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

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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 50 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 Bandura's theory of social learning 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.

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]. Children's social cognitive abilities have far-reaching implications for their social competence, peer acceptance, and success in school [2,3]. A key component of social cognition is the ability to understand and reason about others' mental states, known as “Theory of Mind” (ToM) [4]. ToM enables children to predict and interpret others' actions based on an understanding of their unobservable mental states, such as beliefs, desires, and emotions [5]. The development of ToM follows a predictable sequence throughout childhood, with major milestones occurring between the ages of 3 and 5 years [5]. 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 [6]. This understanding is typically assessed using false belief tasks, which require children to reason about what another person might mistakenly think or believe [7]. Success on these tasks indicates a more adult-like understanding of the mind and is considered a hallmark of ToM development [8].

Advances in neuroimaging techniques have allowed researchers to investigate the neural basis of social cognition and its development [9]. 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 [10]. 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 [11]. 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 [12], and emotions [13], and the internal states of others’ bodies, including pain [14]. 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 [15-17]. 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 [16]. 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 [18,19]. Theories of bio-behavioral synchrony [20] and social learning [21] 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 [20]. This synchronization is thought to facilitate emotional sharing and social understanding and has been linked to positive developmental outcomes [22,23]. 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 [24]. 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 [25,26]. 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[27,28]. 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 [29-31]. 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[32,33]. Previous studies have successfully used movie-viewing paradigms to investigate ToM and social pain processing in children [16,17], 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 [34], and that atypical child-parent neural synchrony in medial prefrontal-hippocampus circuitry is associated with psychopathology in children [35]. 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. Our first goal was to 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 collected fMRI data from 50 child-mother dyads while they viewed an animated movie that depicted characters' mental states and physical sensations. 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. Significantly associations between ToM behavior and age ($r = 0.434$, $p = 0.010$), conflict on Child–Parent Relationship Scale (CPRS) ($r = -0.377$, $p = 0.028$), rejection on the EMBU ($r = 0.388$, $p = 0.023$) (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 = 0.01) and total scores on social responsiveness scale (SRS) (r = -0.598, $p < 0.001$) 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 [36]. 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)** [16].

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). 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) and within-SPM network (r = 0.32, *p* = 0.05) 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)).

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, false discovery rate [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**).

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 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, ISC 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 [37]. 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 (β = -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 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. 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. By demonstrating the relevance of Bandura's theory to the neurobehavioral mechanisms underlying social cognition development, 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.

This result aligns with previous research suggesting that these networks become increasingly specialized and differentiated throughout childhood [16,38,39]. 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 [40]. 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

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 [41], thereby promoting social understanding. Our results corroborate previous behavioral studies linking mother-child synchrony to positive developmental outcomes [26,42]. They also extend prior neuroimaging work on interpersonal neural synchronization in relationships [43] 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 [20,44], 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 [45,46]. 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 [47,48]. 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 Bandura’s social learning theory

Bandura's theory posits that human behavior is shaped by observational learning and modeling from others in one's environment [24,49,50]. 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.

This reciprocal interaction aligns with Bandura's notion of reciprocal determinism. The theory proposes that observational learning is most effective when there is a close relationship and nurturing interactions between the model and learner. The findings that parent-child neural synchrony was specifically linked to relationship quality, rather than children's age, supports this view. Positive parent-child bonds likely facilitate attentional processes and motivation for social learning. 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. Our findings corroborate and extend Bandura's theoretical principles to neural circuit dynamics within the context of parent-child relationships.

Conclusions

Our study provides novel evidence that children's social cognition development is shaped by the intricate interplay between environmental influences, such as parenting, and biological factors, such as neural maturation. Our findings enhance the understanding of the factors contributing to social cognitive development and underscore the critical role of parenting in this process. Specifically, the study highlights the importance of the parent-child relationship in developing social brain circuitry and suggests potential family-based interventions for addressing social deficits. The observed neural synchronization between parent and child, correlated with relationship quality, underscores the significance of positive parental engagement in fostering social cognitive skills. Future longitudinal and clinical research can build on this multimodal approach to further elucidate the neurobehavioral mechanisms underlying social cognitive development. Such research may lead to more effective strategies for promoting healthy social development and mitigating social deficits through targeted family-based interventions.

