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The Role of Neurobiological Bases of Dyadic Emotion Regulation in the Development of Psychopathology: Cross-Brain Associations Between Parents and Children

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Abstract
Daily interactions between parents and children play a large role in children's emotional development and mental health. Thus, it is important to investigate the neural mechanisms underlying this association within the context of these dyadic social interactions. We suggest that examining cross-brain associations, coordinated brain responses, among parents and children increases our understanding of patterns of social and emotion-related processes that occur during parent–child interactions, which may influence the development of child emotion regulation and psychopathology. Therefore, we extend the Parent–Child Emotion Regulation Dynamics Model (Morris et al., in: Cole and Hollenstein (eds) Dynamics of emotion regulation: A matter of time, Taylor & Francis, 2018) to include cross-brain associations involved in dyadic emotion regulation during parent–child social emotional interactions and discuss how this model can inform future research and its broader applications.

Keywords Emotion regulation · Cross-brain associations · Inter-brain synchrony · Cross-brain connectivity · Parent–child relationship · Psychopathology

Introduction

From infancy to adolescence, parents play an influential role in their child's emotion regulation development and psychological well-being (Morris et al., 2007). Moment-to-moment interactions between parents and their children help shape children's emotion regulation abilities over time and serve as the foundation for other interpersonal relationships outside of the parent–child dyad (Eisenberg et al., 2010; Morris et al., 2017). Emerging evidence suggests parenting and parent–child interactions may influence child emotion regulation development through alterations in emotion-related neurocircuitry (Tan et al., 2020). This has implications for child psychopathology and adjustment, as emotion regulation difficulties are associated with children's internalizing and externalizing problems as well as adjustment outcomes such as academic achievement and social competence (Eisenberg et al., 2010; Silk et al., 2003; Zeman et al., 2002). Advances in neuroimaging technology have allowed researchers to begin exploring cross-brain associations, such as inter-brain synchrony and cross-brain connectivity that underlie parent–child interactions and contribute to child adjustment outcomes (e.g., Ratliff et al., 2021; Reindl et al., 2018). Thus, we extend the Parent–Child Emotion Regulation Dynamics Model (see Fig. 1), originally developed by Morris et al. (2018), to further illustrate the importance of understanding cross-brain associations, coordinated brain responses, among parents and children during real time on the development of children's emotion regulation and psychopathology. We begin with a discussion of emotion regulation development in the context of the parent–child relationship. We then present the extended

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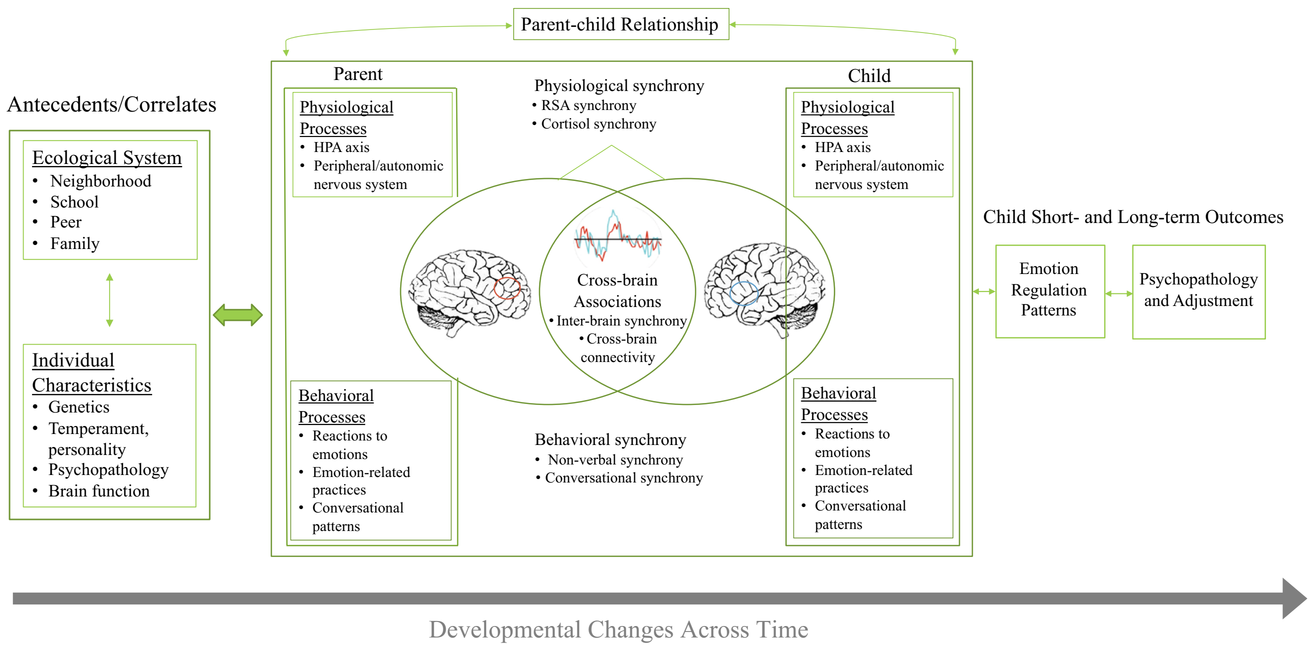

Fig. 1 Extension of the parent–child emotion regulation dynamics model. The extended parent–child emotion regulation dynamics model includes cross-brain associations involved in dyadic emotion regulation during parent–child social emotional interactions and their influence on emotion regulation patterns, psychopathology, and adjustment. *Note.* Brain regions highlighted are for demonstration purposes and represent brain regions salient in dyadic emotion regulation processes. *Red* dorsolateral prefrontal cortex (dlPFC), *Blue* anterior insula (Color figure online)

Parent–Child Emotion Regulation Dynamics model, and we review research regarding the parental brain and the influence of parenting on the child brain. Next, we discuss links between behavioral and physiological synchrony and cross-brain associations, including inter-brain synchrony and cross-brain connectivity. Lastly, we conclude by considering applications for the model in prevention and intervention research, parent education, and practice.

The Parent–Child Relationship and Emotion Regulation

Emotion regulation refers to the ability to recognize and regulate one's own emotions as well as respond appropriately to the emotions of others (Eisenberg et al., 2010). Children, including adolescents, develop emotion regulation abilities in the context of the parent–child relationship through observations of parents' own emotion regulation strategies, emotion coaching and guidance, and the emotional climate of the parent–child relationship (Morris et al., 2007). Emotion regulation development is considered a dyadic process, as children learn to regulate their emotions through both intrapersonal regulation and interpersonal regulation, including co-regulation, during dynamic parent–child social interactions (Morris et al., 2018). Specifically, parent–child co-regulation involves the processes "by which parents and their children regulate one another through their goal-oriented behavior and expressed affect" (Lobo & Lunkenheimer, 2020, p. 1121). Co-regulation occurs during moment-to-moment interactions between children and parents and is aimed at maintaining optimal emotional states through emotional reciprocity, responsiveness, and cooperation (Guo et al., 2021). It is posited that through these repeated interactions, in which active co-regulation is taking place, the foundation for children's self-regulation is established.

