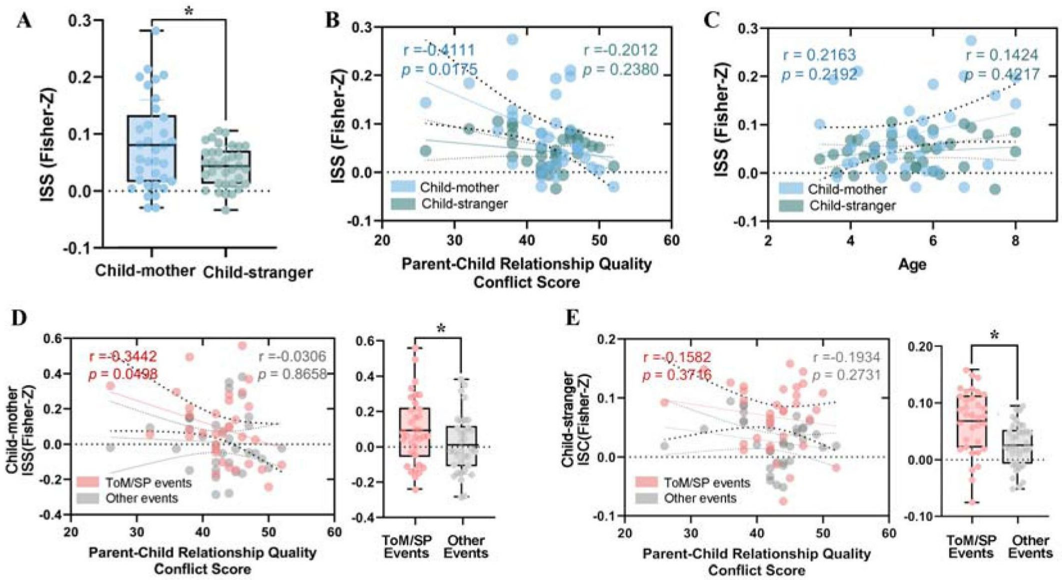
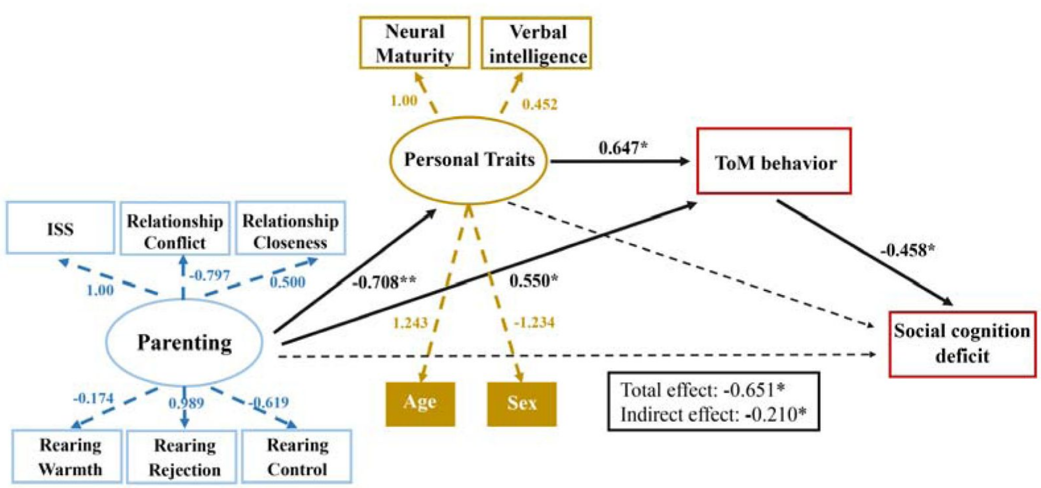


Fig 5.

Structural equation model of latent personal traits, latent parental caregiving, ToM behavior and social development outcomes.

Parenting has a direct and indirect influence on ToM behavior which in turn influences social cognition. Latent factor underlying Personal Trait includes a child's neural maturity, while the latent factor underlying Parenting includes child-mother inter-subject neural synchronization (ISS). Regression coefficients are displayed for each path. Solid lines indicate significant paths (*$p < 0.05$; ** $p < 0.01$), and dashed arrows indicate nonsignificant paths.



outcomes, with ToM performance serving as a mediator (β = −0.210, $p < 0.05$) (**Table S2**). Finally, additional control analyses revealed that both ToM and SPM networks are essential for predicting social cognitive outcomes (see Supplementary Information for details).

Discussion

Our study aimed to elucidate the neurobehavioral mechanisms underlying the development of social cognition in children by examining the interaction between brain maturation with age, and parental caregiving. Using a naturalistic movie-viewing paradigm and advanced neuroimaging analyses, we investigated the neural maturity of social brain networks, neural synchronization between child-mother dyads, and the interplay between neurobehavioral factors in predicting social cognition outcomes. We found that individual factors, such as age, were related to the functional neural maturity of social brain networks, social-environmental factors, such as parent-child relationship quality, were associated with parent-child neural synchronization during naturalistic viewing, and personal and social environmental factors interacted to predict children's social cognition outcomes, with ToM abilities serving as a mediator. Together, our findings support emerging theoretical frameworks emphasizing dyadic neural coupling and developmental plasticity, particularly the biobehavioral synchrony model and neuroconstructivist approaches to brain development. In addition, our findings align with Bandura's theoretical models of social learning, particularly the concept of reciprocal determinism, which posits that individual behavior is influenced by and influences personal factors and the social environment. Our study bridges the gap between theoretical perspectives and empirical research in developmental social neuroscience. This integration of theory and research is crucial for advancing our understanding of the complex processes that shape children's social cognitive abilities and for informing the development of effective interventions aimed at promoting social competence.

Social brain neural network matures with age

We found that the functional neural maturity of social brain networks, specifically the Theory of Mind (ToM) and social pain matrix (SPM) networks, was positively associated with children's physiological age. This relationship was specific to events depicting mental states and bodily sensations, suggesting that the maturation of these networks is tied to children's developing ability to reason about others' minds and experiences. The strengthening of within-network correlations and differentiation between the ToM and SPM networks with age further supports the notion that social brain development involves increasing specialization and refinement of neural circuits. While our primary analyses treated age as a continuous variable, we also performed exploratory group-based comparisons to probe for potential non-linear developmental shifts in social brain network organization. This approach revealed that the differentiation between ToM and SPM networks was already present in the youngest group (ages 3–4), suggesting that early neural specialization may begin prior to the age at which ToM behavior is reliably observed. These group-level observations provide complementary evidence to the continuous analyses and may inform future work examining sensitive periods or early markers of social brain development.

Our findings contribute to and extend prior research using fMRI paradigms to investigate ToM development in children. Previous work has shown that these networks become increasingly specialized and differentiated throughout childhood [17,39,40]. The current study extends these findings by demonstrating that the development of social brain networks is a gradual process that continues beyond the preschool years and is related to children's chronological age. This finding is consistent with behavioral research indicating that ToM and social abilities continue to develop and refine throughout middle childhood and adolescence [41]. Importantly, we move beyond prior work by combining reverse correlation with naturalistic stimuli to isolate discrete, behaviorally meaningful events (e.g., mental state attribution, social rejection) and relate children's brain responses to adult patterns and social outcomes. This event-level analysis in a dyadic context offers greater ecological and interpretive precision than traditional block or condition-based designs. Our study provides novel evidence for the neural underpinnings of this protracted development, suggesting that the functional maturation of social brain networks may support the continued acquisition and refinement of social cognitive skills.

Child-mother neural synchrony is linked to relationship quality

In parallel, our study builds on and extends a growing body of work on parent-child neural synchrony, much of which has relied on fNIRS or EEG hyperscanning to demonstrate interpersonal alignment during communication, shared attention, or cooperative tasks [42–45]. While these modalities offer fine temporal resolution, they are limited in spatial precision and typically focus on surface-level cortical regions such as the prefrontal cortex. By contrast, our naturalistic fMRI approach enables the examination of deep and distributed brain networks—specifically those supporting social cognition—within child-parent dyads during emotionally and cognitively rich scenarios. Intriguingly, we found that neural synchronization during movie viewing was higher in child-mother dyads compared to child-stranger dyads.

Moreover, the degree of neural synchrony between children and mothers was specifically associated with lower parent-child conflict, but not children's age. This brain-to-brain coupling may facilitate the sharing of mental states and co-regulation of emotions between parents and children [46], thereby promoting social understanding. Our results corroborate previous behavioral studies linking mother-child synchrony to positive developmental outcomes [27,47]. They also extend prior neuroimaging work on interpersonal neural synchronization in relationships [48] by demonstrating that synchronous brain activity between parents and children is tied to the quality of their relationship. Notably, the association between neural synchrony and relationship quality was specific to events highlighting mental states and bodily sensations, underscoring the relevance of this neural coupling to children's developing social cognition. These findings support the theory of bio-behavioral synchrony [21,49], which posits that synchronized behavioral, physiological, and neural responses between parent and child facilitate emotional sharing and social understanding, contributing to positive developmental outcomes.

Parenting and biological factors impact social cognition via Theory of Mind

Our next goal was to determine how neurobehavioral factors of parenting and personal growth interact to predict children's social cognition outcomes. SEM revealed that parenting factors, such as the quality of the parent-child relationship and parental rearing behavior, significantly influenced children's personal neurocognitive growth and ToM abilities, which in turn impact social cognition. Specifically, parenting had an indirect effect on social cognition deficits through its influence on children's personal traits and ToM performance. These results highlight the importance of both intrinsic factors (age, neural maturity) and environmental factors (quality of parenting) in shaping the development of social cognition.

This finding accords with long-standing theories positing that children's understanding of mental states is shaped by both environmental input from caregivers and intrinsic neurocognitive maturation [50,51]. By representing these factors as latent variables, our analysis could capture their shared covariance while modeling their distinct pathways to ToM development. The results suggest that parenting and advantageous personal characteristics facilitate children's grasp of others' minds, which in turn supports broader social cognitive competencies.

The mediating role of ToM aligns with research on autism spectrum disorders, where impairments in mental state reasoning are thought to underlie many of the observed social cognition deficits [52,53]. Interventions targeting ToM skills could thus potentially ameliorate social difficulties in both neurotypical and clinical populations. Our findings highlight parenting behavior and parent-child relationship quality as promising targets for such family-based interventions.

Insights into mechanisms of Neuroconstructivist Perspectives and Bandura's social learning theory

Our findings align with a neuroconstructivist perspective, which conceptualizes brain development as an emergent outcome of reciprocal interactions between biological constraints and context-specific environmental inputs. Rather than presuming fixed traits or linear maturation, this perspective highlights how neural circuits adaptively organize in response to experience, gradually supporting increasingly complex cognitive functions[54]. It offers a particularly powerful lens for understanding how early caregiving environments modulate the maturation of social brain networks.

Building on this framework, the present study reveals that moment-to-moment neural synchrony between parent and child, especially during emotionally salient or socially meaningful moments, is associated with enhanced Theory of Mind performance and reduced dyadic conflict. This suggests that beyond age-dependent neural maturation, dyadic neural coupling may serve as a relational signal, embedding real-time interpersonal dynamics into the child's developing neural architecture [55]. Our data demonstrate that children's brains are not merely passively maturing, but are also shaped by the relational texture of their lived experiences—particularly interactions characterized by emotional engagement and joint attention. Importantly, this adds a new dimension to neuroconstructivist theory: it is not simply whether the environment shapes development, but how the quality of interpersonal input dynamically calibrates neural specialization. Interpersonal variation leaves detectable signatures in the brain, and our use of neural synchrony as a dyadic metric illustrates one potential pathway through which caregiving relationships exert formative influence on the developing social brain.

The contribution of this work lies not in reiterating the interplay of nature and nurture, but in specifying the mechanistic role of interpersonal neural alignment as a real-time, context-sensitive developmental input. Neural synchrony between parent and child may function as a form of relationally grounded, temporally structured experience that tunes the child's social brain toward contextually relevant signals. Unlike generalized enrichment, this form of neural alignment is inherently personalized and contingent—features that may be especially potent in shaping social cognitive circuits during early childhood.