Methods

Participants

A total of 50 child-parent 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). 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 [51].
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) [52].
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) [53].

Neurodevelopmental Assessment

The Peabody Picture Vocabulary Test, Fourth Edition (PPVT-4), was used to assess the receptive vocabulary abilities of the children [54], providing an estimate of verbal intelligence [55]. 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 [56,57]. As described in previous literatures [16,58], 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 [59] (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 [15,16,60]. 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 × 3.75 × 3.2 mm. The imaging matrix was 64 × 64, with a flip angle of 90°, and a field of view (FOV) of 240 × 240 mm^2. 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 [33,61], 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 [62,63]. 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 [64]. 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 [65]. Additionally, data scrubbing was performed to address potential motion artifacts [66]. 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

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)[16]. 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. Reverse correlation analyses were conducted on all adults to identify significant events [16]. 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).

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.

ISC in fMRI Time Series

ISC 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, ISC 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 ISC 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 ISC and relationship quality.

A 2×2 ANOVA was used with ISC 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 ISC 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 [67]. 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 [68], fit indices above 0.90 [69], and RMSEA values ≤ 0.10.

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.

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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).

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).

Conflict of interest statement

The authors declare no competing interest.

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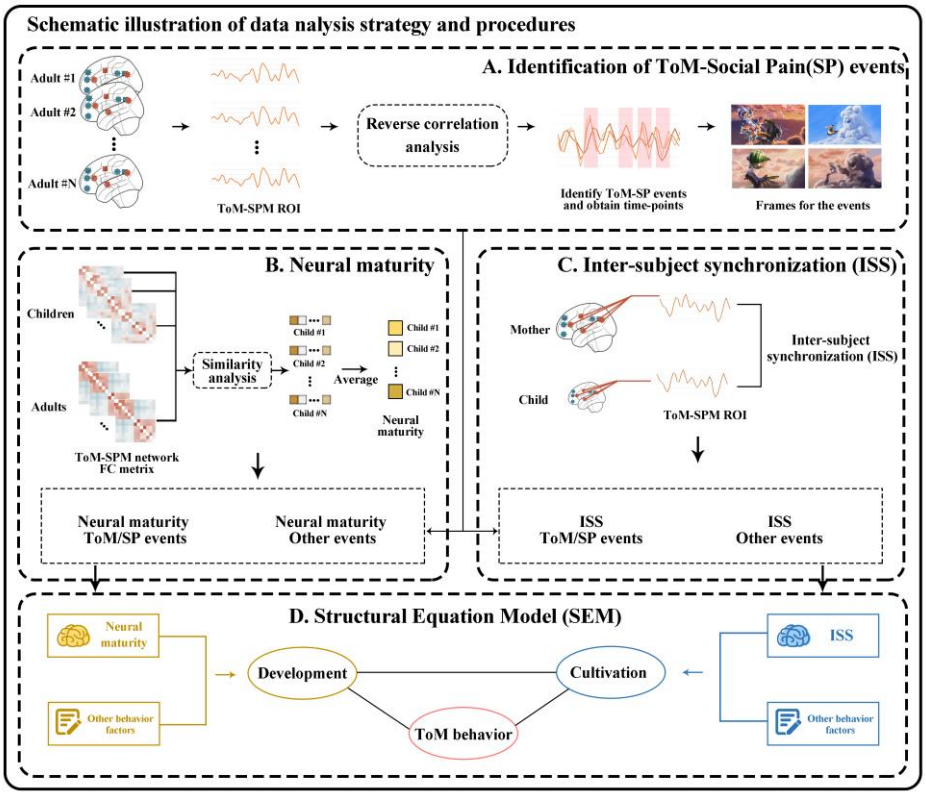

Fig 1. Overview of analysis pipeline. (A) Reverse correlation analysis was conducted on the average response network time-courses to identify ToM and Social Pain events driving activity in Theory of Mind (ToM) and Social Pain Matrix (SPM) related brain regions. **(B)** First, inter-region correlations 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.