Throughout childhood and adolescence, the parent–child relationship remains one of the most important contexts for the development of children's emotion regulation. During infancy and toddlerhood, responsive and predictable interactions with parents help shape emotion regulation patterns and lay the foundation for optimal emotional development (Bernard et al., 2013; Feldman, 2007). The development of the orienting network, which includes parietal regions and the frontal eye field, allows infants to focus on sensory stimuli. The ability of infants to shift their attention away from emotionally distressing stimuli is considered one of the earliest emotion regulation strategies (Rothbart et al., 2011). Parents often promote this strategy by directing an infant's attention away from emotionally distressing stimuli, and studies show greater orienting ability is related to less negative affect in infants (Rothbart et al., 2011). Parent emotion socialization techniques during infancy and toddlerhood also include teaching children about emotions and helping children label and manage their emotions (Morris et al., 2011). Studies show such co-regulation processes are associated with effective emotion regulation, positive affect, and attachment quality in infants and toddlers (Bernard et al., 2013; Somers et al., 2021).

During early and middle childhood, the parent–child relationship continues to shape the development of emotion regulation. This period is often accompanied by the formation and maintenance of interpersonal relationships with peers, teachers, and other individuals outside the home, emphasizing the importance of establishing effective emotion regulation patterns during parent–child interactions. Cognitive advances, including greater reliance on the executive attention network, which is involved in effortful control and problem-solving, supports self-regulation in childhood (Rothbart et al., 2011). Through interactions with the limbic system, the executive attention network allows the child to regulate emotional responses to stimuli (Rothbart et al., 2011). Parent emotion socialization techniques often include emotion coaching (e.g., labeling emotions, problem-solving) and supportive and nurturing responses to children's emotional expressions which support and promote these cognitive advances (Morris et al., 2017). Studies indicate that supportive emotion socialization techniques, like emotion coaching, are associated with more effective emotion regulation abilities among children compared to unsupportive emotion socialization techniques such as denigration or punishment (Cui et al., 2020). In addition, parent–child co-regulation processes, such as the modulation of positive affect during social interactions, are associated with fewer child externalizing and internalizing issues (Guo et al., 2021; Lunkenheimer et al., 2011).

Adolescence is a period characterized by dynamic social, emotional, biological, and cognitive development, as adolescents experience increasingly complex social and emotional demands (Backes & Bonnie, 2019). These developmental changes are accompanied by changes in brain structure and function, specifically in regions associated with emotion regulation and processing, executive function, and social cognition (Guyer et al., 2016). Research indicates adolescents who utilize less effective emotion regulation strategies report greater internalizing and externalizing symptoms as well as an increased risk for developing an internalizing disorder in later adolescence and young adulthood (Silk et al., 2003; Tortella-Feliu et al., 2010). Studies have found negative parental responses to adolescent emotional distress is related to increases in adolescent emotion regulation difficulties and depressive symptoms (Sheeber et al., 2005; Yap et al., 2008). Furthermore, emotion regulation has been shown to play a moderating role in the relationship between parental psychological control (e.g., parental behavior that is intrusive and intended to manipulate youths' thoughts, feelings, and behaviors) and adolescent depressive symptoms, such that the association between psychological control and greater depressive symptoms is stronger for adolescents with less effective emotion regulation strategies (Cui et al., 2014). During this period, adolescents begin to rely more on self-regulation rather than co-regulation; however, parent–child co-regulation processes remain relevant throughout adolescence and have implications for brain development, emotion regulation, and psychopathology. Adolescence is characterized by rapid transformations in brain maturation in emotion-related regions (Tan et al., 2020), and research suggests parent-adolescent co-regulation processes can facilitate this development (e.g., Jiang et al., 2021).

While the findings reviewed above highlight the importance of parenting behaviors and the parent–child relationship in child emotion regulation and mental health, few studies examine emotion regulation dynamics during moment-to-moment interactions between parents and children. Due to the dynamic and dyadic nature of emotion regulation, studies utilizing direct behavioral observation (e.g., Lunkenheimer et al., 2011), ecological momentary assessment (e.g., Cui et al., 2020), and/or physiological measurements (e.g., Somers et al., 2021) obtained during parent–child interactions may provide an enhanced understanding of emotion regulation development. Observations of dynamic parent–child interactions suggests forms of synchrony reflect parent–child co-regulation processes and work in tandem to influence the development of child self-regulatory behaviors. Indeed, studies examining emotional, behavioral, and forms of physiological synchrony (e.g., hormonal, cardiac) have found positive associations between parent–child synchrony and child self-regulation. More recently, advancements in neuroimaging technology have allowed researchers to begin exploring the neural mechanisms underlying emotion regulation development in the context of dynamic parent–child interactions. Initial findings indicate interactions between parents and children, facilitated by parent–child co-regulation processes, influence emotion processing and regulation neurocircuitry with implications for child mental health and well-being (Tan et al., 2020). Therefore, we contend neurobiological mechanisms underlying parent–child emotion regulation patterns are best understood within the context of dynamic and dyadic social interactions between parents and children.

Extending the Parent–Child Emotion Regulation Dynamics Model

Research exploring the impact of parenting on both parent and child brain function demonstrates that what happens during repeated interactions between parents and children matters. We posit differing forms of synchrony work in tandem during these interactions to help shape children's emotion regulation patterns. These emotion regulation patterns develop over time, across thousands of interactions and ultimately provide the foundation for other relationships outside of the parent–child dyad. Therefore, we extend the Parent–Child Emotion Regulation Dynamics Model developed by Morris et al. in 2018 to include neurobiological processes specific to the parent and the child as well as those specific to the interaction between the parent and child. We extend this model through the addition of cross-brain associations, specifically inter-brain synchrony and cross-brain connectivity (discussed in-depth below), nested within the dynamic and dyadic interactions between parents and their children (see Fig. 1). Original features of the model remain, including intrapersonal physiological and behavioral processes, interpersonal physiological and behavioral synchrony, and short- and long-term outcomes including the development of child emotion regulation patterns and psychopathology. The original model developed by Morris et al. (2018) considers ecological contexts and individual characteristics as antecedents and/or correlates influencing parent–child interactions. These constructs provide an important context for parent–child interactions, but an in-depth discussion is beyond the scope of this review (see Morris et al., 2018). In the current adaptation of the model, we have added a focus on the importance of cross-brain associations in moment-to-moment interactions and their implications for emotion regulation and psychopathology. Before moving on to a discussion of the cross-brain associations, it is important to first review the literature related to the neurobiology of parenting and the influences of parenting on children's brain development.

The Parental Brain

Although the relationship between parenting behaviors and child emotion regulation and psychopathology is well-established, less is known regarding the neural mechanisms that may underlie this relationship. Research has often focused on the child brain; however, to fully understand the dynamic nature of parent–child interactions and their influence on child emotional development, a discussion of the parental brain is warranted. The transition to parenthood is accompanied by physiological and neurobiological changes, including increases in hormones spurring changes in networks salient to caregiving (Rutherford et al., 2015). The *parental brain*, sometimes referred to as the parental caregiving neural network, is comprised of several interconnected regions of the parent brain which are believed to enhance caregiving motivation and abilities (Feldman, 2015). Neuroimaging studies of parent–child interactions suggest regions in the reward/motivation network, empathy network, and emotion regulation network make up the parental brain (Feldman, 2015; Swain, 2011; Swain et al., 2012). The reward/motivation network helps to reinforce appropriate caregiving behaviors, while the empathy and emotion regulation networks promote empathetic interactions and emotional support of the child.