Although our study was not designed to directly examine learning mechanisms such as imitation or reinforcement, the findings can be viewed as broadly consistent with social learning theory. Bandura's theory posits that human behavior is shaped by observational learning and modeling from others in one's environment [25,56,57]. According to Bandura, children acquire social cognitive skills by observing and interacting with their parents and other significant figures in their environment. This dynamic interplay shapes their ability to understand and predict the behavior of others, which is crucial for the development of ToM and other social competencies.

Aligned with this theory, we found that neural synchronization between children and their mothers was higher compared to child-stranger dyads. This increased neural coupling likely facilitates the sharing of mental states, emotions, and behaviors between parent and child, allowing children to learn and model social cognition skills through observing and mirroring their parents. The theory also highlights the importance of the social environment, particularly parents, in shaping behavior and cognitive development. Our results also revealed that higher parent-child neural synchrony was associated with lower mother-child conflict and better relationship quality. A supportive parenting environment with positive social interactions enables effective modeling and acquisition of social cognitive abilities in children. We also found that personal factors like children's neural maturity and age influenced the degree of neural synchronization with mothers.

At the same time, parenting quality (relationship, rearing behavior, neural synchrony) impacted children's ToM development and social cognition abilities. Taken together, Bandura's social learning theory, with its emphasis on observational learning from social models, reciprocal influences between personal factors and the social environment, and the role of nurturing interactions, provides a robust framework for understanding the neurobehavioral mechanisms underlying the development of social cognition through parent-child neural synchronization.

Limitations and future directions

While leveraging a naturalistic movie-viewing paradigm allowed us to study children's spontaneous neural responses during a semi-structured yet engaging task, dedicated experimental designs are still needed to make stronger inferences about the cognitive processes involved. Moreover, the ROIs used to define the ToM and SPM networks were based on meta-analyses and task studies primarily conducted with adults. While this approach promotes comparability with existing literature, it assumes that the spatial organization of these networks is stable across age groups. However, theories of interactive specialization suggest that the composition and boundaries of functional networks may undergo reorganization during development, with regions potentially entering or exiting networks based on experience and maturational processes. As a result, the current analysis may not fully capture age-specific functional architecture, particularly in younger children. Future studies using data-driven or age-appropriate parcellation methods could provide more precise characterizations of how social brain networks are constructed and differentiated throughout childhood. Additionally, our region-of-interest approach precluded examination of whole-brain networks; future work could explore developmental changes in broader functional circuits. The cross-sectional nature of our study is a further limitation, as it cannot definitively establish the causal directions of the observed relationships. Longitudinal designs tracking children's brain development and social cognitive abilities over time would help clarify whether early parenting impacts later neural maturation and behavioral outcomes, or vice versa. Another limitation of the current design is the lack of a resting-state baseline for inter-subject synchronization. While our focus was on synchronization during naturalistic social processing, we cannot determine whether individual differences in ISS reflect purely task-induced coupling or are partially shaped by trait-level synchrony present at rest.

Including both resting and task conditions in future work would allow for stronger inferences about stimulus-specific versus baseline-driven synchronization, especially in relation to interpersonal factors such as relationship quality or social responsiveness. In addition, the modest sample size (N = 34 dyads) presents limitations for the application of structural equation modeling (SEM), which typically requires larger samples for stable estimation and generalizable inferences. While the model fit was acceptable, the results should be interpreted as exploratory and hypothesis-generating, rather than confirmatory. Future studies with larger, independent samples will be important for validating the structure and directionality of the proposed relationships. Our sample was also restricted to mother-child dyads, leaving open questions about potential differences in father-child relationships and gender effects on parenting neurobiology [58]. Larger and more diverse samples would enhance the generalizability of the findings.

Several future directions emerge from this research. First, combining naturalistic neuroimaging with structured cognitive tasks could elucidate the specific mental processes underlying children's neural responses during movie viewing. Examining how these processes relate to real-world social behavior would further bridge neurocognitive function and ecological validity. Longitudinal studies beginning in infancy could chart the developmental trajectories of parent-child neural synchrony and their impact on long-term social outcomes. Such work could also explore sensitive periods when parenting may be most influential on social brain maturation. Finally, expanding this multimodal approach to clinical populations like autism could yield insights into atypical social cognitive development and inform tailored intervention strategies targeting parent-child relationships and neural plasticity.

Conclusions

Our study provides novel evidence that children's social cognitive development may be shaped by the intricate interplay between environmental influences, such as parenting, and biological factors, such as neural maturation. Our findings contribute to a growing understanding of the factors associated with social cognitive development and suggest the potential importance of parenting in this process. Specifically, the study points to the possible role of the parent-child relationship in supporting the development of social brain circuitry and highlights the relevance of family-based approaches for addressing social difficulties.

The observed neural synchronization between parent and child, which was associated with relationship quality, underscores the potential significance of positive parental engagement in fostering social cognitive skills. Future longitudinal and clinical research can build on this multimodal approach to further clarify the neurobehavioral mechanisms underlying social cognitive development. Such research may help inform more effective strategies for promoting healthy social functioning and mitigating social deficits through targeted family-based interventions.

Methods

Participants

A total of 50 child-mother dyads (100 participants) were recruited for inclusion in the study from local communities via flyers or internet advertisements. The children had a mean age of 5.43 years (SD = ±1.75 years, range = 3–8 years), and the adults had a mean age of 36.7 years (SD = ±4.0 years, range = 30.7–48.8 years). We chose to focus exclusively on mother-child dyads in this study based on prior evidence suggesting distinct neural and behavioral caregiving profiles between mothers and fathers [58,59], allowing us to maintain role consistency and reduce variability in dyadic interactions. Following quality control, 16 dyads were excluded due to excessive head motion during fMRI scanning, resulting in a final sample of 34 dyads for analysis. None of the participants had a history of psychiatric or neurological disorders, and all had normal or corrected-to-normal visual acuity. Written informed consent was obtained from all participants after a thorough explanation of the study's purpose and protocols. The Institutional Review Board of the University of Electronic Science and Technology of China approved the study, which was conducted in accordance with the Declaration of Helsinki.

Questionnaires

Parents or guardians completed several questionnaires to assess various aspects of the child-parent relationship and the child's social behavior:

1. Child-Parent Relationship Scale (CPRS) : This 22-item scale evaluates the child-mother relationship through two subscales: closeness (10 items) and conflict (12 items). Higher scores indicate higher levels of closeness or conflict. Responses range from 1 (definitely does not apply) to 5 (definitely applies). This scale has demonstrated good psychometric properties in Chinese participants [60].
2. Egna Minnen Betriiffande Uppfostran (EMBU): This scale assesses parents' own parenting behavior toward their child. It includes four subscales: rejection (13 items), emotional warmth (17 items), control attempts (19 items), and preference (3 items). Higher scores indicate greater levels of each respective behavior. Responses range from 1 (no, never) to 4 (yes, always) [61].

3. Social Responsiveness Scale (SRS): This 65-item rating scale evaluates the child's social behavior over the past 6 months, generating a total score that indicates the severity of social deficits. Higher scores reflect greater social impairment. Responses range from 0 (no, never true) to 3 (almost always true) [62].

Neurodevelopmental Assessment

The Peabody Picture Vocabulary Test, Fourth Edition (PPVT-4), was used to assess the receptive vocabulary abilities of the children [63], providing an estimate of verbal intelligence [64]. The Chinese version of the PPVT-4 has been adapted to align closely with the original version, with only minor adjustments for cultural and language differences. Each correct item was awarded one point, and raw scores were converted to standardized scores according to PPVT-4 protocols.

Explicit ToM task and false-belief composite score

All children participated in a custom-made explicit ToM battery, which entailed listening to a series of narrative scenarios and subsequently responding to questions that required them to infer the mental states of the characters involved. This battery was specifically designed to assess first-order and second-order ToM abilities, and has been widely used in previous neuroimaging studies to evaluate children's ToM behavior performance [65,66]. As described in previous literatures [17,67], first-order ToM is associated with the ability to infer other's mental state (e.g., "where does the girl think her ball is?"), and second-order TOM is associated with the ability to infer other's mental state in relation to t third party (e.g., "where does the girl think the boy will go looking for his ball?"). Each task includes a target (e.g., "where does the girl think her ball is?") and a control question (e.g., "where is the actual location of the ball?"), and children received one point for each correct answer to both the test and control questions. A total of 14 tasks were assigned, and the performance was quantified as the total number of correct answers out of 14 tasks, resulting in the performance scores ranging from 0 to 14.

fMRI Paradigm and stimuli

Participants watched "*Partly Cloudy*", a 5.6-minute animated movies [68] (*https://www.pixar.com/partly-cloudy#partly-cloudy-1*), which was originally adopted and validated by Jacoby and Richardson et.al to elicit complex social-cognitive reasoning in an fMRI setting [16,17,69]. Before the movie commenced, participants were given a 10-second rest period to stabilize their attention and physiological state. During this time, they were instructed to relax, remain still, and prepare for the upcoming task. To ensure precise synchronization between the film's presentation and the neuroimaging data acquisition, both the stimuli and the scanning process were initiated simultaneously, allowing for accurate time-point alignment from the start of the experiment.

fMRI data acquisition

Participants were scanned using a 3T GE DISCOVERY MR750 scanner (General Electric), equipped with an eight-channel prototype quadrature birdcage head coil. Functional images were acquired using an echo-planar imaging (EPI) sequence with the following parameters: echo time (TE) of 30 ms, repetition time (TR) of 2,000 ms, and a spatial resolution of $3.75 \times 3.75 \times 3.2$ mm. The imaging matrix was 64×64, with a flip angle of 90°, and a field of view (FOV) of 240×240 mm². A total of 43 interleaved transverse slices, with no inter-slice gap and a slice thickness of 3.2 mm, were obtained. The functional dataset comprised 155 dynamic scans, providing comprehensive coverage of brain activity during the task.

fMRI Data Preprocessing

As previously published [34,70], the standard fMRI preprocessing pipeline was applied using the Data Processing and Analysis of Brain Imaging (DPABI) toolbox, version 4.3 (*rfmri.org/dpabi*). To ensure data quality, the first 5 volumes from each participant were discarded due to initial signal instability. The remaining 145 volumes underwent slice-timing correction and head-motion realignment. Participants were excluded if either the child or the mother exhibited excessive head motion, defined as translation exceeding 3.0 mm or rotation greater than 3°. Consequently, 16 child-mother dyads were excluded, leaving a total of 34 dyads for analysis. The brain images of all remaining children and mothers were spatially normalized to the Montreal Neurological Institute (MNI) standard template and resampled to a 3 × 3 × 3 mm^3 voxel size. This normalization allowed for the application of group ROIs and hypothesis spaces derived from adult datasets, facilitating direct comparisons between child and mother participants. Previous research supports the use of a common space for both adults and children under age seven, as anatomical differences in this age group are minimal relative to the fMRI resolution [71,72]. Subsequently, the normalized images were linearly detrended to mitigate signal drifts. Nuisance covariates, including 24 head-motion parameters, white matter signal, and cerebrospinal fluid signal, were regressed out of the data [73]. To enhance signal-to-noise ratio, all images were smoothed with a 6 × 6 × 6 mm^3 full-width at half-maximum Gaussian kernel. A bandpass filter (0.01–0.15 Hz) was applied to isolate the neural signal associated with movie viewing [74]. Additionally, data scrubbing was performed to address potential motion artifacts [75]. Signal outliers, identified as having a framewise displacement (FD) greater than 0.5 mm with the preceding 1 and subsequent 2 volumes, were corrected by fitting these outliers to the clean portion of the time series using a third-order spline.