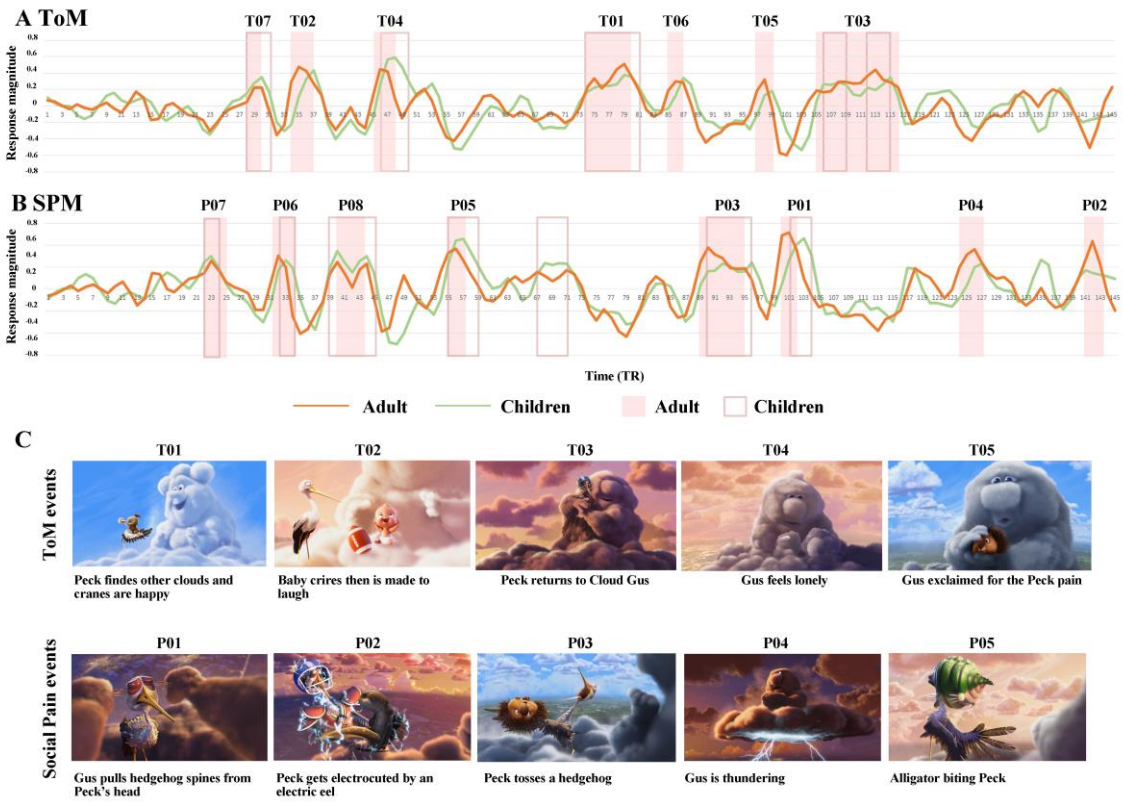

Fig 2. Reverse Correlation Analysis. The average time courses of child (green) and adult (red) groups for the **(A)** Theory of Mind (ToM) and **(B)** Social Pain Matrix (SPM) networks during movie viewing are presented. Each time point along the x-axis corresponds to a single TR (2 seconds). Shaded 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.