The reward network is made up of the mesolimbic and nigrostriatal pathways. Increased activation is found in these regions in parents when exposed to infant cues, such as crying, compared to non-parents (Feldman, 2015), and this activity is related to maternal psychopathology and parenting behaviors. For example, studies have found mothers with depression showed decreased activation in regions of the reward network in response to their infant's emotional distress when compared to psychiatrically healthy mothers (Pechtel et al., 2013). In addition, mothers who engaged in more sensitive parenting behaviors showed increased activation in the reward network regions in response to their infant's positive affect compared to less sensitive mothers (Pechtel et al., 2013). In the context of parent–child interactions, activation of the reward network may be adaptive as it increases motivation and reinforces caregiving behaviors.

The empathy network is thought to be comprised of the dorsal anterior cingulate cortex (dACC), anterior insula, and posterior insula (Feldman, 2015; Swain et al., 2011; Swain et al., 2012). Similar to the reward network, mothers and fathers show increased activation in these regions when presented with infant cues compared to non-parents. Moreover, levels of activation have been shown to vary based on psychiatric symptoms as well as parenting behaviors and attitudes (Feldman, 2015; Musser et al., 2012). Musser et al. (2012) found greater maternal intrusiveness with their infant was related to increased activation in the anterior insula (a region that acts as a hub for coordinating cognitive processes related to emotion), suggesting particularly high empathetic reactions may increase the mother's attempts to soothe the infant to the point of intrusiveness. In a study examining fathers' brain response to their infant's distress signals, researchers found fathers with more restrictive attitudes showed decreased activation in the anterior insula when hearing their infant's cry. Additionally, the researchers found a moderate level of activation in the anterior insula was associated with the ideal level of father engagement (Mascaro et al., 2013). This supports Musser et al.' (2012) findings above—hyperactivation in the anterior insula may be associated with intrusive behavior, whereas hypoactivation in the anterior insula is associated with decreased parental involvement. Preliminary research with parents and adolescents indicates parents recruit the anterior insula when engaged in empathetic responding. Past research is focused on infants, but emerging evidence from our lab suggests parents' anterior insula activation continues to be important throughout childhood and adolescence. For example, we found decreased activation in parents' anterior insula when witnessing their adolescents make an error during a cooperative game was related to lower levels of adolescent-reported parental involvement (Ratliff et al., 2018). These findings provide initial evidence for the neural basis of parental empathetic responding within the context of parent-adolescent relationships, and such processes likely influence the parent–child relationship and vice versa.

There is less consensus regarding the regions that comprise the emotion regulation network, however, most agree the major regions include the dorsolateral prefrontal cortex (dlPFC), dorsomedial prefrontal cortex (dmPFC), ventrolateral prefrontal cortex (vlPFC), ventromedial prefrontal cortex (vmPFC), anterior cingulate cortex (ACC), and the amygdala (Tan et al., 2020). In addition to its role in empathetic responding, research indicates the anterior insula also plays an essential role in emotion processing and regulation. For example, in a meta-analysis of functional magnetic resonance imaging (fMRI) studies, consistent activation in the anterior insula was found when participants engaged in focused efforts to regulate their emotions (Morawetz et al., 2017). Additionally, Atzil et al. (2012) found mothers and fathers showed increased activation in emotion regulation regions (insula and prefrontal cortex) when viewing videos of their own infant versus an unknown infant. Similarly, mothers showed increased dlPFC activation when viewing videos of their infant or listening to their infant's cries compared to non-mothers (Feldman, 2015). These findings provide a foundation for investigating both parent and child emotion regulation neurocircuitry by indicating specific networks and regions of interest to examine in future studies.

In addition to region-specific changes, researchers have also explored how functional connectivity between parental brain networks during infancy predicts children's subsequent emotion regulation abilities and socialization. A longitudinal study by Abraham et al. (2016) found increased functional connectivity within and between emotion regulation and empathy-related networks in parents during infancy is associated with children's later use of emotion regulation strategies and social competence. Moreover, this association was mediated by observed parent-infant behavioral synchrony (Abraham et al., 2016). In a separate longitudinal study (Abraham et al., 2018), researchers found functional connectivity between empathy-related networks in the parent brain was associated with lower cortisol reactivity in children as well as lower child internalizing symptoms. The latter association was mediated by the child's emotion regulation abilities, providing further evidence for the influence of parent neurocircuitry on children's emotion regulation and psychopathology.

Parenting and the Child Brain

Neuroimaging research has found parenting behaviors and the parent–child relationship influence children's structural and functional brain development, specifically in regions implicated in emotion awareness, processing, and regulation (Lee et al., 2017; Romund et al., 2016; Whittle et al., 2014). Studies investigating longitudinal links between parental sensitivity during infancy and structural development in childhood have found greater parental sensitivity and responsiveness predicts increased cortical thickness in children's frontal, temporal, and parietal regions, areas involved in emotion processing and social cognition, (Frye et al., 2010) as well as greater total brain and gray matter volume in children (Kok et al., 2015). Matsudaira et al. (2016) found greater parental praise was related to increased gray matter volume in the left posterior insula, a region involved in emotion processing, in children. In a longitudinal study of adolescent structural brain development, Whittle et al. (2014) found greater maternal positivity was associated with reduced right amygdala growth and increased cortical thinning in prefrontal regions associated with emotion processing. This is consistent with previous findings suggesting reduced amygdala volume and increased cortical thinning are related to less psychopathology during adolescence (Whittle et al., 2013).

Regarding functional changes, research suggests parenting techniques and behaviors influence children's emotion-related neurocircuitry. For example, Pozzi et al. (2020) found greater negative maternal behaviors during a parent–child social interaction were associated with increased amygdala activation in response to fearful faces, while Romund et al. (2016) found greater maternal warmth is associated with decreased amygdala activation in adolescents when presented with negative or emotionally distressing stimuli. In a sample of youth ages 9 to 16, greater parental psychological control was related to decreased activity in the anterior insula during an emotional conflict fMRI task wherein youth attempted to determine facial affect while an incongruent emotion word was displayed across the picture of the face (Marusak et al., 2018). Research indicates increased activation in the anterior insula is associated with increased attempts to process and regulate one's emotions (Lamm & Singer, 2010), suggesting negative parenting techniques, such as psychological control, may contribute to altered emotion regulation neurocircuitry.

Studies examining the influence of maternal social feedback on child brain function have found alterations in emotion-related regions. For example, in a study examining adolescent brain activation in response to maternal criticism, Lee et al. (2015) found adolescents showed increased activation in regions associated with emotion and social pain (lentiform nucleus and poster insula) and decreased activation in regions associated with emotion regulation and cognitive control (dlPFC and ACC). In a similar study, Aupperle et al. (2016) found adolescent females with greater symptoms of depression showed blunted right amygdala response when listening to maternal praise but increased activation when listening to maternal criticism, suggesting hyperactivation in the amygdala may be related to an increased risk for depression in adolescence. Recent studies have also explored the influence of parenting on functional connectivity between emotion-related regions and networks in children. For example, studies have found greater maternal responsiveness and positivity during infancy is related to stronger negative connectivity between regions in the default mode network (e.g., vmPFC and right angular gyrus) and the salience network [e.g., anterior insula and anterior cingulate cortex (Dégeilh et al., 2018)] as well as decreased connectivity between the superior parietal lobule and the executive control network in children [e.g., medial-frontal areas (Pozzi et al., 2021)]. These changes in connectivity are thought to reflect greater maturation, as connectivity between these networks becomes inversely coupled throughout adolescence and adulthood (Dégeilh et al., 2018). A longitudinal study of adolescents found maternal negativity predicted stronger connectivity between the adolescent amygdala and the vlPFC, a neural pathway involved in emotion reactivity and regulation. This altered connectivity, in turn, mediated the relationship between maternal negativity in mid-adolescence and internalizing symptoms in late adolescence (Jiang et al., 2021). This is in line with previous research suggesting hyperconnectivity between the amygdala and vlPFC is associated with internalizing symptoms (e.g., Gee et al., 2013). Together these findings demonstrate the influence of both supportive and unsupportive parenting behaviors on emotion processing and emotion regulation neurocircuitry in children with implications for emotion regulation and psychopathology. For an in-depth review of the impact of parenting on child brain development, see Bhanot et al. (2021).

