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Hyperscanning Studies on Interbrain Synchrony and Child Development: A Narrative Review

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Abstract—Social interactions between parents and children are closely linked with children's development, and interbrain synchrony has been shown to be a neural marker of social interaction. However, to truly capture the essence of social interactions through interbrain synchrony, it is necessary to simultaneously discuss the parental and child brains and adequately record neurological signals during parent–child interactions in interactive tasks. In the current review, we have reviewed three main contents. First, we discuss the correlation between parent–child interbrain synchrony and the development of cognitive (e.g., emotion regulation, attention, and learning) and behavioral abilities (e.g., cooperation, problem-solving) in children. Second, we examine the different neural mechanisms of interbrain synchrony in mother–child and father-child interactions, aiming to highlight the separate roles of mother and father in child development. Last, we have integrated four methods to enhance interbrain synchrony, including communication patterns, nonverbal behavior, music, and multichannel stimulation. A significant correlation exists between parent–child interbrain synchrony and the development of children's cognitive and behavioral abilities. This summary may be useful for expanding researchers' and practitioners' understanding of the ways in which parenting and the parent–child relationship shape children' cognitive and behavioral abilities.**© 2023 IBRO. Published by Elsevier Ltd. All rights reserved.**

Key words: interbrain synchrony, mother, father, child development, hyperscanning.

STUDYING NATURALISTIC DYADIC INTERACTIONS

Social interactions with others are essential for virtually all aspects of human development (Hamilton, 2021). These interactions are fast-paced and multi-layered, requiring the brain to process complex information from multiple visual and auditory sources in a timely manner (Wass et al., 2019). From early life, social interactions between parents and children play an important role in children's structural and functional brain development (Nguyen, Banki, et al., 2020; Ratliff et al., 2022), mental health (Su et al., 2022), affective states, self-regulation (Bell, 2020), emotion regulation abilities (Turk et al., 2022), attention and learning (Kuhl et al., 2003; Begus et al., 2014), internalizing and externalizing problems (Eisenberg et al., 2010; Abulizi et al., 2017) and so on.

Decades of research exploring the relationship between child development and parenting have already revealed that positive socio-emotional outcomes are predicted by supportive parental interactions with children (Knauer et al., 2019; Turk et al., 2022), whereas negative family interactions are detrimental to children's psychological wellbeing, causing and maintaining various psychopathological symptoms and altering emotional brain development (Diaz et al., 2019; Su et al., 2022). The psychosocial and bio-behavioral synchrony models suggest there is a significant correlation between child-parent social interactions and children's development (Ratliff et al., 2022). The bio-behavioral synchrony model integrates both biological and behavioral aspects of parent–child interactions. It posits that the alignment or synchrony in biological and behavioral responses between parents and children can foster effective communication, emotional co-regulation, and social bonding. This synchrony can be manifested in various forms, such as synchronized heart rates, hormonal levels, and brain activities, as well as coordinated behaviors and emotional expressions.Table 1.

It is crucial to understand how very young children begin to make sense of their parents in order to interact with them effectively. In their relationships with others, children are embodied agents rather than passive observers, actively participating in dynamic exchanges

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Key words: EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy; dlPFC, the bilateral dorsolateral prefrontal cortex; TPJ, temporo-parietal junction; NAcc, the Nucleus Accumbens; PFC, the prefrontal cortex; ERP, Event-Related Potentials.

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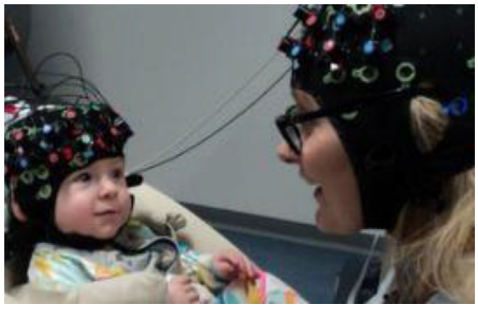
Table 1. Increasing interbrain synchrony to promote parent–child behavior.