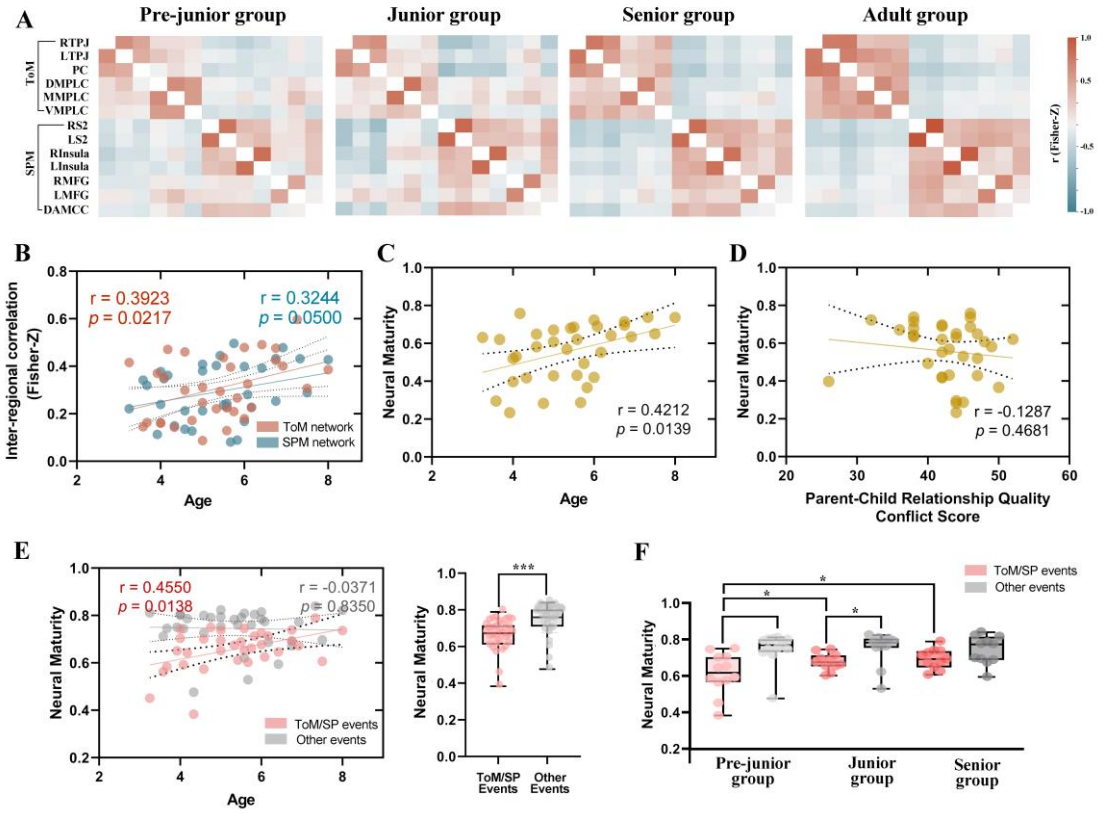

Fig 3. Inter-region correlation analysis and neural maturity. (A) Average z-scored correlation matrices were computed across all Theory of Mind (ToM) and Social Pain Matrix (SPM) regions of interest for each age group (Pre-junior: n = 12; Junior: n = 11; Senior: n = 11; Adults: n = 34). The nomenclature 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. * $p < 0.05$.