Researchers have also utilized simultaneous fMRI scanning to examine brain responses in interacting parents and children. Cosgrove et al. (2020) examined activity in the brains of parent-adolescent dyads while completing a dyadic error processing task during simultaneous fMRI scanning. They found parents who showed decreased activity in the medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC) when witnessing their adolescent's error had adolescents with greater depressive and anxiety symptoms. They also found adolescents who exhibited increased activity in the anterior insula when witnessing their parent's error had parents with greater anxiety symptoms. Utilizing the same dyadic error processing task, Kerr et al. (2020) found positive parenting practices were associated with greater activity in the parent vmPFC when witnessing their adolescent's error. Using the same sample, Cosgrove et al. (2020) found greater parent negative statements made during an fMRI conflict discussion task was related to increased activation in the thalamus of adolescents while completing an emotion processing task. Findings from these studies highlight the importance of examining moment-to-moment dynamics and cross-brain associations during parent–child social interactions and their influence on emotion regulation development and psychological adjustment.

Linking Behavioral and Physiological Synchrony

Having reviewed literature related to the neurobiology of parenting and the influences of parenting on children's brain development, we now want to consider approaches that focus on dyadic, reciprocal processes in the context of the parent–child relationship. When parents and children interact, synchrony can be observed in behaviors but there is also evidence of physiological synchrony. Behavioral, or observed, synchrony refers to the coordination of behaviors such as facial expressions, verbalizations, body positions, and other nonverbal gestures during social interactions, whereas physiological synchrony refers to the coordination of biological responses such as respiratory sinus arrhythmia (RSA), coordinated heart rhythms, cortisol, and brain synchrony (Bell, 2020). Research suggests that the behavioral and physiological processes occurring within one member of the parent–child dyad continually influence those in the other member throughout social interactions (Bell, 2020). These mutually influencing processes, often representative of parent–child co-regulation, impact emotion processing, regulation, and responding and so contribute to dyadic emotion regulation development. For example, studies measuring physiological synchrony, in the form of coordinated heart rhythms, have found parents and infants show increased physiological synchrony during periods of emotional and vocal synchrony (Feldman et al., 2011; McFarland et al., 2020). In parent–child dyads, physiological synchrony (e.g., coordinated heart rhythms) is associated with positive behavioral synchrony during parent–child interactions. Notably, this association was moderated by family risk, such that when family risk was high, positive behavioral synchrony was highest when physiological synchrony between parent and child was lower (Suveg et al., 2016). Regarding brain physiological synchrony and behavioral synchrony, Markova et al. (2019) suggest many of the behavioral processes occurring during parent–child interactions likely drive forms of brain physiological synchrony. We posit brain physiological synchrony and other forms of physiological synchrony (e.g., hormonal, cardiac) facilitate parent–child co-regulation processes. However, it is important to note that research does suggest relationships between behavioral and physiological synchrony can be non-linear, emerging selectively with periods of synchronization and segregation [i.e., low levels of interpersonal synchrony (Mayo & Gordon, 2020)]. This suggests interactions between behavioral and physiological synchrony are likely more nuanced than originally hypothesized and cannot be reduced to statements such as greater synchrony is adaptive and less is maladaptive. This is in line with evolving perspectives suggesting synchrony is not always promotive or protective (for reviews, see Creavy et al., 2020; Davis et al., 2018). Therefore, we contend the emergence of brain physiological synchrony likely varies by context as does its influence on emotion regulation patterns and adjustment. We discuss several studies linking brain physiological synchrony and behavioral synchrony in the next sections.

Parent–Child Inter-brain Synchrony

Thus far, the research we have discussed has focused on the relationships between the parental brain and parenting behavior and the influence of parenting on the child brain. However, to best understand parent–child interactions and their influence on child and adolescent emotion regulation and psychopathology, an approach that considers the dynamic, reciprocal nature of these interactions is needed (Morris et al., 2018). The Parent–child Emotion Regulation Dynamics Model outlines how daily interactions between parents and children help to form children's emotion regulation abilities (Morris et al., 2018). During parent–child interactions, children learn to regulate their emotions through both intrapersonal regulation and interpersonal regulation, such as co-regulation, thus supporting the idea of emotion regulation as a dyadic process that can be understood during dynamic social interactions (Morris et al., 2018). In the past decade, hyperscanning (i.e., simultaneous scanning of two interacting individuals) technology has enabled researchers to examine how activation in one individual's brain relates to activation in the brain of a different individual during a social interaction (Montague et al., 2002). Specifically, hyperscanning technology allows researchers to measure cross-brain associations, coordinated brain responses, among parents and children. We have identified two forms of cross-brain associations in the literature, inter-brain synchrony and cross-brain connectivity. We begin with an in-depth discussion of parent–child inter-brain synchrony. Inter-brain synchrony is defined as concurrent and/or lagged neural activity between brain regions in two interacting individuals (Feldman, 2015; Valencia & Froese, 2020). Inter-brain synchrony has emerged from research on other forms of parent–child synchrony including behavioral, physiological, and emotional synchrony (Feldman, 2007). Research has found these forms of parent–child synchrony are related to attachment, parent–child relationship quality, social competence, empathetic responding, and emotion regulation (Barber et al., 2001; Criss et al., 2003; Feldman, 2007). In the next section, we review findings from studies of parent–child inter-brain synchrony that provide support for the extended Parent–Child Emotion Regulation Dynamics model.

Hyperscanning technology can be utilized with several different neuroimaging modalities including electroencephalogram (EEG), functional near-infrared spectroscopy (fNIRS), magnetoencephalography (MEG), and fMRI to examine parent–child inter-brain synchrony. Using fNIRS hyperscanning technology, studies have found increased parent–child inter-brain synchrony in the dlPFC and the frontopolar cortex (FPC)—regions associated with emotion regulation—during a cooperative task compared to during a competitive task or a task completed independently (Miller et al., 2019; Reindl et al., 2018). Moreover, higher levels of inter-brain synchrony in the parent–child dyad were related to greater child emotion regulation abilities (Reindl et al., 2018). Studies have also begun to uncover links between parent–child inter-brain synchrony and child internalizing and externalizing symptoms. In a sample of mothers and their preschoolers, researchers found evidence of inter-brain synchrony during both the frustration and recovery context of the Disruptive Behavior Diagnostic Observation Schedule: Biological Synchrony paradigm (behavioral paradigm measuring children's affect regulation and dyadic coregulation across contexts, adapted for use with fNIRS). However, during the recovery context, less parent–child inter-brain synchrony between the prefrontal cortex (PFC) was associated greater child irritability (Quinones-Camacho et al., 2020). In a longitudinal study of parent–child dyads using the Disruptive Behavior Diagnostic Observation Schedule: Biological Synchrony paradigm, researchers found greater inter-brain synchrony between the PFC, as evidenced during the recovery context, was related to a more rapid reduction in child internalizing symptoms across four follow-up timepoints (Quinones-Camacho et al., 2021). Taken together, these findings provide additional support for the role of parent–child co-regulation following distressing or negative emotion-eliciting interactions which, through repeated interactions, may promote self-regulatory strategies and decrease emotion regulation difficulties and risk for psychopathology.