Behavior analysis

Of the 50 initial mother-child dyads recruited, 16 were excluded due to excessive head motion (n = 11), incomplete scan sessions (n = 3), or technical issues during data acquisition (n = 2). The final sample consisted of 34 dyads. To assess potential bias introduced by data exclusion, we compared included and excluded dyads on child age, gender, and Theory of Mind performance. Comparison between included and excluded dyads revealed no significant differences in child age ($t = 1.23$, $p = 0.24$), ToM scores ($t = -0.54$, $p = 0.59$), or sex distribution ($\chi^2 < 0.01$, $p = 0.98$), indicating that data exclusion did not bias the sample in a systematic way. No significant differences were found across these variables (all ps > 0.1), suggesting that the analytic sample was demographically representative of the full cohort. Multiple linear regression and Person correlation analysis was performed to evaluate the relationship between ToM behavior and general demographic and behavioral measures.

Reverse correlation analysis

Timecourse analyses were performed by extracting preprocessed timecourses from 9 mm ROIs centered on peaks identified in previous studies (6 ToM regions, 7 SPM regions, **Table 3**)[17]. Each ROI timecourse was z-normalized to standardize the data. For each network, the timecourses across ROIs were averaged, resulting in a single timecourse for the ToM network and another for the SPM network per participant. We employed reverse correlation analysis in adults to identify discrete events within the movie that elicited reliable neural responses across participants in ToM and SPM networks [17]. The network timecourse for each timepoint across adult subjects was compared to the baseline (0) using a one-tailed *t*-test. Events were defined as sequences of two or more consecutive timepoints with significantly positive responses within each network. Since reverse correlation analyses assess responses relative to baseline, the identified events are considered to drive responses in the ROIs compared to other moments in the stimulus. Events were then rank-ordered based on the average magnitude of response at the peak timepoint and labeled accordingly (e.g., event T01 represents the ToM event that elicited the highest magnitude of response in the ToM network). The events of adults were chosen for this analysis due to the relative stability and maturity of their social brain responses, allowing for robust detection of canonical ToM and social pain-related moments. These events, once identified, served as stimulus-locked timepoints for subsequent analyses in the child cohort. This approach enables us to examine how children's responses to well-characterized, socially meaningful events vary with age and parent-child dyadic dynamics.

Inter-region correlation analyses and functional neural maturity

In inter-region correlation analyses, each ROI timecourse was correlated with every other ROI's timecourse to obtain correlation metrices, per subject, and these correlation values were Fisher z-transformed. Then the average correlation matrices were conducted for different age groups. Within-ToM correlations were the average correlation from each ToM ROI to every other ToM ROI, within-SPM correlations were the average correlation from each SPM ROI to every other SPM ROI, and across-network correlations were the average correlation from each ToM ROI to each SPM ROI. Pearson correlation was used to determine the relationship between age and the within-ToM/SPM network correlations.

Next, we tested whether the functional neural maturity of each child's timecourse responses (i.e., similarity to adults) was related to the inter-region network correlations. Neural maturity was calculated as average value of the Pearson correlation between child's correlation metrices and each adult's correlation metrices. Pearson correlation was used to determine the relationship between neural maturity and age/relationship quality. Pair *t*-tests were performed on the neural maturity during ToM/SP events and other events between different age groups. In addition, a 2× 3 ANOVA with neural maturity as the dependent variable was used to determine the effects of ToM/SP events (ToM/SP events vs. other events), development (Pre-junior group vs. Junior group, Senior group), and their interaction.

ISS in fMRI Time Series

ISS was defined as the temporal correlation between the mean timecourses of social brain networks (averaged across ROIs) in child-mother dyads, determined through Pearson correlation analysis. Similarly, ISS for child-stranger dyads was calculated by correlating each child's network timecourse with the average adult timecourse (excluding their own mothers). The Fisher's r-to-z transform was applied to convert the correlation coefficient (r) values to normally distributed z scores. Two-sample t-tests were then conducted to compare ISS values between child-mother dyads and child-stranger dyads. Partial correlation analysis, with children's age as a covariate, was performed separately for child-mother and child-stranger dyads to examine the relationship between ISS and relationship quality.

A 2×2 ANOVA was used with ISS as the dependent variable to assess the effects of ToM/Pain events (ToM/SP events vs. other events), parental relationship (child-mother dyads vs. child-stranger dyads), and their interaction. Pairwise *t*-tests were conducted to compare ISS values between child-mother and child-stranger dyads across ToM/SP events and other events.

Structural Equation Modeling

SEM was conducted using R package lavaan [76]. The analyses employed lavaan settings consistent with standard practices in other software packages like AMOS. These settings included Wishart estimation, maximum likelihood estimation for handling missing data, and the use of expected information for estimating standard error variance. Within the hypothetical model, a latent factor was constructed for a *personal growth/trait* variable, another latent factor was constructed for a *parenting* variable, and social responsiveness was represented as manifest variable for output. *Personal growth/trait* and ToM behavior were included in the regression as the mediator. The hypothesized research model is depicted in **Fig 5**. To determine the model fit, we examined the χ^2/df ratio, Comparative Fit Index (CFI) and root mean square error of approximation (RMSEA). A good model fit is reflected by χ^2/df ratios <3 [77], fit indices above 0.90 [78], and RMSEA values ≤ 0.10.

Code availability

All process of code needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additionally, this study used openly available software and codes, specifically DPABI (*https://rfmri.org/DPABI*) and R Package lavaan (*https://cran.r-project.org/web/packages/lavaan/lavaan.pdf*).

Data availability

Anonymized fMRI used for analyses have been deposited in a Zenodo under "Neurobehavioral Synchrony and Social Cognition Development" (*https://zenodo.org/records/12730121*).

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Additional information

Author contributions

L.L. and X.D. designed research; L.L., J.X., Q.Z., W.Z., X.H., X.S., Y.M. and P.W. contributed to data acquisition; L.L., X.H., J.X., Q.Z., X.S., C.H. and X.D. contributed new analytic tools; L.L. analyzed data; L.L., X.D. and V.M. created the figures and wrote the manuscript; H.C. and X.D. led the project. All authors reviewed and commented on the manuscript.

Supplementary Materials

I. Supplemental Methods: Theory of Mind (ToM) Behavioral Tasks

Overview

Children completed a structured battery of 14 Theory of Mind (ToM) questions, designed to assess multiple components of social-cognitive reasoning. These tasks were adapted from prior validated paradigms and covered a range of developmental levels, including false belief understanding, knowledge access, deception, and second-order reasoning. Tasks were administered in a fixed order from simple to complex. Each task included a brief narrative and one or more questions targeting the child's ability to infer mental states (e.g., beliefs, intentions, perspectives). Correct responses to test questions (with or without control questions) were scored as 1; incorrect or no response was scored as 0. The total score ranged from 0 to 14.

To reduce cognitive fatigue for younger children, testing was discontinued if a child failed two consecutive tasks, reflecting a ceiling in their performance level.

Task Descriptions

Note: In the following descriptions,

- 🟧 = experimenter's spoken instructions
- 🟦 = experimenter's actions
- 🟩 = story narration

Tasks 1–2: Unexpected Contents Task (Rock in Candy Wrapper)

- 🟧 "Look, what do I have in my hand?"
- 🟩 (The object is a wrapped candy.)
- 🟧 "What do you think is inside?" → "Candy."

- 🟧 "Great, now let's open it and see what's really inside."
- 🟦 (The experimenter unwraps the candy in front of the child.)
- 🟧 "What's actually inside?" → "A rock."

- 🟦 (The experimenter re-wraps the candy.)

- 🟧 Control Question: "Do you know what's inside the wrapper now?" → "A rock."
- 🟧 Test Question 1: "Before we opened it, what did you think was inside?" → "Candy."
- 🟧 Test Question 2: "Now another child walks in and hasn't seen what's inside. What will they think is in the wrapper?" → "Candy."

Task 3–4: Unexpected Location Task (Ping-pong Ball in Colored Cups)

- 🟧 "What color are these two cups?" → "Blue and red."
- 🟩 "Now here come a boy and a girl. They are playing with a ball together."
- 🟦 (Experimenter uses figures to act out playing)
- 🟩 "The boy gets hungry and goes to eat. To hide the ball, he puts it in the blue cup and leaves."
- 🟩 "The girl, not hungry yet, takes the ball out and plays some more."
- 🟦 (Experimenter acts out girl playing)
- 🟩 "Then she hides the ball in the red cup before going to eat."

- 🟧 Memory Questions:
- – "Where did the boy hide the ball at first?" → "Blue cup"
- – "Did the boy see the girl move the ball?" → "No"

- 🟧 Test Question 3: "When the boy comes back, where will he think the ball is?" → "Blue cup"
- 🟧 Test Question 4: "Which cup will he look in first?" → "Blue cup

Tasks 5–8: Birthday Bunny Scenario

- 🟩 "Today is Xiaoming's birthday. He really wants a bunny. His mom actually bought him the bunny he wanted most, but she wanted to surprise him. So she hid the bunny in the cupboard and didn't tell Xiaoming."

- 🟧 (Experimenter says as the mom): "Sorry Xiaoming, I didn't buy you a bunny for your birthday. I got you an electric fan instead."

- 🟧 Control Question 1: "Did Xiaoming's mom really get him an electric fan for his birthday?" → "No"

- 🟧 Control Question 2: “Did the mom tell Xiaoming she got him an electric fan?” → “Yes”
- 🟧 Control Question 3: “Why did the mom say she got an electric fan?” → “To surprise him.”

- 🟩 “Then, the mom went out. Xiaoming went to the cupboard to get some clothes. When he opened it, he discovered the bunny! He was so happy and said: ‘Wow! Mom really got me the bunny I wanted!’”

- 🟩 “Remember: the mom didn’t see Xiaoming go to the cupboard or find the bunny.”

- 🟧 Test Question 5: “Does Xiaoming now know that his mom got him a bunny for his birthday?” → “Yes”
- 🟧 Test Question 6: “Does the mom know that Xiaoming found the bunny?” → “No”

- 🟩 “Later, Xiaoming left with his bunny. Then, the mom returned home with Xiaoming’s grandmother.”

- 🟧 Test Question 7: (As Grandma asks the mom): “Does Xiaoming know what gift you really got him for his birthday?”
- 🟧 “What does the mom think — does Xiaoming know, or not?” → “Not”

- 🟩 Memory cue: “Remember, the mom didn’t see Xiaoming find the bunny.”

- 🟧 Test Question 8: (Grandma continues): “Then what does Xiaoming think the gift is?”
- 🟧 “What does the mom think Xiaoming believes the gift is — the bunny, or the electric fan?” → “Electric fan”

- 🟧 Test Question 9: “Why does the mom think so?” → “Because she told him it was a fan, and doesn’t know he saw the bunny.”

Tasks 9–12: Picture Book Deception Scenario

- 🟩 “A girl had a picture book she really liked. One day, a boy came over to her house to play. He said: ‘I heard you have a really fun picture book! Where did you put it? I want to read it too.’”

- 🟩 “But the girl was afraid the boy might damage the book, so she didn’t want to share it. She decided to lie and said: ‘Sorry, I left my picture book at kindergarten. I didn’t bring it home, so you can’t read it.’”

- 🟧 Control Question 1: “Was the picture book actually left at kindergarten?” → “No”
- 🟧 Control Question 2: “Did the girl tell the boy the book was at kindergarten?” → “Yes”
- 🟧 Control Question 3: “Why did the girl say that?” → “Because she was afraid he’d damage it and wanted to keep it for herself.”

- 🟩 “Later, the boy got bored and went out to play. As soon as he left, the girl was happy she could finally read her book alone. She went to the cupboard to get it.”

- 🟦 (As the girl opens the cupboard and takes out the picture book)

- 🟩 “At that very moment, the boy turned back and saw her taking the book from the cupboard.”

- 🟩 “But the girl didn’t notice that the boy had seen her.”

- 🟧 Test Question 10: “Does the boy now know where the book really is?” → “Yes”
- 🟧 Test Question 11: “Does the girl know the boy saw her get the book?” → “No”

- 🟩 “Later, the girl’s mom came home and asked:”

- 🟧 Test Question 12: “‘Does the boy know where the book is?’”
- 🟧 “What does the girl think — does the boy know or not?” → “Not”

- 🟩 Memory cue: “Remember, the girl didn’t see the boy watching her take the book from the cupboard.”