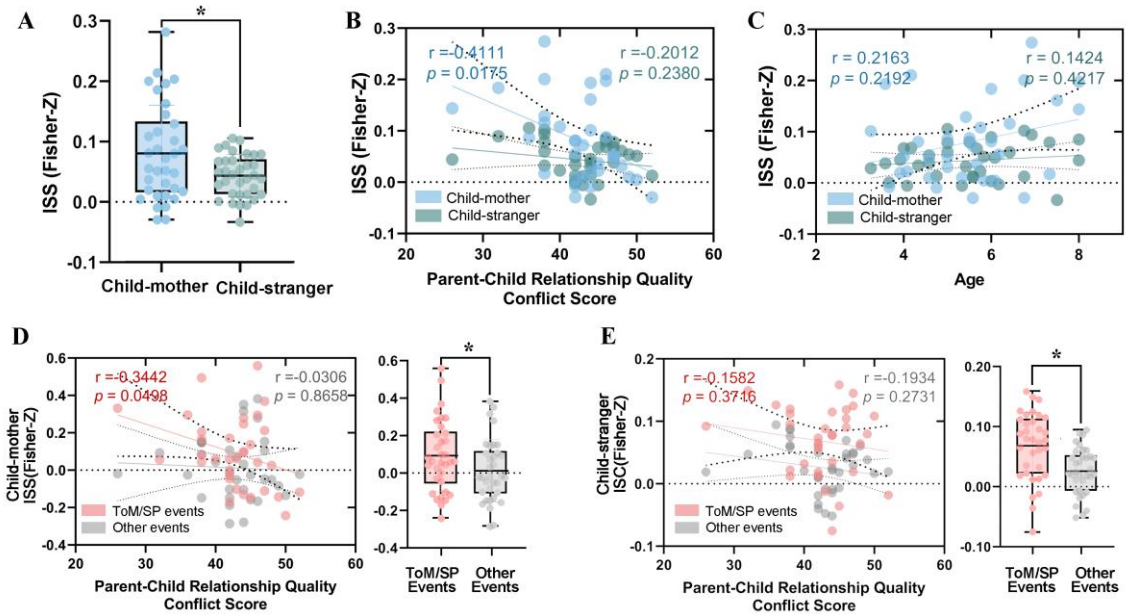

Fig 4. Inter-subject neural synchronization. (A) Group differences in inter-subject synchronization (ISS) during movie viewing. **(B)** Partial correlation between conflict scores of CPRS and ISS within child-mother and child-stranger dyads. **(C)** Correlation between age and ISS within child-mother 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 ISC during ToM/SP and other events are displayed on the right. * $p < 0.05$.

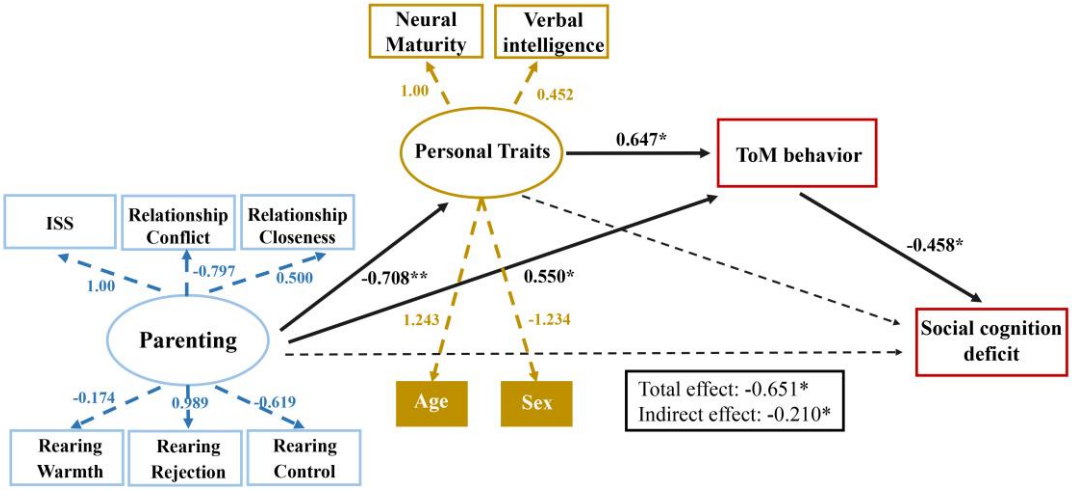

Fig 5. Structural equation model of latent personal traits, latent parental caregiving, ToM behavior and social development outcomes. Parenting has a direct and indirect influence on ToM behavior which in turn influences social cognition. Latent factor underlying Personal Trait includes a child's neural 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.

Table 1. Relationship between individual behavioral characteristics and ToM behavior.