More recently, the impact of parenting attitudes, stress, and adversity on parent–child inter-brain synchrony has also been explored using fNIRS hyperscanning technology. Studies have found greater parenting stress is related to less inter-brain synchrony between prefrontal regions in mothers and their children when watching an animated movie (Azhari et al., 2019) or completing a cooperative task (Nguyen et al., 2020). Notably, increased inter-brain synchrony during a cooperative task compared to a competitive task also predicted the dyad's ability to solve the problem presented in both tasks (Nguyen et al., 2020). In a sample of father-child dyads, Nguyen et al. (2021) found increased inter-brain synchrony between the bilateral dlPFC as well as the left temporo-parietal junction (TPJ) when dyads were completing a cooperative task compared to a task completed individually. Fathers' positive perceptions of their role was associated with greater inter-brain synchrony during the cooperative task (Nguyen et al., 2021a, 2021b). Finally, Hoyniak et al. (2021) examined associations between adversity and inter-brain synchrony in parents and preschoolers aged 4 to 5 using fNIRS hyperscanning. The researchers found adversity, such as material deprivation, was associated with reduced parent–child inter-brain synchrony between prefrontal regions during a frustration induction task, which required parents and children to solve a challenging puzzle (Hoyniak et al., 2021).

We have also incorporated conversational patterns as an important factor to consider during parent–child interactions, as research suggests conversational patterns between parents and children may be associated with inter-brain synchrony. Conversational synchrony, a form of behavioral synchrony, refers to the tendency for individuals' word production and speech turn-taking to become more similar over the course of their social interaction. Conversational synchrony also includes convergence of nonverbal communication such as gestures and emotional expressions (Gordon et al., 2019) and is commonly coded in studies of parent–child behavioral synchrony as well (Criss et al., 2003; Harrist & Waugh, 2002). Researchers studying parent–child conversational synchrony have found synchrony is associated with parent–child bonding and attachment (Kelly, 2018), social competence (Levinson, 2016), and cooperation (Leonardi et al., 2016). Though limited, researchers have begun to examine the neural mechanisms that may underlie conversational synchrony. Nguyen et al. (2021) used fNIRS hyperscanning to examine temporal dynamics of inter-brain synchrony during an unstructured parent–child conversation. The sample consisted of 40 parents and their child (ages 4 to 6). Dyads were asked to engage in a 4-min unstructured conversation task. The role of conversation patterns such as turn-taking, relevance (e.g., the verbalization is related to the preceding verbalization), contingency (e.g., responding to a question/request), and intrusiveness (e.g., failing to allow time for the other individual to respond, rapid questioning, interruptions) on inter-brain synchrony were explored. Results of the study showed that only turn-taking predicted inter-brain synchrony during the conversation. Specifically, a greater number of turns between the parent and child during the conversation predicted greater inter-brain synchrony in frontal regions of the brain. Moreover, greater turn-taking was also related to an increase in inter-brain synchrony over the course of the conversation (Nguyen et al., 2021a, 2021b). These findings have important implications for the parent–child relationship, as studies have found greater turn-taking during parent–child social interactions is associated with more successful conflict resolution and greater child perspective-taking (Lougheed et al., 2020; Main et al., 2016). These dynamics have been shown to promote psychosocial adjustment in adolescence as the parent–child relationship becomes increasingly egalitarian (Lougheed, 2019). While limited, studies of conversational synchrony suggest conversation patterns, such as turn-taking, may support cross-brain associations and further point to the importance of understanding dynamic emotion-related processes and their relation to psychological well-being during parent–child social interactions.

Cross-Brain Connectivity

The second of the two forms of cross-brain associations included in the extended model is cross-brain connectivity, defined as concurrent and/or time-lagged functional connectivity between same and different brain regions in two interacting individuals (Bilek et al., 2015; Ratliff et al., 2021). We would like to clearly define what we mean by "cross-brain connectivity" and discuss how it is similar to and different from inter-brain synchrony. The term "inter-brain synchrony" has been used in different ways. In the developmental literature, inter-brain synchrony is often referred to as a broad construct that incorporates nearly all brain-to-brain relationships between individuals in a dyad. Within social neuroscience, "inter-brain synchrony" is more often used to describe methods wherein activity in specific brain regions or voxels (the same area in both individuals' brains) is correlated across time, with the goal of identifying regions that activate in sync in both brains. This method has also often been termed "inter-subject correlation," particularly within the fMRI literature (Redcay & Schilbach, 2019). Cross-brain connectivity as introduced by Bilek et al. (2015) and used in our model is both an extension of these methods as well as a more specific concept within past developmental studies on inter-brain synchrony. It extends these methods because cross-brain connectivity refers to relationships between both the same (for example, how the child's amygdala activity relates to the parent's amygdala activity) and different regions in each person's brain (for example, how the child's amygdala activity relates to the parent's dlPFC activity) and also includes regions that are negatively correlated with one another in time (for example, if the child's amygdala activity decreases when the parent's dlPFC activity increases).

Cross-brain connectivity is thus similar methodologically to within-subject functional connectivity, but the functional connections are occurring between two different individuals' brains. As such, cross-brain connectivity fits within the broader construct of inter-brain synchrony often used in the developmental literature, but we have chosen to use the term cross-brain connectivity in our model to precisely define the construct and avoid confusion with methods such as inter-subject correlation, which refer to correlations between the same brain regions in both individuals.

Hyperscanning can be used with different imaging modalities (e.g., fNIRS, MEG, EEG, and fMRI) to examine cross-brain connectivity during real-time, dynamic parent–child social interactions. Each imaging modality offers unique advantages and disadvantages, and selection often depends on the research questions of interest. Methods such as EEG and fNIRS can enhance ecological validity by allowing subjects to interact face-to-face. EEG has greater temporal resolution compared to both fNIRS and fMRI, while fNIRS and fMRI have greater spatial resolution. fMRI hyperscanning is useful when examining deep brain structures, such as subcortical regions involved in socioemotional processing, with high spatial resolution (Koike et al., 2015, Misaki et al., 2021) though paradigms can lack ecological validity due to limitations of the scanning environment (i.e., subjects are not interacting face-to-face). Hyperscanning is most useful when researchers are interested in measuring neurobiological mechanisms underlying spontaneous, real-time social interactions. See Redcay and Shilbach (2019) and Misaki et al. (2021) for reviews of second-person neuroscience methodological approaches, including hyperscanning, as well as analytical approaches, useful for studying social interactions.

To the best of our knowledge, the first published study to examine cross-brain connectivity, as defined here, was conducted by Bilek et al. (2015) and used fMRI hyperscanning to examine cross-brain connectivity during a joint attention task. In this study, stranger dyads completed the joint attention task while undergoing fMRI hyperscanning. Utilizing a video feed, the task required one member of the dyad (the "sender") to indicate the location of a fixation cross on their screen using their gaze, and the other member of the dyad (the "receiver") used this non-verbal information to guess the correct location of the cross. The researchers selected the rTPJ as a region of interest due to its role in orienting attention to social stimuli as well as its role in inferring others' mental states (Decety & Lamm, 2007). Results of the study showed cross-brain connectivity between the sender's TPJ and the receiver's mPFC. Additionally, participants' self-reports of the size of their social network were measured and results showed dyads reporting larger social networks exhibited greater cross-brain connectivity during the joint attention task (Bilek et al., 2015), suggesting cross-brain connectivity between these brain regions may have implications for social interaction and expertise.