- 🟧 Test Question 13: “What does the girl think the boy believes — where is the book?” → “At kindergarten”

- 🟧 Test Question 14: “Why does she think that?” → “Because she told him it was there and didn’t see him watching her.”

II. Supplementary Results

To further investigate the specificity of our findings, we conducted additional control analyses focusing on the individual components of the social brain networks examined in our study: the Theory of Mind (ToM) and Social Pain Matrix (SPM) networks.

When analyzing these networks separately, we found significant correlations between neural maturity and age, as well as between inter-subject synchronization (ISS) and parent-child relationship quality for both the ToM and SPM networks individually (**Fig. S1**). Specifically, neural maturity within each network was positively correlated with age, indicating that both networks undergo maturation during childhood. Similarly, ISS within each network was negatively correlated with parent-child conflict scores, suggesting that both networks contribute to the observed relationship between neural synchrony and parent-child relationship quality.

However, when we applied our structural equation model to each network separately, we found that the interactive effect of parenting and personal growth factors could not significantly predict children’s social cognition outcomes (**Fig. S2**). This finding suggests that the integration of information from both the ToM and SPM networks is essential for comprehensively predicting social cognitive outcomes in children.

These results highlight the importance of considering the social brain as an integrated system, where the ToM and SPM networks work in concert to support social cognitive development. While each network shows age-related maturation and sensitivity to parent-child relationship quality, their combined functioning appears to be crucial for predicting broader social cognitive outcomes.

III. Supplementary Figures

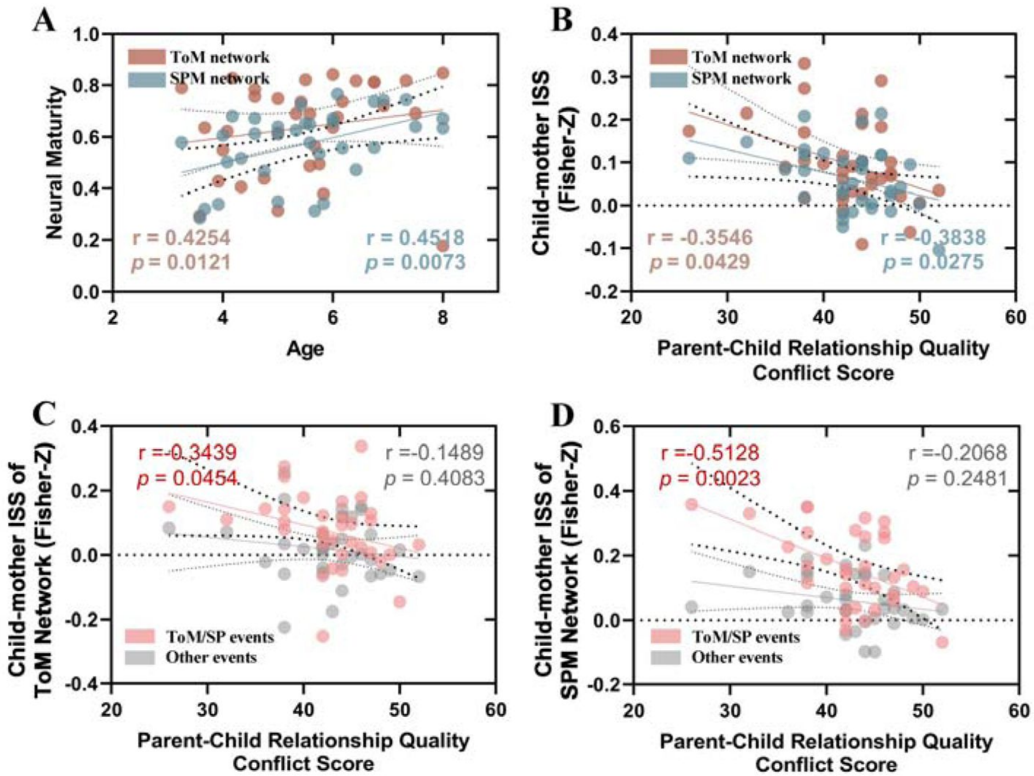

Fig S1.

Relationship between personal traits, neural measures and parent-child relationship quality for Theory of Mind (ToM) and Social Pain Matrix (SPM) networks analyzed separately.

(A) Correlation between neural maturity within ToM and SPM networks and age. **(B)** Correlation between parent-child relationship quality and inter-subject synchronization (ISS) within ToM and SPM networks in child-mother dyads. **(C-D)** Partial correlation between CPRS conflict scores and ISS within ToM/SPM networks in child-mother dyads during ToM/Social Pain and other events, shown in red and black circles respectively.

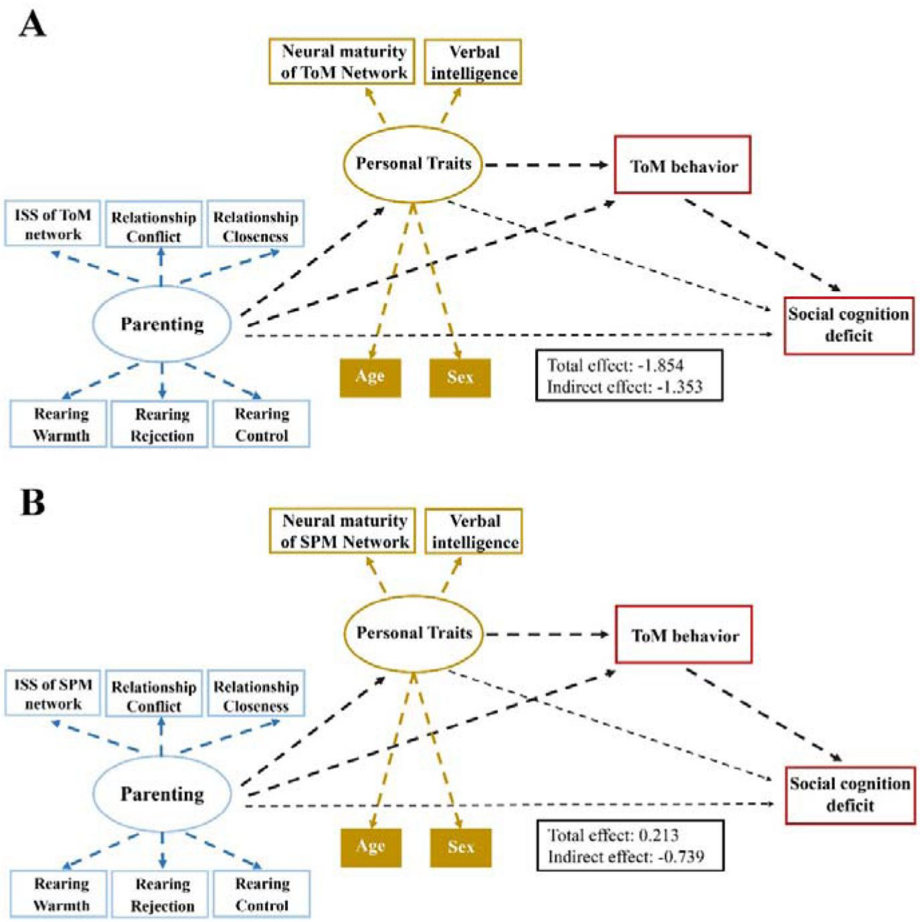

Fig S2.

Structural equation modeling using (A) Theory of Mind (ToM) and (B) Social Pain Matrix (SPM) networks separately.

Solid lines indicate significant paths, and dashed arrows indicate nonsignificant paths. No significant direct effects on social cognition outcomes were observed when analyzing the networks individually, highlighting the importance of considering both networks together for predicting social cognitive outcomes.

IV. Supplementary Tables

ToM events			
Events	Time point (in stimulus)	Duration	Description
T07	1:00-1:04	4s	Clouds create baby animals accompanied by laughter.
T02	1:12-1:18	6s	Baby cries, Cloud gives him a helmet and he's happy.
T04	1:30-1:36	6s	Gus is a lonely cloud.
T01	2:38-2:50	12s	Peck (crane) gazed longingly at the happy cloud that was making puppies, and wore a look of envy.
T06	2:54-2:58	4s	Peck notices that Gus caught him looking longingly, and feels bashful.
T05	3:18-3:22	4s	Gus saw Peck scream in agony as he was stabbed by the porcupine's thorns, and exclaimed.
T03	3:34-4:56	22s	Peck dons football gear to explain to Gus that he did not abandon him, but rather was acquiring protective equipment so that he could continue to deliver Gus's babies.
Social Pain events			
Events	Time point (in stimulus)	Duration	Description
P07	0:48-0:54	6s	Cloud makes baby cat (lightning).
P06	1:08-1:12	4s	Puppy's chewing on a bone.
P08	1:24-1:32	8s	Gus makes baby alligator (lightning).
P05	2:04-2:08	4s	Peck got bitten on the head by a baby alligator.
P03	3:02-3:14	12s	Peck's wing was repeatedly stabbed by porcupine baby's pinprick
P01	3:24-3:28	4s	Gus pulls porcupine spines out of Peck's head
P04	4:12-4:18	6s	Gus expresses anger through thunder
P02	4:52-5:00	8s	Peck is electrocuted by baby eel (lightning).

Table S1.

ToM and Social Pain Event details.

Time (Events in neural responses were then shifted 6s in time to account for the hemodynamic lag), duration (seconds) and description for each ToM and Social Pain event. Event labels (T01, P01) reflect rank order of average response magnitude in adults.

X→	Y	Estimate	St. Err	Z-value	P
Latent Variables					
Neural maturity	Personal growth	1.00			
Verbal intelligence	Personal growth	0.452	0.290	-1.556	0.12
Age	Personal growth	1.243	0.560	2.238	0.025
Sex	Personal growth	-1.234	0.552	-2.236	0.025
ISS	Parenting	1.00			
Relationship Conflict	Parenting	-0.797	0.261	-3.047	0.002
Relationship Closeness	Parenting	0.500	2.254	1.971	0.049
Rearing Warmth	Parenting	-0.174	0.249	-0.698	0.485
Rearing Rejection	Parenting	0.989	0.268	3.692	<0.001
Rearing Control	Parenting	-0.619	0.257	-2.412	0.016
Regressions					
Parenting	Personal growth	-0.708	0.271	-2.618	0.009
Parenting	ToM behavior	0.550	0.288	1.909	0.050
Personal growth	ToM behavior	-0.647	0.338	-1.916	0.049
ToM behavior	Social cognition deficit	-0.458	0.209	-2.193	0.028
Parenting	Social cognition deficit	0.427	0.319	-1.336	0.182
Personal growth	Social cognition deficit	-0.491	0.323	-1.521	0.128
Defined Parameters:					
Direct effect		-0.491	0.323	-1.521	0.128
Indirect effect		-0.210	0.106	-1.976	0.048
Total		-0.651	0.325	-2.005	0.045

Table S2.

Structural equation modeling (SEM) details.

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Reviewer #1 (Public review):

The authors have undertaken a significant revision of the manuscript and addressed the vast majority of our original comments. The manuscript is significantly improved as a result and will make a nice contribution to the literature. The new framing is especially impactful.

We have a few remaining comments to improving the manuscript:

Q1: The authors clarified the multiple comparison correction appropriately, and included a comprehensive of the study limitations related to causality and SEM. We think there could be a few further improvements to the manuscript to fully address our initial comment.

Under the results section where the authors describe the use of structural equation modeling, we think that it would be helpful to readers to further emphasize that the current design doesn't allow for delineation of temporal sequences in development and do cannot reflect true mediation. These are important caveats that the readers describe beautifully in their response.

In addition to think about the mediating variables, can the authors conduct a sensitivity analysis that re-orders the IV, mediator, and DV? That way, a formal comparison can be made between model fits. It would provide an empirical basis for how to temper the discussion of these findings.