	Coefficient β	SE	*P*_Regress	*R*_Pearson	*P*_Pearson
PPVT	0.203	0.030	0.206	**0.434**	**0.010**
SRS_Total	-0.295	0.040	0.074	**-0.598**	**<0.001**
CPRS_Conflict	-0.191	0.103	0.189	**-0.377**	**0.028**
CPRS_Closeness	0.164	0.061	0.264	0.265	0.130
EMBU_rejection	0.296	0.151	0.075	**0.388**	**0.023**
EMBU_Emotional warmth	0.258	0.100	0.184	0.056	0.753
EMBU_Control attempts	0.170	0.104	0.210	0.148	0.405
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. Bold font indicates the significance level at $p < 0.05$.

Table 2. Demographic information and behavioral data by age group.

Group	N	Age (Range)	Gender (Female/Male)	Handedness (Right/Left/Mix)	TOM behavior score	PPVT-4 (Standard score)	Parents-children relationship (CPRS)		Parents' rearing behavior (EMBU)			Total score (SRS)
							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±5.8	22.5±9.0	16.4±4.46	59.4±7.0	43.1±5.0	36.7±15.0
Junior	11	5.5±0.3 (5.0~5.8)	5/6	10/0/1	10.6±2.3	152.3±10.8	44.4±5.0	26.5±8.0	18.8±3.0	56.2±8.8	41.0±4.8	32.0±13.7
Senior	11	6.7±0.7 (6.0~8.0)	6/5	10/0/1	11.8±1.9	151.5±19.0	40.2±3.8	27.5±9.33	19.2±3.4	56.5±5.1	42.0±4.6	23.0±13.8
Adult (Mother)	34	36.7±4.0 (30.7~48.8)	34/0	33/0/1	NA	NA	NA	NA	NA	NA	NA	NA

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.

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]