In an extension of this research aimed at understanding the temporal dynamics of social interactions using fMRI hyperscanning, Goelman et al. (2019) examined bidirectional signal exchanges between stranger dyads during the joint attention task used in the previously described studies. Results of the study confirmed that joint attention requires bidirectional signal exchanges between the sender and the receiver. Investigating the temporal dynamics of synchronization further, Bilek (2020) utilized dynamic causal modeling and Bayesian model comparison to examine causal and directed connectivity between brain regions in two interacting individuals. Again, stranger dyads completed the joint attention task while undergoing fMRI hyperscanning. Results of the study showed cross-brain connectivity between dyad members emerged selectively throughout the task and increased over time. Notably, results from the dynamic causal modeling analysis suggested the sender's brain activity had a causal impact on the receiver's brain activity, such that activity in the sender's rTPJ predicted activity in the receiver's rTPJ during the task. Together, these findings present a more nuanced view of cross-brain connectivity including the influence of contextual factors on the emergence and continuation of cross-brain connectivity throughout social interactions.

In our own lab, we have used fMRI hyperscanning to uncover evidence of cross-brain connectivity in parent-adolescent dyads during a naturalistic conversation paradigm (Ratliff, 2019; Ratliff et al., 2021). Adolescents and one of their biological parents completed a conflict discussion task using headsets to communicate with each other while undergoing fMRI hyperscanning. Average cross-brain connectivity over the course of the task was measured using lagged cross-correlation analyses, and group-level analyses were conducted using linear mixed-effects modeling. Results of the study showed cross-brain connectivity between regions-of-interest (ROIs) selected a priori (anterior insula, vlPFC, dlPFC, and the amygdala) and other emotion-related regions in the parent and adolescent brain during the task. In total, 60 significant region pairs were found, with 54 of these being parent-driven effects, meaning parent brain activity preceded adolescent brain activity. Using Bayesian analyses, associations between parent-adolescent cross-brain connectivity and behavioral measures were tested. Results revealed moderate to strong evidence for positive effects between cross-brain connectivity and adolescent-reported depressive symptoms, such that greater cross-brain connectivity between regions was associated with fewer depressive symptoms. One pattern to emerge from this analysis was cross-brain connectivity between parent cortical regions and the adolescent anterior insula was associated with fewer adolescent depressive symptoms. This may reflect the adolescent integrating the cognitive and/or emotional stimuli received from the parent to inform their own regulatory response. Additionally, evidence for negative effects between cross-brain connectivity and adolescent-reported parent emotion socialization behaviors was found, such that greater cross-brain connectivity between regions was associated with fewer supportive parenting behaviors (Ratliff et al., 2021). This finding was surprising but points to the importance of considering both the task and context of measurement in future research. Overall, our preliminary study provides evidence for parent-adolescent cross-brain connectivity during dynamic social exchange and suggests cross-brain connectivity may be influential in adolescent developmental outcomes.

Ample research suggests parent–child interactions shape child brain structure and function. We contend cross-brain connectivity aids in parent–child co-regulation processes that support the development of child self-regulatory behaviors. These processes, in the form of emotional reciprocity, responsiveness, and cooperation, allow for the emergence of cross-brain connectivity which may contribute to child brain development. The emergence of cross-brain connectivity appears to be context dependent and dynamically linked to behavioral synchrony. In our research, we have found cross-brain connectivity varies based on the emotional valence of statements made during a parent–child conflict discussion task (Ratliff et al., 2021). This is in line with past research suggesting forms of inter-brain synchrony are context dependent and can vary based on the overall emotional valence of the interaction (e.g., Nguyen et al., 2020; Reindl et al., 2018). We have also found that levels of cross-brain connectivity as well as the direction of activation vary between regions. Findings from our initial study on parent–child cross-brain connectivity suggest the direction of activation varies among different brain region pairs which likely influences its role in behavioral outcomes (Ratliff et al., 2021) and thus are critical to consider when interpreting the role of cross-brain connectivity in child adjustment outcomes. Moreover, because cross-brain connectivity captures negatively correlated activation, we can examine periods of segregation in addition to synchronization. This could have implications for understanding emotion regulation development, for example, when decoupling during social interactions serves an adaptive function (Mayo & Gordon, 2020). Further, cross-brain connectivity may better capture developmental changes due to its dynamic nature allowing for greater variability across contexts.

Implications and Applications

The extended model has potential to inform prevention and intervention research, parent education, and practice. This conceptual model could be helpful in furthering researchers' and practitioners' understanding of how the child brain is influenced by parenting and the parent–child relationship. Previous research indicates interventions focused on emotion regulation within the parent–child relationship can promote healthy brain development and protect against internalizing and externalizing disorders (Kehoe et al., 2014; Marusak et al., 2018). This model could be applied to research seeking to identify emotion-related neural targets for early intervention. For example, several studies are currently testing neurofeedback paradigms which allow the participant to not only see their own brain activation in real-time but also learn to modulate activation in the presence of emotion-provoking stimuli. By doing so, participants may be able to better manage their emotions. Similarly, parent training and neurofeedback procedures could be developed allowing parents and children to view how their interactions affect one another's neural responses in real-time. Kerr et al. (2020) recently developed and tested a dyadic neurofeedback paradigm in which parents received neurofeedback from their child during a social interaction. Initial results of the study showed parents can respond in ways that effectively downregulate activity in their child's emotion-related brain regions (Kerr, Cosgrove, et al., 2020; Kerr, Ratliff, et al., 2020). In addition to demonstrating feasibility, these findings suggest dyadic neurofeedback paradigms could be useful for parents by showing how neurobiological mechanisms, such as cross-brain connectivity, are influenced during dynamic moment-to-moment interactions with their children.

Additional research applications for the extended Parent–Child Emotion Regulation Dynamics Model might include examining sex and age differences among children and parents as well as differences due to dyad type (e.g., father-daughter, mother-daughter, father-son, etc.), as these are likely to influence cross-brain associations during parent–child interactions. Other individual characteristics, such as temperament, personality, psychopathology, puberty, and genetic and epigenetic factors may affect the emergence and maintenance of parent–child cross-brain associations. Future research is also warranted to more fully understand how cross-brain associations interact with various forms of behavioral and physiological synchrony to influence dyadic emotion regulation. Research on parent–child conversational patterns, a form of behavioral synchrony, suggests cross-brain associations and conversational synchrony are intrinsically linked (Nguyen et al., 2021a, 2021b), which might have implications for parent education aimed at improving parent–child communication and the outcomes associated. Further, studies that take into consideration cultural and historical factors, neighborhood and school settings, and family dynamics would help elucidate how these broader ecological contexts influence cross-brain associations as well as other forms of synchrony during daily parent–child interactions. Lastly, future longitudinal research designs could demonstrate if and how parent–child cross-brain associations change across development and how this might influence the development of emotion regulation patterns and child psychopathology and adjustment outcomes. Extending the Parent–Child Emotion Regulation Dynamics model to include cross-brain associations is necessary to keep up with the rapidly emerging interdisciplinary research bridging neuroscience and child emotion regulation development. By applying the model to one's interest, researchers can gain a greater understanding of the neural mechanisms underlying parent–child interactions and their role in child psychopathology and adjustment outcomes.