Q7: We think that this analysis (lack of significant correlations between ISS, child age, and neural maturity) and corresponding discussion by the authors would be very interesting for readers. It does not appear as though they've added this information to the text (even in a supplementary file would suffice), but I think their conclusions about the data are strengthened related to context specific neural dynamics.

https://doi.org/10.7554/eLife.103017.2.sa3

Reviewer #2 (Public review):

Summary:
This study investigates the impact of mother-child neural synchronization and the quality of parent-child relationships on the development of Theory of Mind (ToM) and social cognition. Utilizing a naturalistic fMRI movie-viewing paradigm, the authors analyzed inter-subject neural synchronization in mother-child dyads and explored the connections between neural maturity, parental caregiving, and social cognitive outcomes. The findings indicate age-related maturation in ToM and social pain networks, emphasizing the importance of dyadic interactions in shaping ToM performance and social skills, thereby enhancing our understanding of the environmental and intrinsic influences on social cognition.

Strengths:
This research addresses a significant question in developmental neuroscience, by linking social brain development with children's behaviors and parenting. It also uses a robust methodology by incorporating neural synchrony measures, naturalistic stimuli, and a substantial sample of mother-child dyads to enhance its ecological validity. Furthermore, the SEM approach provides a nuanced understanding of the developmental pathways associated with Theory of Mind (ToM). The manuscript also addressed many concerns raised in the initial review. The adoption of the neuroconstructivist framework effectively frames neural and cognitive development as reciprocal, addressing prior concerns about causality. The justification for methodological choices, such as omitting resting-state baselines due to scanning challenges in children and using unit-weighted scoring for ToM tasks, further strengthens the study's credibility.

Weaknesses:
(1) The revised introduction has improved, particularly in framing the first goal-developmental changes in ToM and SPM networks-as a "developmental anchor" for goals 2 and 3. However, given prior research on age-related changes in these networks (e.g., Richardson et al., 2018), the authors should clarify whether this goal seeks to replicate prior findings or to extend them under new contexts. Specifying how this part differs from existing work and articulating specific hypotheses would enhance the focus.
(2) I still have some reservations about retaining the slightly causal term "shape" in the title. While the manuscript now carefully avoids causal claims, the title may still be interpreted as implying directionality, especially by non-specialist audiences.

(3) One more question about Figure 2A and 2B: adults and children showed highly similar response curves for video frames, yet some peaks (e.g., T02, T05, T06) are identified as ToM or SPM events only in adults. Whether statistical methods account for the differences? Or whether the corresponding video frames contain subtle social cues that only adults can process?

https://doi.org/10.7554/eLife.103017.2.sa2

Reviewer #3 (Public review):

Summary:
The article explores the role of mother-child interactions in the development of children's social cognition, focusing on Theory of Mind (ToM) and Social Pain Matrix (SPM) networks. Using a naturalistic fMRI paradigm involving movie viewing, the study examines relationships among children's neural development, mother-child neural synchronization, and interaction quality. The authors identified a developmental pattern in these networks, showing that they become more functionally distinct with age. Additionally, they found stronger neural synchronization between child-mother pairs compared to child-stranger pairs, with this synchronization and neural maturation of the networks associated with the mother-child relationship and parenting quality.

Strengths:
This is a well-written paper, and using dyadic fMRI and naturalistic stimuli enhances its ecological validity, providing valuable insights into the dynamic interplay between brain development and social interactions.

Weaknesses:
The current sample size (N = 34 dyads) is a limitation, particularly given the use of SEM, which generally requires larger samples for stable results. Although the model fit appears adequate, this does not guarantee reliability with the current sample size.

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Author response:

The following is the authors' response to the original reviews

> ***Reviewer #1:***
>
> *The authors sought to examine the associations between child age, reports of parent-child relationship quality, and neural activity patterns while children (and also their parents) watched a movie clip. Major methodological strengths include the sample of 3-8 year-old children in China (rare in fMRI research for both age range and non-Western samples), use of a movie clip previously demonstrated to capture theory of mind constructs at the neural level, measurement of caregiver-child neural synchrony, and assessment of neural maturity. Results provide important new information about parent-child neural synchronization during this movie and associations with reports of parent-child relationship quality. The work is a notable advance in understanding the link between the caregiving context and the neural construction of theory of mind networks in the developing brain.*

We are grateful for the reviewer's generous and thoughtful summary of our work. We particularly appreciate the recognition of the methodological strengths—including the rare developmental sample, culturally diverse context, and use of naturalistic, theory of mind-relevant stimuli—as well as the importance of integrating neural synchrony and relational variables. The reviewer's comments affirm the core motivation behind this study: to advance our understanding of how the caregiving environment shapes the neurodevelopment of social cognition in early childhood. We have taken all specific suggestions seriously and hope the revised manuscript more clearly communicates these contributions.

> *We appreciate that the authors wanted to show support for a mediational mechanism. However, we suggest that the authors drop the structural equation modeling because the data are cross-sectional so mediation is not appropriate. Other issues include the weak justification of including the parent-child neural synchronization as part of parenting.... it could just as easily be a mechanism of change or driven by the child rather than a component of parenting behavior. The paper would be strengthened by looking at associations between selected variables of interest that are MOST relevant to the imaging task in a regression type of model. Furthermore, the authors need to be more explicit about corrections for multiple comparisons throughout the manuscript; some of the associations are fairly weak so claims may need to be tempered if they don't survive correction.*

Thanks for feedback on the use of SEM in our study. We recognize the limitations of using SEM to infer mediation with cross-sectional data and acknowledge that longitudinal designs are better suited for such analyses. However, our goal was not to establish causality but to explore potential pathways linking parenting, personal traits, and Theory of Mind (ToM) behavior to social cognition outcomes. SEM allowed us to simultaneously examine the relationships among these latent constructs, providing a cohesive framework for understanding the interplay of these factors. That said, we understand your concern and are willing to revise the manuscript to de-emphasize causal interpretations of the SEM findings.

We thank the reviewer for raising the corrections for multiple comparisons. We confirm that all correlation analyses reported in the manuscript have been corrected for multiple comparisons using the False Discovery Rate (FDR) procedure. In the revised manuscript, we now explicitly indicate FDR correction for all relevant p-values to ensure clarity and transparency. Where this information was previously missing, we have corrected the oversight and clearly labeled the results as FDR-corrected or uncorrected where appropriate. Additionally, we have carefully reviewed our interpretation of all reported associations. For any results that were close to the significance threshold, we have tempered our claims and now describe them as a marginally significant association to avoid overstating our findings.

The corresponding changes have been made on Discussion section of the revised manuscript.

> *Reverse correlation analysis is sensible given what prior developmental fMRI studies have done. But reverse correlation analysis may be more prone to overfitting and noise, and lacks sensitivity to multivariate patterns. Might inter-subject correlation be useful for *within* the child group? This would minimize noise and allow for non-linear patterns to emerge.*

We appreciate the reviewer's thoughtful suggestion regarding potential limitations of reverse correlation analysis. While we agree that inter-subject correlation (ISC) within the child group may be useful in other contexts, our primary goal in using reverse correlation was not to identify temporally distributed or multivariate response patterns, but rather to isolate specific events within the naturalistic stimulus that reliably evoke Theory of Mind (ToM) and Social Pain-related responses in adults—who possess more stable and mature neural signatures. These adult-derived events serve as anchors for subsequent developmental comparisons and provide a principled way to define timepoints of interest that are behaviorally and theoretically meaningful.

Using reverse correlation in adults allows us to identify canonical ToM and Social Pain events in a data-driven yet hypothesis-informed manner. We then examine how children's neural responses to these same events vary with age, neural maturity, and dyadic synchrony. This approach is consistent with prior work in developmental social neuroscience (e.g., Richardson et al., 2018) and offers a valid framework for identifying interpretable social-cognitive events in naturalistic stimuli.

We have now clarified the rationale for using adult-based reverse correlation in the revised manuscript and explicitly stated its advantages for identifying targeted ToM and Social Pain content in the stimulus.

The corresponding changes have been made on pages 17 of the revised manuscript.

"We employed reverse correlation analysis in adults to identify discrete events within the movie that elicited reliable neural responses across participants in ToM and SPM networks.

The events of adults were chosen for this analysis due to the relative stability and maturity of their social brain responses, allowing for robust detection of canonical ToM and social pain-related moments. These events, once identified, served as stimulus-locked timepoints for subsequent analyses in the child cohort. This approach enables us to examine how children's responses to well-characterized, socially meaningful events vary with age and parent-child dyadic dynamics."

> *No learning effects or temporal lagged effects are tested in the current study, so the results do not support the authors' conclusions that the data speak to Bandura's social learning theory. The authors do mention theories of biobehavioral synchrony in the introduction but do not discuss this framework in the discussion (which is most directly relevant to the data). The data can also speak to other neurodevelopmental theories of development (e.g.,neuroconstructivist approaches), but the authors do not discuss them. The manuscript would benefit from significantly revising the framework to focus more on biobehavioral synchrony data and other neurodevelopmental approaches given the prior work done in this area rather than a social psychology framework that is not directly evaluated.*

We appreciate the reviewer's thoughtful and constructive feedback. We agree that the current study does not directly test mechanisms central to Bandura's social learning theory, such as observational learning over time or behavioral modeling. In light of this, we have significantly revised the theoretical framing of the manuscript to focus more directly on the biobehavioral synchrony framework, which more accurately reflects the dyadic neural measures employed in this study and is better supported by our findings.

Specifically, we have expanded the Discussion to contextualize our findings in terms of biobehavioral synchrony, emphasizing how inter-subject neural synchronization may reflect coordinated parent-child engagement and emotional attunement. We have also incorporated insights from neurodevelopmental and neuroconstructivist models, acknowledging that social cognitive development is shaped by dynamic interactions between neural maturation and environmental input over time.

Although we continue to briefly reference Bandura's theory to situate our findings within broader social-cognitive frameworks, we have clearly delineated the boundaries of what our data can support and have tempered previous claims. These changes are intended to better align our conceptual framing with the empirical evidence and relevant theoretical models.

The corresponding changes have been made on pages 11-12 of the revised manuscript.

“Insights into mechanisms of Neuroconstructivist Perspectives and Bandura’s social learning theory

Our findings align with a neuroconstructivist perspective, which conceptualizes brain development as an emergent outcome of reciprocal interactions between biological constraints and context-specific environmental inputs. Rather than presuming fixed traits or linear maturation, this perspective highlights how neural circuits adaptively organize in response to experience, gradually supporting increasingly complex cognitive functions49. It offers a particularly powerful lens for understanding how early caregiving environments modulate the maturation of social brain networks.

Building on this framework, the present study reveals that moment-to-moment neural synchrony between parent and child, especially during emotionally salient or socially meaningful moments, is associated with enhanced Theory of Mind performance and reduced dyadic conflict. This suggests that beyond age-dependent neural maturation, dyadic neural coupling may serve as a relational signal, embedding real-time interpersonal dynamics into the child’s developing neural architecture [1] . Our data demonstrate that children’s brains are not merely passively maturing, but are also shaped by the relational texture of their lived experiences—particularly interactions characterized by emotional engagement and joint attention. Importantly, this adds a new dimension to neuroconstructivist theory: it is not simply whether the environment shapes development, but how the quality of interpersonal input dynamically calibrates neural specialization. Interpersonal variation leaves detectable signatures in the brain, and our use of neural synchrony as a dyadic metric illustrates one potential pathway through which caregiving relationships exert formative influence on the developing social brain.

The contribution of this work lies not in reiterating the interplay of nature and nurture, but in specifying the mechanistic role of interpersonal neural alignment as a real-time, context-sensitive developmental input. Neural synchrony between parent and child may function as a form of relationally grounded, temporally structured experience that tunes the child’s social brain toward contextually relevant signals. Unlike generalized enrichment, this form of neural alignment is inherently personalized and contingent—features that may be especially potent in shaping social cognitive circuits during early childhood.

Although our study was not designed to directly examine learning mechanisms such as imitation or reinforcement, the findings can be viewed as broadly consistent with social learning theory. Bandura's theory posits that human behavior is shaped by observational learning and modeling from others in one's environment [2-4]. According to Bandura, children acquire social cognitive skills by observing and interacting with their parents and other significant figures in their environment. This dynamic interplay shapes their ability to understand and predict the behavior of others, which is crucial for the development of ToM and other social competencies.”

References

(1) Hughes, C. et al. Origins of individual differences in theory of mind: From nature to nurture? Child development 76, 356-370 (2005).