Conversational patterns The conversational synchrony indicated that conversation patterns, such as turn-taking, may support cross-brain associations and emphasize the significance of understanding dynamic emotion-related processes and their relationship to psychological well-being during parent–child social interactions.	
Nonverbal behavior Affectionate touch: an essential pathway to establishing Speaker eye contact and gaze: enhances information coupling Gestural imitation: nonverbal interpersonal contact is established Joint attention: promoted mutual entrainment	
Music Music has been an integral facilitator of social bonds among variety of different species, including humans. Musical intervention children can enhance brain-to-brain coupling with their parents.	
Multimodal stimulation Adults often use multiple modalities to interact with children, and these multimodal forms of stimulation (such as joint attention, play, speech, and daily routines) are more likely to improve the interbrain synchrony present in the interaction than a single mode of stimulation.	

(De Jaegher et al., 2016). And naturalistic interaction offer promising avenues for investigating brain function across the rich, realistic spectrum of parent–child interactions experiences, which are integral to the naturalistic paradigm (Finn et al., 2020; Ogilvie et al., 2020; Simony and Chang, 2020). Optimal parental interactions can be defined as synchronous relationships in which the parent is aware of the child's current condition and social signals and responds appropriately (Feldman, 2007). The theoretical synchrony model postulates that healthy interactions between parents and children play a crucial role in regulating the child's developing social skills and their neurobiological states (Carollo et al., 2021). This model offers a comprehensive perspective on the complex interplay between social, emotional, and biological dimensions of development. Healthy interactions between parents and children, according to this model, are characterized by a synchronous, reciprocal, and responsive relationship. This synchrony, often referred to as 'attunement', involves the alignment of emotional states, behaviors, and physiological responses between the parent and child. Such interactions provide a rich social environment that nurtures the child's developing social skills, such as empathy, cooperative behavior, and conflict resolution skills.

INTERBRAIN SYNCHRONY WITH PARENT–CHILD

However, to truly capture the essence of social interactions through interbrain synchrony, it is necessary to simultaneously discuss the parental and child brains and adequately record neurological signals during

parent–child interactions in interactive tasks. Interbrain synchrony has been shown to be a neural marker of social interaction. It is more commonly used to describe methods in which activity in specific brain regions (the same area in both individuals' brains) is correlated over time to identify regions that activate in sync in parent–child relationships (Ratliff et al., 2021; Roque et al., 2022). Research indicates that, compared to performing identical tasks separately or interacting with a third party, parents and children synchronize their brain processes more in interactive contexts that involve mutual participation when they are together (Nguyen, Schleihauf, et al., 2020; Ratliff et al., 2022). In addition, the research conducted by Carollo et al., (2021) investigated the neural correlates of parent–child interbrain synchrony, employing a neuroscience lens to illuminate the psychological dynamics of these interactions. Nevertheless, further researches are required to understand the several fine ways in which synchrony at all level of analysis emerges and is dynamically modulated.

So far, hyperscanning studies have demonstrated that interbrain synchronizations is associated with successful communication (Nguyen, Banki, et al., 2020), enhanced cooperation (Ratliff, 2019), improved emotion regulation (Atzaba-Poria et al., 2017), and increased mutual understanding between parents and children, rather than merely being a physiological response to physical speech signals. Extending beyond these aspects, interbrain synchrony could play a role in the long-term development of attachment (Atzaba-Poria et al., 2017; Feldman, 2017; Wong et al., 2018; Markova et al., 2019; Djalovski et al., 2021). Hyperscanning, capturing neural activity from multiple individuals simultaneously, employs 'naturalistic' designs to glean insights from real-life interactions (Cui et al., 2012; Samadani et al., 2021). As such, it is essential to simultaneously record the neural signals of all participants in the interaction task using hyperscanning, as this approach can truly capture the essence of parent–child social interactions through inter-brain synchronization. We believe that this may promote interpersonal coordination during parent–child interactions.