Supplementary Materials

I. 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.

II. Supplementary Figures

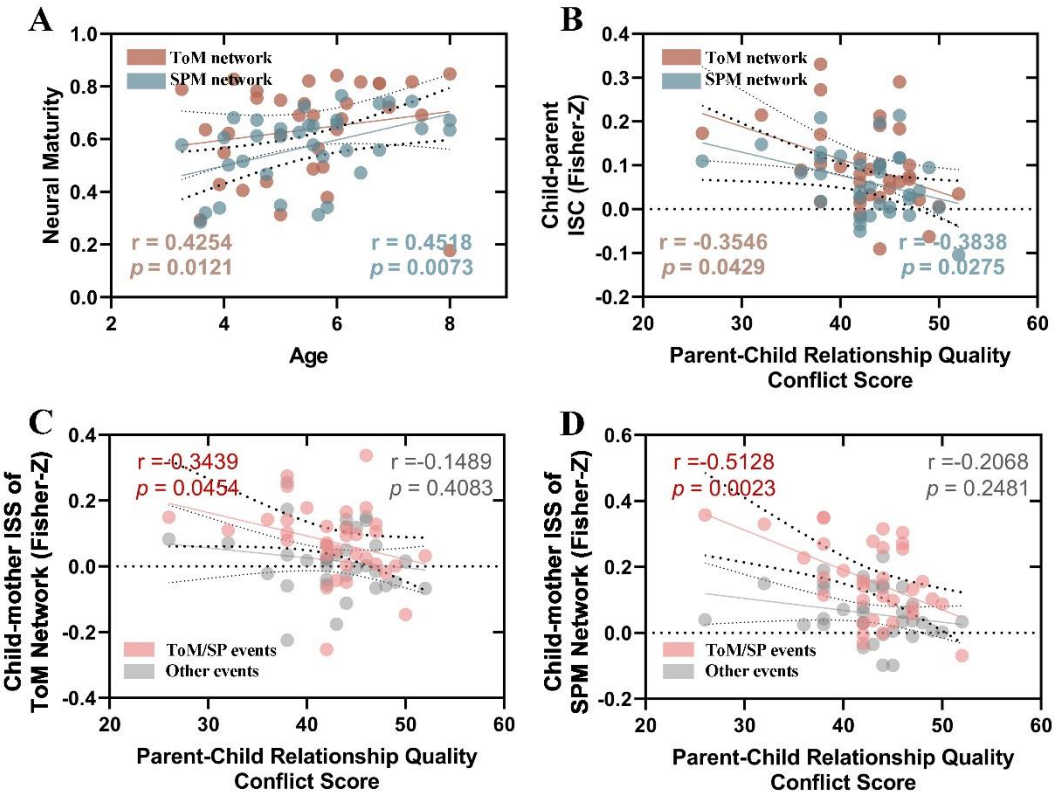

Fig S1. Relationship between personal traits, neural measures and parent-child relationship quality for Theory of Mind (ToM) and Social Pain Matrix (SPM) networks analyzed separately. (A) Correlation between neural maturity within ToM and SPM networks and age. **(B)** Correlation between parent-child 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.

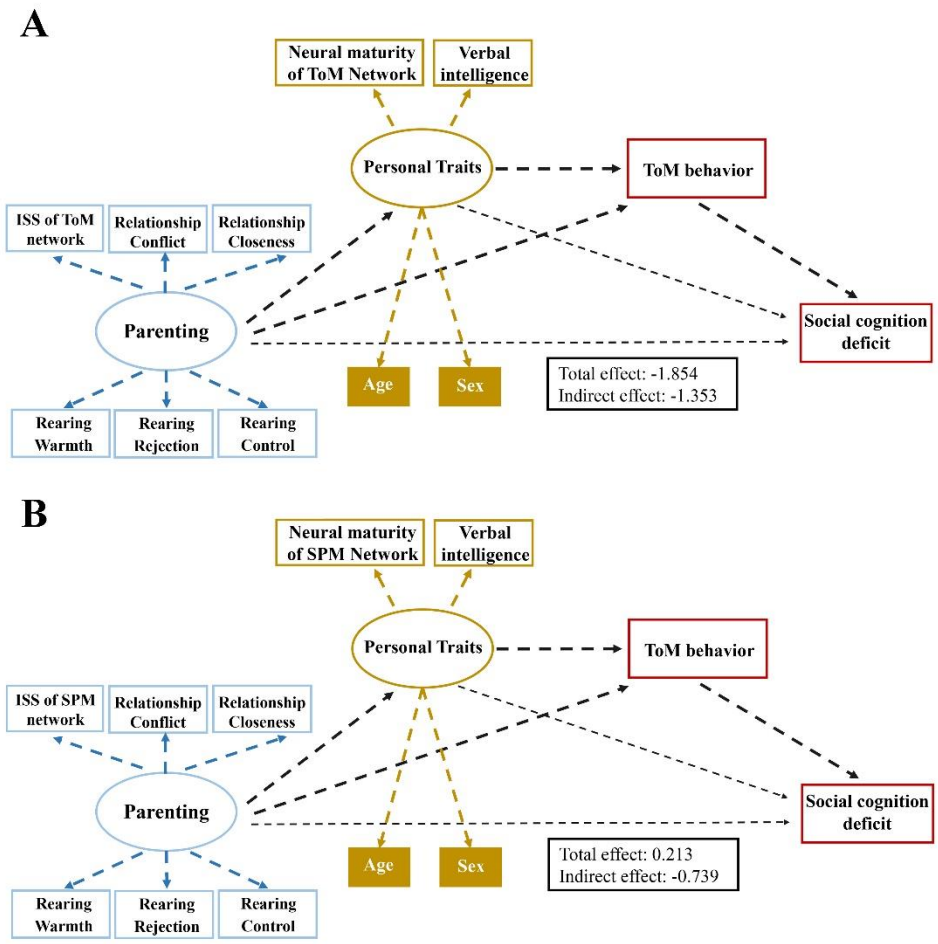

Fig S2. Structural equation modeling using (A) Theory of Mind (ToM) and (B) Social Pain Matrix (SPM) networks separately. Solid lines indicate significant paths, and dashed arrows indicate nonsignificant paths. No significant direct effects on social cognition outcomes were observed when analyzing the networks individually, highlighting the importance of considering both networks together for predicting social cognitive outcomes.

III. Supplementary Tables

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.

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 S2. Structural equation modeling (SEM) details.

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
ISC	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