(2) Koole, S. L. & Tschacher, W. Synchrony in psychotherapy: A review and an integrative framework for the therapeutic alliance. Frontiers in psychology 7, 862 (2016).

(3) Liu, D., Wellman, H. M., Tardif, T. & Sabbagh, M. A. Theory of mind development in Chinese children: a meta-analysis of false-belief understanding across cultures and languages. Developmental Psychology 44, 523 (2008).

(4) Frith, U. & Frith, C. D. Development and neurophysiology of mentalizing. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 358, 459-473 (2003).

> *The significance and impact of the findings would be clearer if the authors more clearly situated the findings in the context of (a) other movie and theory of mind fMRI task data during development; and (b) existing data on parent-child neural synchrony (often uses fNIRS or EEG). What principles of brain and social cognition development do these data speak to? What is new?*

We thank the reviewer for this thoughtful comment. In response, we have revised the Discussion section to more clearly situate our findings within two key literatures: (a) fMRI studies examining Theory of Mind using movie-based and traditional task paradigms across development, and (b) research on parent-child neural synchrony. We now articulate more explicitly how our findings advance current understanding of the neural architecture of social cognition in childhood, and how they contribute new insights into the relational processes shaping brain function. These revisions clarify the conceptual and empirical novelty of our study, particularly in its use of naturalistic fMRI, simultaneous child-parent dyads, and integration of neural maturity with interpersonal synchrony.

The corresponding changes have been made on pages 12 of the revised manuscript.

"Our findings contribute to and extend prior research using fMRI paradigms to investigate ToM development in children. Previous work has shown that these networks become increasingly specialized and differentiated throughout childhood [1-3]. The current study extends these findings by demonstrating that the development of social brain networks is a gradual process that continues beyond the preschool years and is related to children's chronological age. This finding is consistent with behavioral research indicating that ToM and social abilities continue to develop and refine throughout middle childhood and adolescence [4]. Importantly, we move beyond prior work by combining reverse correlation with naturalistic stimuli to isolate discrete, behaviorally meaningful events (e.g., mental state attribution, social rejection) and relate children's brain responses to adult patterns and social outcomes. This event-level analysis in a dyadic context offers greater ecological and interpretive precision than traditional block or condition-based designs. Our study provides novel evidence for the neural underpinnings of this protracted development, suggesting that the functional maturation of social brain networks may support the continued acquisition and refinement of social cognitive skills.

In parallel, our study builds on and extends a growing body of work on parent-child neural synchrony, much of which has relied on fNIRS or EEG hyperscanning to demonstrate interpersonal alignment during communication, shared attention, or cooperative tasks [5-7]. While these modalities offer fine temporal resolution, they are limited in spatial precision and typically focus on surface-level cortical regions such as the prefrontal cortex. By contrast, our naturalistic fMRI approach enables the examination of deep and distributed brain networks—specifically those supporting social cognition—within child-parent dyads during emotionally and cognitively rich scenarios. Intriguingly, we found that neural synchronization during movie viewing was higher in child-mother dyads compared to child-stranger dyads."

Reference

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Astington, J. W. & Jenkins, J. M. A longitudinal study of the relation between language and theory-of-mind development. Developmental Psychology 35, 1311 (1999).

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(4) Im-Bolter, N., Agostino, A. & Owens-Jaffray, K. Theory of mind in middle childhood and early adolescence: Different from before? Journal of experimental child psychology 149, 98-115 (2016).

(5) Deng, X. et al. Parental involvement affects parent-adolescents brain-to-brain synchrony when experiencing different emotions together: an EEG-based hyperscanning study. Behavioural brain research 458, 114734 (2024).

(6) Miller, J. G. et al. Inter-brain synchrony in mother-child dyads during cooperation: an fNIRS hyperscanning study. Neuropsychologia 124, 117-124 (2019).

(7) Nguyen, T., Bánki, A., Markova, G. & Hoehl, S. Studying parent-child interaction with hyperscanning. Progress in brain research 254, 1-24 (2020).

> *There is little discussion about the study limitations, considerations about the generalizability of the findings, and important next steps and future directions. What can the data tell us, and what can it NOT tell us?*

We appreciate the reviewer's recommendation to elaborate on the study's limitations, generalizability, and future directions. In response, we have added a dedicated section to the Discussion that critically addresses these considerations. We acknowledge the cross-sectional nature of the study, the modest sample size, and the use of a single stimulus context as key limitations. We also clarify the inferences that can be drawn from our data and what remains speculative. Finally, we outline specific future research directions.

The corresponding changes have been made on pages 13-14 of the revised manuscript.

"While leveraging a naturalistic movie-viewing paradigm allowed us to study children's spontaneous neural responses during a semi-structured yet engaging task, dedicated experimental designs are still needed to make stronger inferences about the cognitive processes involved. Additionally, our region-of-interest approach precluded examination of whole-brain networks; future work could explore developmental changes in broader functional circuits. The cross-sectional nature of our study is a further limitation, as it cannot definitively establish the causal directions of the observed relationships. Longitudinal designs tracking children's brain development and social cognitive abilities over time would help clarify whether early parenting impacts later neural maturation and behavioral outcomes, or vice versa. Our sample was restricted to mother-child dyads, leaving open questions about potential differences in father-child relationships and gender effects on parenting neurobiology. Larger and more diverse samples would enhance the generalizability of the findings.

Several future directions emerge from this research. First, combining naturalistic neuroimaging with structured cognitive tasks could elucidate the specific mental processes underlying children's neural responses during movie viewing. Examining how these processes relate to real-world social behavior would further bridge neurocognitive function and ecological validity. Longitudinal studies beginning in infancy could chart the developmental trajectories of parent-child neural synchrony and their impact on long-term social outcomes. Such work could also explore sensitive periods when parenting may be most influential on social brain maturation. Finally, expanding this multimodal approach to clinical populations like autism could yield insights into atypical social cognitive development and inform tailored intervention strategies targeting parent-child relationships and neural plasticity."

> *To evaluate associations between child neural activity patterns during the movie AND parent-child synchronization patterns AND other variables such as parent-child communication and theory of mind behavior, it seems like a robust approach could be to examine whether similar synchronization patterns are associated with similar scores on different variables. Would allow for non-linear and multivariate associations.*

We greatly appreciate the reviewer's thoughtful suggestion regarding the use of similarity-based or multivariate analyses to assess whether dyads with similar neural synchronization profiles also exhibit similar scores on behavioral or relational variables. We agree that this type of analysis—such as representational similarity analysis (RSA) or inter-subject pattern similarity—offers a powerful framework for capturing non-linear and multivariate associations, and could provide deeper insights into shared neurobehavioral patterns across participants. However, the analytic logic of similarity-based approaches typically requires the availability of comparable measures across individuals or dyads (e.g., child A and child B must both have measures of brain activity, behavior, and environment). In the present study, our focus was on the child as the behavioral and developmental target, and we did not collect parallel behavioral or cognitive variables from the parent side (e.g., adult Theory of Mind ability, emotional traits, parenting style questionnaires beyond dyadic reports). As a result, it was not feasible to construct pairwise similarity matrices across dyads that include both neural synchrony and matched behavioral dimensions from both individuals.

Instead, our study was designed to examine how child-level outcomes (e.g., Theory of Mind performance, social functioning) are associated with (a) the child's neural responses to specific social events, and (b) the degree of neural synchronization with their mother, as a marker of relational engagement. The analytical emphasis, therefore, remained on within-child variation, modulated by the quality of the parent-child interaction.

> *Were there associations between parent-child neural synchronization and child age? What was the association between neural maturity and parent-child neural synchronization*

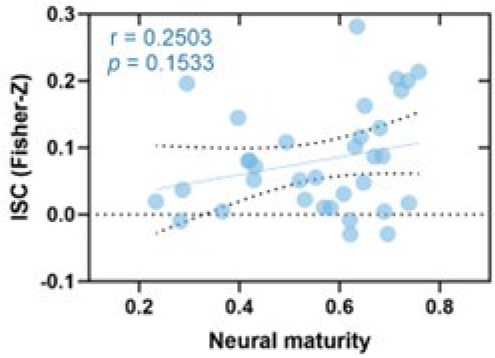
We thank the reviewer for raising this important point regarding associations between parent-child neural synchronization (ISS), child age, and neural maturity.

As reported in the original manuscript, we did not observe significant correlations between parent-child ISS and child age for either the Theory of Mind (ToM) or Social Pain Matrix (SPM) networks (all ps > 0.1). Additionally, we conducted additional analysis, we found no significant correlations between ISS and neural maturity (Author response image 1, $r = 0.2503$, $p = 0.1533$).

These findings indicate that parent-child neural synchronization in this naturalistic viewing context is not simply explained by age-related maturation or children's neural maturity level. Instead, ISS may predominantly reflect real-time interpersonal engagement or relational dynamics rather than individual developmental trajectories or neural maturity.

Author response image 1.

Scatterplot showing the association between parent-child inter-subject synchronization (ISS) and neural maturity, averaged across the Theory of Mind (ToM) and Social Pain Matrix (SPM) networks. Each point represents one dyad. No significant correlation was observed between ISS and neural maturity ($r = 0.2503$, $p = 0.1533$, suggesting that interpersonal neural synchronization and individual neural maturation may reflect dissociable aspects of social brain development.



> *The rationale for splitting the ages into 3 groups is unclear and creates small groups that could be more prone to spurious associations. Why not look at age continuously?*

We thank the reviewer for raising this important point. We fully agree that analyzing age as a continuous variable is statistically more robust and minimizes concerns about spurious associations due to arbitrary groupings.

To clarify, all primary statistical models—including correlational analyses—treated age as a continuous variable, and our core developmental inferences are based on these continuous-age findings.

In addition to these analyses, we included age group comparisons as a supplementary approach, guided by both theoretical considerations and visual inspection of the data. Specifically, we aimed to explore whether functional differentiation between social brain networks (e.g., ToM and SPM) might begin to emerge non-linearly or earlier than expected, particularly in the youngest children. Such early neural divergence may not be well-captured by linear trends alone. The grouped analysis allowed us to illustrate that network differentiation was already observable in children under age 5, suggesting that certain aspects of social brain organization may emerge earlier than classically assumed.

We have now clarified this rationale in the revised manuscript and emphasized that the group-based analysis was used solely to highlight developmental shifts that may not follow a linear pattern, and not for formal hypothesis testing.

The corresponding changes have been made on pages 9 of the revised manuscript.

“While our primary analyses treated age as a continuous variable, we also performed exploratory group-based comparisons to probe for potential non-linear developmental shifts in social brain network organization. This approach revealed that the differentiation between ToM and SPM networks was already present in the youngest group (ages 3–4), suggesting that early neural specialization may begin prior to the age at which ToM behavior is reliably observed. These group-level observations provide complementary evidence to the continuous analyses and may inform future work examining sensitive periods or early markers of social brain development.”

> *Tables would be improved if they were more professionally formatted (e.g., names of the variables rather than variable abbreviation codes).*

We appreciate the reviewer’s suggestion to improve the clarity and professionalism of our tables. In the revised manuscript, we have reformatted all tables to include full variable names rather than abbreviations or coded labels, and we ensured consistency in terminology across the manuscript text, tables, and figure legends. We have also added explanatory footnotes where needed to clarify any derived or composite measures. We hope these revisions improve the accessibility and readability of the results for a broader audience

> ***Reviewer #2:***
>
> *Summary:*
>
> *This study investigates the impact of mother-child neural synchronization and the quality of parent-child relationships on the development of Theory of Mind (ToM) and social cognition. Utilizing a naturalistic fMRI movie-viewing paradigm, the authors analyzed inter-subject neural synchronization in mother-child dyads and explored the connections between neural maturity, parental caregiving, and social cognitive outcomes. The findings indicate age-related maturation in ToM and social pain networks, emphasizing the importance of dyadic interactions in shaping ToM performance and social skills, thereby enhancing our understanding of the environmental and intrinsic influences on social cognition.*
>
> *Strengths:*
>
> *This research addresses a significant question in developmental neuroscience, by linking social brain development with children's behaviors and parenting. It also uses a robust methodology by incorporating neural synchrony measures, naturalistic stimuli, and a substantial sample of mother-child dyads to enhance its ecological validity. Furthermore, the SEM approach provides a nuanced understanding of the developmental pathways associated with Theory of Mind (ToM).*

We appreciate the positive evaluation and valuable comments of the reviewer. According to the reviewers̓ comments, we have revised the manuscript thoroughly to address the concerns raised by the reviewer. A point-by-point response to each of the issues raised by the reviewer has been made. We believe that the revision of our manuscript has now been significantly improved.