PARENT-CHILD INTERACTION AND CHILD DEVELOPMENT

Interbrain synchrony may embody an underlying neural mechanism that facilitates the emotional connection between parent and child, which in turn is associated with the child's developing cognitive abilities (e.g., emotion regulation, attention, and learning) and behavioral competencies (e.g., cooperation, problem-solving). Longitudinal research has demonstrated that the degree of parent–child synchrony is predictive of child development (Feldman and Greenbaum, 1997).

Emotional regulation ability. Studies have shown that greater child emotion regulation abilities are associated with higher levels of interbrain synchrony (Reindl et al., 2018). This relationship between synchrony and child emotion regulation may be mediated by attachment security (Feldman, 2007). Reindl et al. (2018) found that both parental and child habitual emotion regulation were positively related to interbrain synchrony when parent–child cooperation was compared to stranger-child cooperation. Similarly, Lee et al. (2017) discovered that greater interbrain synchrony between parent and child led to improved emotional regulation in the child. Previous parent–child electroencephalography (EEG) studies have shown that a mother's positive emotional expression is associated with greater frontal alpha asymmetry (Atzaba-Poria et al., 2017; Perone et al., 2020) and stronger brain-to-brain alpha connectivity between mother and child (Santamaria et al., 2020). Conversely, decreased dual-functional near-infrared spectroscopy (fNIRS) based interbrain synchrony between a mother and child has been linked to the child displaying increased irritability after experiencing frustration (Camacho et al., 2020).

Attention and learning. Attention and learning in infants are closely related to parent-infant interbrain synchrony (Wass et al., 2018; Zhao et al., 2021). Research has shown that a stronger connection between a child's attention and their parents' brain activity increases the likelihood that the child will be more attentive. Wass et al. (2018) observed that 12-month-old infants paid more attention to toys when playing with their mothers compared to when playing alone. Moreover, when the mother's EEG was monitored during the interaction, it was found that her neural response was heightened when the child sustained attention for longer periods. This suggests that parent-infant interbrain synchrony plays a crucial role in enhancing attention and learning in infants.

Interbrain synchrony serves as a mechanism for learning from social partners in children (Bevilacqua et al., 2019; Leong et al., 2019). In child-teacher interactions, interbrain synchrony is associated with learning success. Furthermore, interbrain synchrony during joint play between mother and child has been linked to enhanced learning in the child, starting from infancy. Leong et al. (2019) demonstrated that 10-month-old infants are more likely to learn during social interactions with their mothers when interbrain synchrony is present at central and parietal scalp locations. This evidence highlights the importance of interbrain synchrony between children and their social partners in promoting learning and development.

Cooperation. Synchrony during cooperation has been positively associated with dyadic task performance, as higher levels of interpersonal synchrony are linked to better cooperative performance (Cui et al., 2012; Cheng et al., 2015; Baker et al., 2016). Interbrain synchrony increases during cooperation compared to baseline, and is higher for mother–child dyads than stranger-child dyads (Reindl et al., 2022). Similarly, mother–child cooperation during a cooperative task may enhance overall interbrain synchrony when compared to a non-cooperative task (Miller et al., 2019). In a study of father-child dyads, Nguyen et al. (2021) found increased interbrain synchrony between the bilateral dorsolateral prefrontal cortex (dlPFC) and the left temporo-parietal junction (TPJ) when dyads completed a cooperative task as opposed to an individual task. Ultimately, interbrain synchrony has been shown to predict parent–child coop-

erative performance, which can assist future studies in examining different levels of cooperative behavior.

Problem-solving. Increased interbrain synchrony has been shown to predict a dyad's ability to solve presented problems, with higher interbrain synchronization being associated with successful joint problem-solving (Nguyen, Banki, et al., 2020; Zhao et al., 2023). The father-child and mother–child studies found increased interbrain synchrony in prefrontal and temporo-parietal regions during problem-solving compared to individual (Nguyen, Banki, et al., 2020; Nguyen et al., 2021). In other words, the more synchronized the brain activity between parents and children, the more tangram templates they solved in a tangram puzzle task.