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Data Availability N/A.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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References

Abraham, E., Hendler, T., Zagoory-Sharon, O., & Feldman, R. (2016). Network integrity of the parental brain in infancy supports the development of children's social competencies. *Social Cognitive and Affective Neuroscience, 11*(11), 1707–1718. https://doi.org/10.1093/scan/nsw090

Abraham, E., Raz, G., Zagoory-Sharon, O., & Feldman, R. (2018). Empathy networks in the parental brain and their long-term effects on children's stress reactivity and behavior adaptation. *Neuropsychologia, 116*, 75–85. https://doi.org/10.1016/j.neuropsychologia.2017.04.015

Atzil, S., Hendler, T., Zagoory-Sharon, O., Winetraub, Y., & Feldman, R. (2012). Synchrony and specificity in the maternal and the paternal brain: Relations to oxytocin and vasopressin. *Journal of the American Academy of Child & Adolescent Psychiatry, 51*(8), 798–811. https://doi.org/10.1016/j.jaac.2012.06.008

Azhari, A., Leck, W. Q., Gabrieli, G., Bizzego, A., Rigo, P., Setoh, P., ... & Esposito, G. (2019). Parenting stress undermines mother-child brain-to-brain synchrony: A hyperscanning study. *Scientific Reports*, *9*(1), 1-9. https://doi.org/10.1038/s41598-019-47810-4

Backes, E. P., & Bonnie, R. J. (2019). *The promise of adolescence: realizing opportunity for all youth*. National Academies of Sciences.

Barber, J. G., Bolitho, F., & Bertrand, L. (2001). Parent-child synchrony and adolescent adjustment. *Child and Adolescent Social Work Journal, 18*(1), 51–64. https://doi.org/10.1023/A:1026673203176

Bell, M. A. (2020). Mother-child behavioral and physiological synchrony. *Advances in Child Development and Behavior., 58*, 163–188. https://doi.org/10.1016/bs.acdb.2020.01.006

Bernard, K., Meade, E. B., & Dozier, M. (2013). Parental synchrony and nurturance as targets in an attachment based intervention: Building upon Mary Ainsworth's insights about mother-infant interaction. *Attachment & Human Development, 15*, 507–523. https://doi.org/10.1080/14616734.2013.820920

Bhanot, S., Bray, S., McGirr, A., Lee, K., & Kopala-Sibley, D. C. (2021). A narrative review of methodological considerations in magnetic resonance imaging of offspring brain development and the influence of parenting. *Frontiers in Human Neuroscience,*. https://doi.org/10.3389/fnhum.2021.694845

Bilek, E. (2020). *Directed coupling in multi-brain networks underlies generalized synchrony during social exchange*. PsyArXiv. https://doi.org/10.31234/osf.io/njhba

Bilek, E., Ruf, M., Schäfer, A., Akdeniz, C., Calhoun, V. D., Schmahl, C., ... & Meyer-Lindenberg, A. (2015). Information flow between interacting human brains: Identification, validation, and relationship to social expertise. *Proceedings of the National Academy of Sciences*, *112*(16), 5207–5212. https://doi.org/10.1073/pnas.1421831112

Cosgrove, K. T., Kerr, K. L., Ratliff, E. L., Moore, A. J., Misaki, M., DeVille, D. C., Aupperle, R. L., Simmons, W. K., Bodurka, J., & Morris, A. S. (2020). Effects of parent emotion socialization on the neurobiology underlying adolescent emotion processing: A multimethod fMRI study. *Research on Child and Adolescent Psychopathology*. https://doi.org/10.1007/s10802-020-00736-2

Creavy, K. L., Gatzke-Kopp, L. M., Zhang, X., Fishbein, D., & Kiser, L. J. (2020). When you go low, I go high: Negative coordination of physiological synchrony among parents and children. *Developmental Psychobiology, 62*(3), 310–323. https://doi.org/10.1002/dev.21905

Criss, M. M., Shaw, D. S., & Ingoldsby, E. M. (2003). Mother–son positive synchrony in middle childhood: Relation to antisocial behavior. *Social Development, 12*(3), 379–400. https://doi.org/10.1111/1467-9507.00239

Cui, L., Criss, M. M., Ratliff, E., Wu, Z., Houltberg, B. J., Silk, J. S., & Morris, A. S. (2020). Longitudinal links between maternal and peer emotion socialization and adolescent girls' socioemotional adjustment. *Developmental Psychology, 56*(3), 595–607. https://doi.org/10.1037/dev0000861

Davis, M., West, K., Bilms, J., Morelen, D., & Suveg, C. (2018). A systematic review of parent–child synchrony: It is more than skin deep. *Developmental Psychobiology*, *60*(6), 674–691. https://doi.org/10.1002/dev.21743

Dégeilh, F., Bernier, A., Leblanc, É., Daneault, V., & Beauchamp, M. H. (2018). Quality of maternal behaviour during infancy predicts functional connectivity between default mode network and salience network 9 years later. *Developmental Cognitive Neuroscience, 34*, 53–62. https://doi.org/10.1016/j.dcn.2018.06.003

Decety, J., & Lamm, C. (2007). The role of the right temporoparietal junction in social interaction: How low-level computational processes contribute to meta-cognition. *The Neuroscientist, 13*(6), 580–593. https://doi.org/10.1177/1073858407304654

Eisenberg, N., Spinrad, T. L., & Eggum, N. D. (2010). Emotion-related self-regulation and its relation to children's maladjustment. *Annual Review of Clinical Psychology, 6*, 495–525. https://doi.org/10.1146/annurev.clinpsy.121208.131208

Feldman, R., Magori-Cohen, R., Galili, G., Singer, M., & Louzoun, Y. (2011). Mother and infant coordinate heart rhythms through episodes of interaction synchrony. *Infant Behavior and Development, 34*(4), 569–577. https://doi.org/10.1016/j.infbeh.2011.06.008

Feldman, R. (2007). Parent–infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of Child Psychology and Psychiatry,* *48*(3–4), 329–354. https://doi.org/10.1111/j.1469-7610.2006.01701.x

Feldman, R. (2015). The adaptive human parental brain: Implications for children's social development. *Trends in Neurosciences, 38*(6), 387–399. https://doi.org/10.1016/j.tins.2015.04.004

Frye, R. E., Malmberg, B., Swank, P., Smith, K., & Landry, S. (2010). Preterm birth and maternal responsiveness during childhood are associated with brain morphology in adolescence. *Journal of the International Neuropsychological Society, 16*(5), 784–794. https://doi.org/10.1017/S1355617710000585

Gee, D. G., Gabard-Durnam, L. J., Flannery, J., Goff, B., Humphreys, K. L., Telzer, E. H., ... & Tottenham, N. (2013). Early developmental emergence of human amygdala–prefrontal connectivity after maternal deprivation. *Proceedings of the National Academy of Sciences*, *110*(39), 15638–15643. https://doi.org/10.1073/pnas.1307893110

Goelman, G., Dan, R., Stößel, G., Tost, H., Meyer-Lindenberg, A., & Bilek, E. (2019). Bidirectional signal exchanges and their mechanisms during joint attention interaction: A hyperscanning fMRI study. *NeuroImage, 198*, 242–254. https://doi.org/10.1016/j.neuroimage.2019.05.028

Gordon, R. G., Rigon, A., Covington, N. V., Voss, M., & Duff, M. C. (2019). Higher resting state functional connectivity between the vmPFC and rTPJ in individuals who display conversational synchrony. *Journal of Neurolinguistics, 51*, 212–220. https://doi.org/10.1016/j.jneuroling.2019.03.003