> *Upon reviewing the introduction, I feel that the first goal - developmental changes of the social brain and its relation to age - seems somewhat distinct from the other two goals and the main research question of the manuscript. The authors might consider revising this section to enhance the overall coherence of the manuscript. Additionally, the introduction lacks a clear background and rationale for the importance of examining age-related changes in the social brain.*

We thank the reviewer for this thoughtful observation. In response, we have revised the Introduction to better integrate the developmental aspect of the social brain with the broader research aims. We now explicitly link age-related changes in social brain organization to the emergence of social cognitive abilities and highlight why early childhood (ages 3–8) represents a particularly formative period. This revision clarifies that our first aim—examining functional specialization and neural maturity in Theory of Mind (ToM) and Social Pain Matrix (SPM) networks—serves as a developmental foundation for understanding how dyadic influences, such as neural synchrony and caregiving quality, shape children’s social cognition.

We have also improved the rationale for examining age-related change, drawing on key literature in developmental neuroscience to show how the early emergence and specialization of social brain networks provide a necessary context for interpreting interpersonal neural dynamics.

The corresponding changes have been made on pages 3 of the revised manuscript.

“These findings suggest that the development of specialized brain regions for reasoning about others' mental states and physical sensations is a gradual process that continues throughout childhood.

Understanding how these networks differentiate with age is essential not only for mapping typical brain development, but also for contextualizing the role of environmental influences. By establishing normative patterns of neural maturity and differentiation, we can better interpret how relational experiences—such as caregiver-child synchrony and parenting quality—modulate these trajectories. Thus, our first goal provides a developmental anchor that grounds our investigation of interpersonal and environmental contributions to social brain function.”

> *The manuscript uses both "mother-child" and "parent-child" terminology. Does this imply that only mothers participated in the fMRI scans while fathers completed the questionnaires? If so, have the authors considered the potential impact of parental roles (father vs. mother)?*

We thank the reviewer for raising this important point regarding terminology and parental roles. To clarify, all participating caregivers in the current study were biological mothers, and all behavioral questionnaires were also completed by these same mothers. No fathers were included in this study. We have revised the manuscript throughout to consistently use the term “mother-child” when referring to the specific dyads in our sample.

We also appreciate the opportunity to elaborate on the rationale for including only mothers. Prior research has shown that maternal and paternal influences on child development are not interchangeable, and that the neural correlates of caregiving behaviors differ between mothers and fathers. For example, studies have demonstrated distinct patterns of brain activation during social and emotional processing in mothers versus fathers (Abraham et al., 2014; JE Swain et al., 2014). Given these differences, we deliberately focused on mother-child dyads to maintain neurobiological consistency in our analysis and reduce variance associated with heterogeneous caregiving roles. We now clarify this rationale in the revised Methods and Discussion sections.

The corresponding changes have been made on pages 14 of the revised manuscript.

“We chose to focus exclusively on mother-child dyads in this study based on prior evidence suggesting distinct neural and behavioral caregiving profiles between mothers and fathers [1-2], allowing us to maintain role consistency and reduce variability in dyadic interactions.

Our sample was restricted to mother-child dyads, leaving open questions about potential differences in father-child relationships and gender effects on parenting neurobiology [1]. Larger and more diverse samples would enhance the generalizability of the findings.”

Reference:

(1) Swain, J. E. et al. Approaching the biology of human parental attachment: Brain imaging, oxytocin and coordinated assessments of mothers and fathers. Brain research 1580, 78-101 (2014).

(2) Abraham, E. et al. Father's brain is sensitive to childcare experiences. Proceedings of the National Academy of Sciences 111, 9792-9797 (2014).

> *There is inconsistent usage of the terms ISC and ISS in the text and figures, both of which appear to refer to synchronization derived from correlation analysis. It would be beneficial to maintain consistency throughout the manuscript.*

We thank the reviewer for highlighting the inconsistent use of “ISC” and “ISS” in the original manuscript. We agree that clarity and consistency in terminology are essential. In response, we have revised the manuscript to consistently use “ISS” (inter-subject synchronization) throughout the text, figures, tables, and legends.

> *Of the 50 dyads, 16 were excluded due to data quality issues, which constitutes a significant proportion. It would be helpful to know whether these excluded dyads exhibited any distinctive characteristics. Providing information on demographic or behavioral differences-such as Theory of Mind (ToM) performance and age range between the excluded and included dyads would enhance the assessment of the findings' generalizability.*

We thank the reviewer for this important observation. We agree that understanding the characteristics of excluded participants is essential for assessing the generalizability of the findings.

In response, we conducted comparative analyses between included and excluded dyads ($N = 34$ included; $N = 16$ excluded) on key demographic and behavioral variables, including child age, gender, and Theory of Mind (ToM) performance. These analyses revealed no significant differences between groups on any of these measures ($ps > 0.1$), suggesting that data exclusion due to quality issues (e.g., excessive motion, incomplete scans) did not introduce systematic bias.

We have now added this information to the Results and Methods sections of the manuscript.

The corresponding changes have been made on pages 6 and 17 of the revised manuscript.

“Of the 50 initial mother-child dyads recruited, 16 were excluded due to excessive head motion ($n = 11$), incomplete scan sessions ($n = 3$), or technical issues during data acquisition ($n = 2$). The final sample consisted of 34 dyads. To assess potential bias introduced by data exclusion, we compared included and excluded dyads on child age, gender, and Theory of Mind performance. No significant differences were found across these variables (all $ps > 0.1$), suggesting that the analytic sample was demographically representative of the full cohort.

Comparison between included and excluded dyads revealed no significant differences in child age ($t = 1.23$, $p = 0.24$), ToM scores ($t = -0.54$, $p = 0.59$), or sex distribution ($\chi^2 < 0.01$, $p = 0.98$), indicating that data exclusion did not bias the sample in a systematic way.”

> *The article does not adhere to the standard practice of using a resting state as a baseline for subtracting from task synchronization. Is there a rationale for this approach? Not controlling for a baseline may lead to issues, such as whether resting state synchronization already differs between subjects with varying characteristics.*

We thank the reviewer for raising this important methodological point. We agree that controlling for baseline synchronization, such as using a resting-state scan as a comparison, can help disambiguate whether task-induced synchrony reflects genuine stimulus-driven coupling or baseline differences across individuals or dyads.

In the present study, we focused on inter-subject synchronization (ISS) during naturalistic movie viewing, a task condition that has been widely used in previous developmental and social neuroscience research to assess shared neural engagement. We did not include a resting-state scan in the current protocol due to time constraints and the young age of our participants (ages 3–8), as longer scanning sessions often result in increased motion and reduced data quality in pediatric populations. Moreover, many prior studies using ISS in naturalistic paradigms have similarly focused on task-driven synchrony without subtracting a resting baseline (e.g., Hasson et al., 2004; Nguyen et al., 2020; Reindl et al., 2018).

That said, we acknowledge that baseline neural synchrony across dyads may vary depending on individual or relational characteristics (e.g., temperament, arousal, attentional style), and this remains an important question for future research. In the revised Discussion, we now explicitly note the absence of a resting-state baseline as a limitation and highlight the need for future studies to examine how resting and task-based ISS may interact, particularly in the context of child-caregiver dyads.

The corresponding changes have been made on page 13 of the revised manuscript.

"Another limitation of the current design is the lack of a resting-state baseline for inter-subject synchronization. While our focus was on synchronization during naturalistic social processing, we cannot determine whether individual differences in ISS reflect purely task-induced coupling or are partially shaped by trait-level synchrony present at rest. Including both resting and task conditions in future work would allow for stronger inferences about stimulus-specific versus baseline-driven synchronization, especially in relation to interpersonal factors such as relationship quality or social responsiveness."

> *The title of the manuscript suggests a direct influence of mother-child interactions on children's social brain and theory of mind. However, the use of structural equation modeling (SEM) may not fully establish causal relationships. It is possible that the development of children's social brain and ToM also enhances mother-child neural synchronization. The authors should address this alternative hypothesis of the potential bidirectional relationship in the discussion and exercise caution regarding terms that imply causality in the title and throughout the manuscript.*

We appreciate the reviewer's careful attention to issues of causality in our manuscript. We agree that our cross-sectional design limits causal inference, and that the use of structural equation modeling (SEM) in this context does not allow for conclusions about directional or mechanistic pathways. In response, we have revised the Discussion to explicitly acknowledge these limitations, and now include an expanded section on the potential for bidirectional or co-constructed processes, consistent with neuroconstructivist frameworks.

We have also tempered the interpretation of our SEM findings, avoiding causal language throughout the manuscript and clarifying that our analyses are exploratory and associational in nature. We hope that these changes provide a more cautious and developmentally grounded interpretation of the data.

With regard to the title, we respectfully chose to retain the original wording, as we believe it captures the thematic focus and central research question of the paper—namely, the potential role of mother-child interaction in the development of children's social brain and Theory of Mind. While we understand the reviewer's concern, we note that the interpretation of this phrasing is contextualized within the manuscript, which now includes clear qualifications regarding the limits of causal inference. We have taken care to ensure that no claims of unidirectional causality are made in the body of the paper.

The corresponding changes have been made on pages 11- 12 of the revised manuscript.

"Our findings align with a neuroconstructivist perspective, which conceptualizes brain development as an emergent outcome of reciprocal interactions between biological constraints and context-specific environmental inputs. Rather than presuming fixed traits or linear maturation, this perspective highlights how neural circuits adaptively organize in response to experience, gradually supporting increasingly complex cognitive functions54. It offers a particularly powerful lens for understanding how early caregiving environments modulate the maturation of social brain networks.

Building on this framework, the present study reveals that moment-to-moment neural synchrony between parent and child, especially during emotionally salient or socially meaningful moments, is associated with enhanced Theory of Mind performance and reduced dyadic conflict. This suggests that beyond age-dependent neural maturation, dyadic neural coupling may serve as a relational signal, embedding real-time interpersonal dynamics into the child's developing neural architecture. Our data demonstrate that children's brains are not merely passively maturing, but are also shaped by the relational texture of their lived experiences—particularly interactions characterized by emotional engagement and joint attention. Importantly, this adds a new dimension to neuroconstructivist theory: it is not simply whether the environment shapes development, but how the quality of interpersonal input dynamically calibrates neural specialization. Interpersonal variation leaves detectable signatures in the brain, and our use of neural synchrony as a dyadic metric illustrates one potential pathway through which caregiving relationships exert formative influence on the developing social brain.

The contribution of this work lies not in reiterating the interplay of nature and nurture, but in specifying the mechanistic role of interpersonal neural alignment as a real-time, context-sensitive developmental input. Neural synchrony between parent and child may function as a form of relationally grounded, temporally structured experience that tunes the child's social brain toward contextually relevant signals. Unlike generalized enrichment, this form of neural alignment is inherently personalized and contingent—features that may be especially potent in shaping social cognitive circuits during early childhood.

The cross-sectional nature of our study is a further limitation, as it cannot definitively establish the causal directions of the observed relationships. Longitudinal designs tracking children's brain development and social cognitive abilities over time would help clarify whether early parenting impacts later neural maturation and behavioral outcomes, or vice versa."