So far, increased interbrain synchrony has been linked to children's positive emotions, enhanced attention and learning abilities, better cooperative performance, and problem-solving skills. This suggests that interbrain synchrony could be a sensitive marker for successful mutual attunement between parents and their children.

DIFFERENCES IN SYNCHRONY BY FATHER AND MOTHER ROLE

The traditional view that mothers are typically the first to seek safety and comfort and act as the primary caregivers in daily life is supported by contemporary data (Umemura et al., 2013). However, traditional parenting roles are changing. The latest U.S. Census data shows that 7% of fathers do not work outside the home, with 24% of these fathers reporting that they care for their children (Livingston, 2018). Research has indicated that fathers and mothers play distinct roles in parent–child interactions. Fathers generally spend less time interacting with their children and tend to engage in more physically active and outdoor activities. In contrast, mothers usually spend more time interacting with their children, participating in caregiving and domestic interactions (Oliveri et al., 2018). As a result, fathers and mothers may play different roles in their interactions with their children, reflecting the ongoing changes in parenting interaction.

Meanwhile, the attachment specific hypothesis suggests that children have unique experiences of interaction with different caregivers, and the multiple attachments formed have neither primary nor secondary effects on children's social and psychological development (Bretherton, 2010). In other words, the effects of mother and father attachment on children's development are not superimposed or combined, but have independent effects (Cabrera et al., 2014; Oliveri et al., 2018).

Interbrain synchrony may also differ between father-child and mother–child interactions (Davis et al., 2018; Bell, 2020). Thus, examining the differences between father-child and mother–child interactions may provide new insights into the distinctions between father-mother relationships. Additionally, understanding the variations in brain activity patterns between mother–child and father-child dyads could reveal their unique contributions to child development.

Brain structure and activation pathways. When parents are exposed to infant cues, such as crying, specific brain regions become more active, and this activity is associated with maternal psychopathology and parenting behaviors(Feldman, 2015). Research has shown that depressed mothers exhibit lower activation in reward network regions in response to their infants (Goodman et al., 2021). Furthermore, mothers who engage in more sensitive parenting behaviors demonstrate increased activation in reward network regions when responding to their children (Goodman et al., 2021). Lambert et al. (2011) found that active paternal care increased the integration of brain networks in fathers involved in nurturance, learning, and motivation. Previous research comparing brain activation responses of mothers and fathers revealed that mothers had greater amygdala activation (Atzil et al., 2012; Carter, 2014), while fathers had greater cortical activation (Abraham et al., 2014), supporting the distinct pathway hypothesis. In terms of functional connectivity, mothers who exhibited more interactive synchrony with their children displayed greater connectivity between the Nucleus Accumbens (NAcc, reward circuit) and mentalizing, mirror, and empathy networks, suggesting that reward motivation underlies the conscious aspects of parenting (Atzil et al., 2012). Additionally, a longitudinal study of mothers' and fathers' brains from the first to the fourth postnatal month found that mothers' gray-matter volume increased (amygdala, hypothalamus, thalamus, and substantia nigra) (Kim et al., 2010). However, the increase in gray matter volume (amygdala, striatum, hypothalamus, subgenual cortex, lateral prefrontal cortex, and superior temporal gyrus) in fathers was different. This difference may contribute to the variations in interbrain synchrony between father-child and mother–child interactions (Kim et al., 2014).

Gender effects. Some research has reported gender effects in parent–child interaction situations, suggesting that father-child and mother–child dyads might display different interbrain synchrony patterns (Cheng et al., 2015; Azhari et al., 2021). For instance, positive father role perceptions have been associated with increased unique interbrain synchronization during cooperative tasks and co-viewing video in the prefrontal cortex (PFC) (Azhari et al., 2021; Nguyen et al., 2021). More specifically, fathers' involvement in child care has been linked to their sensitivity in caregiving and subsequent positive outcomes in child development (Flouri et al., 2016; Cowan et al., 2019). In adolescent interactions with mothers, Lee et al. (2015) discovered increased activation in regions associated with emotional and social pain (the lentiform nucleus and the posterior insula) and decreased activation in regions associated with emotional regulation and cognitive control (Dorsolateral Prefrontal Cortex and Anterior Cingulate Cortex). Endevelt-Shapira and Feldman (2023) research underscores the role of the mother's frontal brain regions and the infant's temporal regions in achieving interbrain synchrony during direct communication. Their findings suggest that maternal sensitivity enhances this synchrony, while maternal intrusiveness may reduce it. Moreover, the extended Parent–Child