> *I would appreciate more details about the 14 Theory of Mind (ToM) tasks, which could be included in supplemental materials. The authors score them on a scale from 0 to 14 (each task 1 point); however, the tasks likely vary in difficulty and should carry different weights in the total score (for example, the test and the control questions should have different weights). Many studies have utilized the seven tasks according to Wellman and Liu (2004), categorizing them into "basic ToM" and "advanced ToM." Different components of ToM could influence the findings of the current study, which should be further examined by a more in-depth analysis.*

We thank the reviewer for raising this important point regarding the structure and scoring of the Theory of Mind (ToM) tasks. We will provide a detailed description of all 14 tasks in the Supplemental Materials, including their content, targeted mental state concepts (e.g., beliefs, desires, intentions), and design features (e.g., test/control items, task format).

We fully agree that ToM tasks differ in complexity, and in principle, a weighted or component-based scoring approach (e.g., distinguishing basic and advanced ToM) could offer greater interpretive value. However, in our study design, tasks were administered in a fixed sequence from lower to higher difficulty, and testing was terminated if the child was unable to successfully complete three consecutive tasks. This approach is developmentally appropriate for younger children but results in non-random missingness for more advanced tasks—particularly among children at the lower end of the age range (3–4 years).

Given this adaptive task structure, re-scoring using weighted or subscale-based approaches would introduce systematic bias, as children who struggled with early items were not administered more complex ones. As a result, a full breakdown by task type (e.g., basic vs. advanced ToM) would only reflect a restricted subsample and would not be comparable across the full cohort. For this reason, we retained the unit-weighted total ToM score as the most developmentally valid and comparable metric across participants.

> ***Reviewer #3:***
>
> *Summary:*
>
> *The article explores the role of mother-child interactions in the development of children's social cognition, focusing on Theory of Mind (ToM) and Social Pain Matrix (SPM) networks. Using a naturalistic fMRI paradigm involving movie viewing, the study examines relationships among children's neural development, mother-child neural synchronization, and interaction quality. The authors identified a developmental pattern in these networks, showing that they become more functionally distinct with age. Additionally, they found stronger neural synchronization between child-mother pairs compared to child-stranger pairs, with this synchronization and neural maturation of the networks associated with the mother-child relationship and parenting quality.*
>
> *Strengths:*
>
> *This is a well-written paper, and using dyadic fMRI and naturalistic stimuli enhances its ecological validity, providing valuable insights into the dynamic interplay between brain development and social interactions. However, I have some concerns regarding the analysis and interpretation of the findings. I have outlined these concerns below in the order they appear in the manuscript, which I hope will be helpful for the revision.*

We appreciate the reviewer's thoughtful and constructive summary of the manuscript. The concerns raised regarding aspects of the analysis and interpretation have been carefully considered. Detailed point-by-point responses are provided below, along with descriptions of the corresponding revisions made to improve the clarity, precision, and interpretive caution of the manuscript.

> *Given the importance of social cognition in this study, please cite a foundational empirical or review paper on social cognition to support its definition. The current first citation is primarily related to ASD research, which may not fully capture the broader context of social cognition development.*

We thank the reviewer for this helpful suggestion. We agree that a broader, foundational reference is more appropriate for introducing the concept of social cognition. In response, we have revised the Introduction to include a widely cited theoretical or review paper on social cognition to provide a more general developmental context.

The corresponding changes have been made on pages 3 of the revised manuscript.

"Social cognition, defined as the ability to interpret and predict others' behavior based on their beliefs and intentions and to interact in complex social environments and relationships is a crucial aspect of human development [1-2]"

(1) Adolphs, R. The social brain: neural basis of social knowledge. Annual review of psychology 60, 693-716 (2009).

(2) Frith, C. D. & Frith, U. Mechanisms of social cognition. Annual review of psychology 63, 287-313 (2012).

> *It is standard practice to report the final sample size in the Abstract and Introduction, rather than the initial recruited sample, as high attrition rates are common in pediatric*

> *studies. For example, this study recruited 50 mother-child dyads, and only 34 remained after quality control. This information is crucial for interpreting the results and conclusions. I recommend reporting the final sample size in the abstract and introduction but specifying in the Methods that an additional 16 mother-child dyads were initially recruited or that 50 dyads were originally collected.*

We thank the reviewer for this helpful recommendation. In the original version of the manuscript, the Abstract and Introduction referenced the total number of dyads recruited (N = 50). In line with standard reporting practices and to ensure clarity regarding the analytic sample, we have now revised both the Abstract and Introduction to report the final sample size (N = 34). The full recruitment and exclusion details—including the number of dyads removed due to excessive motion or technical issues—are now clearly described in the Methods section.

The corresponding changes have been made on pages 1 and 4 of the revised manuscript.

> *In the "Neural maturity reflects the development of the social brain" section, the authors report the across-network correlation for adults, finding a negative correlation between ToM and SPM. However, the cross-network correlations for the three child groups are not reported. The statement that "the two networks were already functionally distinct in the youngest group of children we tested" is based solely on within-network positive correlations, which does not fully demonstrate functional distinctness. Including cross-network correlations for the child groups would strengthen this conclusion.*

We thank the reviewer for this insightful comment. We agree that within-network correlations alone do not fully establish functional distinctness, particularly in early development. To more directly test whether the ToM and SPM networks were already differentiated in children, we have now included the cross-network correlations between the two networks for each of the three age groups in the revised manuscript. These findings support and strengthen our original claim that the ToM and SPM networks are functionally dissociable even in early childhood, and we have revised the relevant Results sections accordingly to reflect this.

The corresponding changes have been made on page 7 of the revised manuscript.

"In children, each network also exhibited positive correlations within-network and negative correlations across networks (within-ToM correlation M(s.e.) = 0.31(0.04); within-SPM correlation M(s.e.) = 0.29(0.04); across-network M(s.e.) = −0.09 (0.02).

In the Pre-junior group only (3-4 years old children, n = 12), both ToM and SPM networks had positive within-network correlations (within-ToM correlation M (s.e.) = 0.29(0.06); within-SPM correlation M(s.e.) = 0.23(0.05), across-network M(s.e.) = −0.05(0.02))."

> *The ROIs for the ToM and SPM networks are defined based on previous literature, applying the same ROIs across all age groups. While I understand this is a common approach, it's important to note that this assumption may not fully hold, as network architecture can evolve with age. The functional ROIs or components of a network might shift, with regions potentially joining or exiting a network or changing in size as children develop. For instance, Mark H. Johnson's interactive specialization theory suggests that network composition may adapt over developmental stages. Although the authors follow the approach of Richardson et al. (2018), it would be beneficial to discuss this limitation in the Discussion. An alternative approach would be to apply data-driven analysis to justify the selection of the ROIs for the two networks.*

We thank the reviewer for this thoughtful and theoretically grounded comment. In our study, we followed the approach of Richardson et al. (2018), using a priori ROIs defined from adult meta-analyses and ToM/SPM task studies. This approach facilitates comparison with prior work and provides anatomical consistency across participants. However, we fully agree that applying adult-defined ROIs to pediatric populations involves important assumptions about the stability of network architecture across development, which may not fully hold in early childhood.

We have now addressed this limitation more explicitly in the revised Discussion, emphasizing that the fixed-ROI approach may not capture the dynamic reorganization of social brain networks during development.

The corresponding changes have been made on pages 13 of the revised manuscript.

“Moreover, the ROIs used to define the ToM and SPM networks were based on meta-analyses and task studies primarily conducted with adults. While this approach promotes comparability with existing literature, it assumes that the spatial organization of these networks is stable across age groups. However, theories of interactive specialization suggest that the composition and boundaries of functional networks may undergo reorganization during development, with regions potentially entering or exiting networks based on experience and maturational processes. As a result, the current analysis may not fully capture age-specific functional architecture, particularly in younger children. Future studies using data-driven or age-appropriate parcellation methods could provide more precise characterizations of how social brain networks are constructed and differentiated throughout childhood.”

> *The current sample size (N = 34 dyads) is a limitation, particularly given the use of SEM, which generally requires larger samples for stable results. Although the model fit appears adequate, this does not guarantee reliability with the current sample size. I suggest discussing this limitation in more detail in the Discussion.*

We thank the reviewer for highlighting the limitations of applying structural equation modeling (SEM) with a relatively modest sample size. We agree that SEM generally benefits from larger samples to ensure model stability and parameter reliability, and that satisfactory model fit does not guarantee robustness in small-sample contexts.

In the revised Discussion, we now more clearly acknowledge that the use of SEM in the current study is exploratory in nature, and that all results should be interpreted with caution due to potential sample size-related constraints. The model was constructed to provide an integrated view of the observed associations rather than to establish definitive pathways. We have also added a note that future research with larger samples and longitudinal designs will be needed to validate and extend the proposed model.

The corresponding changes have been made on pages 13 of the revised manuscript.

“In addition, the modest sample size (N = 34 dyads) presents limitations for the application of structural equation modeling (SEM), which typically requires larger samples for stable estimation and generalizable inferences. While the model fit was acceptable, the results should be interpreted as exploratory and hypothesis-generating, rather than confirmatory. Future studies with larger, independent samples will be important for validating the structure and directionality of the proposed relationships”

> *Based on the above comment, I believe that conclusions regarding the relationship between social network development, parenting, and support for Bandura's theory*

> *should be tempered. The current conclusions may be too strong given the study's limitations.*

We thank the reviewer for this important and balanced observation. We agree that the conclusions drawn from the current study should reflect the exploratory nature of the analyses, as well as the methodological limitations, including the modest sample size and cross-sectional design.

In response, we have revised the Conclusion sections to use more cautious, associative language when describing the observed relationships among social brain development, parenting factors, and Theory of Mind outcomes. In particular, we have tempered statements regarding support for Bandura's social learning theory, clarifying that while our findings are consistent with social learning frameworks, the data do not allow for direct tests of modeling or observational learning mechanisms.

We hope these revisions help clarify the scope of the findings and improve the conceptual rigor of the manuscript.

The corresponding changes have been made on pages 14 of the revised manuscript.

"Our study provides novel evidence that children's social cognitive development may be shaped by the intricate interplay between environmental influences, such as parenting, and biological factors, such as neural maturation. Our findings contribute to a growing understanding of the factors associated with social cognitive development and suggest the potential importance of parenting in this process. Specifically, the study points to the possible role of the parent-child relationship in supporting the development of social brain circuitry and highlights the relevance of family-based approaches for addressing social difficulties. The observed neural synchronization between parent and child, which was associated with relationship quality, underscores the potential significance of positive parental engagement in fostering social cognitive skills. Future longitudinal and clinical research can build on this multimodal approach to further clarify the neurobehavioral mechanisms underlying social cognitive development. Such research may help inform more effective strategies for promoting healthy social functioning and mitigating social deficits through targeted family-based interventions."

> *The SPM (pain) network is associated with empathic abilities, also an important aspect of social skills. It would be relevant to explore whether (or explain why) SPM development and child-mother synchronization are (or are not) related to parenting and the parent-child relationship.*

We thank the reviewer for this thoughtful and important comment regarding the role of the Social Pain Matrix (SPM) network in social cognition and empathy. We agree that this network represents a critical component of social-cognitive development and is theoretically linked to affective processing and interpersonal understanding.

We would like to clarify that in our existing analyses—already included in the original submission and detailed in the Supplemental Results—SPM network measures showed similar significant associations with behavioral outcomes than the ToM network. These outcomes included children's performance on ToM tasks as well as broader measures of social functioning. We have added more discussion in the supplementary results.

"To further investigate the specificity of our findings, we conducted additional control analyses focusing on the individual components of the social brain networks examined in our study: the Theory of Mind (ToM) and Social Pain Matrix (SPM) networks.

When analyzing these networks separately, we found significant correlations between neural maturity and age, as well as between inter-subject synchronization (ISS) and parent-child relationship quality for both the ToM and SPM networks individually (Fig. S1). Specifically, neural maturity within each network was positively correlated with age, indicating that both networks undergo maturation during childhood. Similarly, ISS within each network was negatively correlated with parent-child conflict scores, suggesting that both networks contribute to the observed relationship between neural synchrony and parent-child relationship quality.

These results highlight the importance of considering the social brain as an integrated system, where the ToM and SPM networks work in concert to support social cognitive development. While each network shows age-related maturation and sensitivity to parent-child relationship quality, their combined functioning appears to be crucial for predicting broader social cognitive outcomes.

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