Emotion Regulation Dynamics Model proposes that there are gender differences between children and parents, including distinctions in father-daughter, mother-daughter, father-son, and mother-son relationships, which may influence cross-brain associations during parent–child interactions (Ratliff et al., 2022).

Age differences. To investigate differences interbrain synchronization between father-child and mother–child interactions, we must consider age differences in the findings on interpersonal synchrony and its role as a mechanism for dynamic mutual adjustments of brain activity. In the first year of life, mother–child interactions (such as touching, gazing, singing, and vocalizing) are more frequent than father-child interactions (Feldman, 2007). This is because infants experience synchrony between their own physiology and behavior and the mother's body, physical presence, and sensory cues. Furthermore, age-related changes have diverse effects on the temporal and rhythmic characteristics of brain responses (Dumas et al., 2011). For instance, from age 20 to age 80, the N400, an Event-Related Potentials (ERP) component associated with semantic access, demonstrates a progressive increase in latency of approximately 1.5–2 ms per year (Kutas and Iragui, 1998; Federmeier, 2022). This highlights that the influence of aging on the timing of neural responses is complex and varies with modality.

Personality traits. There is a correlation between interbrain synchrony and personality traits such as affective empathy and sensitivity (Cohen et al., 2017; Parada and Rossi, 2017; Bevilacqua et al., 2019; Czeszumski et al., 2020). Nguyen et al. (2021) showed that variations in paternal neural synchronization could be related to differences in the trait-like parenting attitude of fathers. Furthermore, it was found that the sensitivity of fathers in child care was associated with positive outcomes in child development (Harrist and Waugh, 2002; Leclere et al., 2014). However, females are generally considered more pro-social and moral (Heinla et al., 2020). Openness and the need to belong were additional traits where females scored higher (Vecchione et al., 2012).

OPTIMAL LEVEL OF PARENT–CHILD INTERBRAIN SYNCHRONIZATION

Previous research has demonstrated that high levels of interbrain synchrony are strongly associated with more positive cognition and behavior. Based on existing evidence, outcomes of neurobehavioral synchrony are enhanced social connectedness, effective communication as well as interpersonal regulation (Feldman, 2007; Stephens et al., 2010; Leong et al., 2017). However, whether there is an optimal level of parent–child synchronization is a crucial question for the research. An ‘‘optimum midrange model" of behavioral contingency in parent–child interactions is supported by a variety of empirical studies (Beebe et al., 2008; Beebe and Steele, 2013). How can we increase interbrain synchrony to promote parent–child behavior? Communication patterns, nonverbal behavior, music, and multichannel stimulation have all been demonstrated to increase synchronization between parents and children (Table).

Conversational patterns. Family Systems Theory has long held that family members function as a relational unit and that a pattern of organized, flexible, and positive exchanges between individuals in the relational unit leads to optimal relational and emotional health (Rothbaum et al., 2002; Haefner, 2014). For example, Nozawa et al. (2016) found that social communication enhanced interbrain synchrony in frontal areas is connected with successful information sharing and cooperative behavior using spoken language. Nguyen et al. (2021, 2023) used fNIRS hyperscanning to explore the temporal dynamics of interbrain synchrony during parent–child conversations and found that frequent turns-taking in conversation predicted a higher level of interbrain synchronization and later vocabulary size. These studies of conversational synchrony indicated that conversation patterns, such as turn-taking, may support cross-brain associations and emphasize the significance of understanding dynamic emotion-related processes and their relationship to psychological well-being during parent–child social interactions.

Nonverbal behavior. Parent-child interbrain synchrony is facilitated not only by verbal communication but also by nonverbal activities such as affective touch, eye contact and gaze, gestural mimicry, and joint attention. First, affectionate touch serves as an essential pathway for establishing and maintaining parent–child interbrain synchrony at neural levels. In terms of physical touch, the closer the distance between parent and child, the stronger the connection they feel, resulting in increased interbrain synchrony between them (Carozza and Leong, 2021; Trinh et al., 2021). For instance, mother–child dyads displayed increased interbrain synchrony in the prefrontal cortex when the child was seated on the mother's lap while watching videos. One possible explanation for this effect is that proximity may have promoted mutual entrainment through micro-adjustments of bodily touch, as well as the perception of heart rhythms and respiration (Wass et al., 2020). Second, speaker eye contact and gaze enhance information coupling between the brains of child and the parents. Leong et al. (2017) discovered through empirical studies that direct gaze enhances bidirectional parent-infant brain connections. Third, gestural imitation and joint attention both involve a partner with whom nonverbal interpersonal contact is established. They serve as excellent ecological models for the study of human social interaction.

Music. Music serves as a medium for social interaction across various species. Evidence demonstrates that music has played a crucial role in fostering social connections among numerous species, including humans. For instance, a recent parent–child EEG study indicates that musical interventions can enhance brain-to-brain connections between children and their parents (Samadani et al., 2021). Furthermore, Fachner et al. (2019) used the EEG hyperscanning method to discover that classical music induced significant interbrain synchronization between a music therapist and client during sessions of Guided Imagery and Music

(Fachner et al., 2019). Therefore, musical activities are intimately connected to parent–child interbrain synchrony.

Multimodal stimulation. In addition to examining each modality individually, combining modalities might result in a more potent form of rhythm induction in parent–child interactions (Levinson and Holler, 2014). Adults frequently employ multiple modalities when engaging with children, and these multimodal forms of stimulation (such as joint attention, play, speech, and daily routines) are more likely to enhance the interbrain synchrony within the interaction compared to a single mode of stimulation.

CONCLUSION AND FUTURE DIRECTIONS

Hyperscanning provides a new perspective into parent–child interactions and the quality of early relationships by capturing the dynamics and reciprocity of social exchanges and involving parents and children as active and engaged partners, as opposed to the passive perception required by traditional neuroimaging approaches. In this review, we first highlight the use of hyperscanning techniques to simultaneously measure dyadic brain activity in dynamic parent–child interactions in order to reveal differences in interbrain synchrony as well as mother–child and father-child interactions, especially in infancy, to provide a deeper understanding of the link between body and brain (Markova et al., 2019). Moreover, by summarizing the important factors influencing the interbrain synchrony between parents and children, we propose ways to promote interbrain synchrony. These findings, when taken as a whole, suggest that interpersonal neural synchrony may serve as a useful neural marker for mutual engagement in social interactions between parents and children that rely on both parties being responsive and attentive to one another. This summary may be useful for expanding researchers' and practitioners' understanding of the ways in which parenting and the parent–child relationship shape children' brains. Similarly, neurofeedback and parent training methods could be developed so that adults and children could see the effects of their interactions on each other's brain activity in real time.

Hyperscanning has greater potential for future studies of the interpersonal neural dynamics of natural parent–child interactions, and we can conduct more studies. Firstly, we do not know what is normal or how synchrony between parent and child develops, and to explain these issues, a longitudinal design as a potential approach in future studies to investigate how the relationship between parent–child relationships and interbrain synchrony accompanies children's brain development and maturation during parent–child interactions is required. Secondly, previous research has focused on more mother–child interactions, with relatively few studies on father-child interactions, and no detailed studies of mother-son, mother-daughter, or father-son and father-daughter by gender. Further research may focus on detailed gender distinctions. Furthermore, mother-father-child triads could also be considered, or even multi-person dynamics interactions between caregivers and several siblings could be studied. Finally, it is unclear whether and how exactly behavioral and physiological synchronization between parents and children is related to neural synchronization, therefore, future research could use multimodal simultaneous assessment of synchrony in parent–child interactions.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any real or perceived conflicts of interest.

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