Guo, Y., Spieker, S. J., & Borelli, J. L. (2021). Emotion co-regulation among mother-preschooler dyads completing the strange situation: Relations to internalizing and externalizing symptoms. *Journal of Child and Family Studies, 30*(3), 699–710. https://doi.org/10.1007/s10826-020-01812-3

Guyer, A. E., Silk, J. S., & Nelson, E. E. (2016). The neurobiology of the emotional adolescent: From the inside out. *Neuroscience & Biobehavioral Reviews, 70*, 74–85. https://doi.org/10.1016/j.neubiorev.2016.07.037

Harrist, A. W., & Waugh, R. M. (2002). Dyadic synchrony: Its structure and function in children's development. *Developmental Review, 22*(4), 555–592. https://doi.org/10.1016/S0273-2297(02)00500-2

Hoyniak, C. P., Quiñones-Camacho, L. E., Camacho, M. C., Chin, J. H., Williams, E. M., Wakschlag, L. S., & Perlman, S. B. (2021). Adversity is linked with decreased parent-child behavioral and neural synchrony. *Developmental Cognitive Neuroscience, 48*, 100937. https://doi.org/10.1016/j.dcn.2021.100937

Jiang, N., Xu, J., Li, X., Wang, Y., Zhuang, L., & Qin, S. (2021). Negative parenting affects adolescent internalizing symptoms through alterations in amygdala-prefrontal circuitry: A longitudinal twin study. *Biological Psychiatry, 89*(6), 560–569. https://doi.org/10.1016/j.biopsych.2020.08.002

Kehoe, C. E., Havighurst, S. S., & Harley, A. E. (2014). Tuning in to teens: Improving parent emotion socialization to reduce youth internalizing difficulties. *Social Development, 23*, 413–431. https://doi.org/10.1111/sode.12060

Kelly, K. R. (2018). Maternal autonomy support and dyadic verbal synchrony during narrative coconstruction: Links with child attachment representations and independent narrative competence. *Infant and Child Development, 27*(3), e2074. https://doi.org/10.1002/icd.2074

Kerr, K. L., Cosgrove, K. T., Ratliff, E. L., Burrows, K., Moore, A. J., DeVille, D. C., Silk, J. S., Tapert, S. F., Bodurka, J., Simmons, W. K., & Morris, A. S. (2020). TEAMwork: Testing emotional attunement and mutuality during concurrent parent-adolescent fMRI. *Frontiers in Human Neuroscience., 14*, 24. https://doi.org/10.3389/fnhum.2020.00024

Kerr, K. L., Ratliff, E. L., Fuller, S., DeVille, D. C., Cosgrove, K. T., Misaki, M., Morris, A. S., & Bodurka, J. (2020). *Parent-adolescent fMRI hyperscanning and dyadic neurofeedback for influencing brain response* [Poster presentation]. Annual Meeting of the Organization for Human Brain Mapping, Montreal.

Koike, T., Tanabe, H. C., & Sadato, N. (2015). Hyperscanning neuroimaging technique to reveal the "two-in-one" system in social interactions. Neuroscience research, 90, 25-32. https://doi.org/10.1016/j.neures.2014.11.006

Kok, R., Thijssen, S., Bakermans-Kranenburg, M. J., Jaddoe, V. W., Verhulst, F. C., White, T., ... & Tiemeier, H. (2015). Normal variation in early parental sensitivity predicts child structural brain development. *Journal of the American Academy of Child & Adolescent Psychiatry*, *54*(10), 824-831. https://doi.org/10.1016/j.jaac.2015.07.009

Lamm, C., & Singer, T. (2010). The role of anterior insular cortex in social emotions. *Brain Structure and Function, 214*(5–6), 579–591. https://doi.org/10.1007/s00429-010-0251-3

Lee, T. H., Miernicki, M. E., & Telzer, E. H. (2017). Families that fire together smile together: Resting state connectome similarity and daily emotional synchrony in parent-child dyads. *NeuroImage, 152*, 31–37. https://doi.org/10.1016/j.neuroimage.2017.02.078

Lee, K. H., Siegle, G. J., Dahl, R. E., Hooley, J. M., & Silk, J. S. (2015). Neural responses to maternal criticism in healthy youth. *Social Cognitive and Affective Neuroscience, 10*(7), 902–912. https://doi.org/10.1093/scan/nsu133

Leonardi, G., Nomikou, I., Rohlfing, K. J., & Rączaszek-Leonardi, J. (2016). Vocal interactions at the dawn of communication: the emergence of mutuality and complementarity in mother-infant interaction. In *2016 Joint IEEE International Conference on Development and Learning and Epigenetic Robotics (ICDL-EpiRob)* (pp. 288–293). IEEE. https://doi.org/10.1109/DEVLRN.2016.7846835

Levinson, S. C. (2016). Turn-taking in human communication–origins and implications for language processing. *Trends in Cognitive Sciences, 20*(1), 6–14. https://doi.org/10.1016/j.tics.2015.10.010

Lobo, F. M., & Lunkenheimer, E. (2020). Understanding the parent-child coregulation patterns shaping child self-regulation. *Developmental Psychology, 56*(6), 1121. https://doi.org/10.1037/dev0000926

Lougheed, J. P. (2019). Conflict dynamics and the transformation of the parent–adolescent relationship 1. In *Psychosocial Development in Adolescence* (pp. 69–82). Routledge.

Lougheed, J. P., Main, A., & Helm, J. L. (2020). Mother–adolescent emotion dynamics during conflicts: Associations with perspective taking. *Journal of Family Psychology, 34*(5), 566. https://doi.org/10.1037/fam0000632

Lunkenheimer, E. S., Olson, S. L., Hollenstein, T., Sameroff, A. J., & Winter, C. (2011). Dyadic flexibility and positive affect in parent–child coregulation and the development of child behavior problems. *Development and Psychopathology, 23*(2), 577–591. https://doi.org/10.1017/S095457941100006X

Main, A., Paxton, A., & Dale, R. (2016). An exploratory analysis of emotion dynamics between mothers and adolescents during conflict discussions. *Emotion, 16*, 913–928. https://doi.org/10.1037/emo0000180

Markova, G., Nguyen, T., & Hoehl, S. (2019). Neurobehavioral interpersonal synchrony in early development: The role of interactional rhythms. *Frontiers in Psychology, 10*, 2078. https://doi.org/10.3389/fpsyg.2019.02078

Marusak, H. A., Thomason, M. E., Sala-Hamrick, K., Crespo, L., & Rabinak, C. A. (2018). What's parenting got to do with it: Emotional autonomy and brain and behavioral responses to emotional conflict in children and adolescents. *Developmental Science, 21*(4), e12605. https://doi.org/10.1111/desc.12605

Mascaro, J. S., Hackett, P. D., Gouzoules, H., Lori, A., & Rilling, J. K. (2013). Behavioral and genetic correlates of the neural response to infant crying among human fathers. *Social Cognitive and Affective Neuroscience, 9*(11), 1704–1712. https://doi.org/10.1093/scan/nst166

Matsudaira, I., Yokota, S., Hashimoto, T., Takeuchi, H., Asano, K., Asano, M., ... & Kawashima, R. (2016). Parental praise correlates with posterior insular cortex gray matter volume in children and adolescents. *PLoS ONE*, *11*(4), e0154220. https://doi.org/10.1371/journal.pone.0154220

McFarland, D. H., Fortin, A. J., & Polka, L. (2020). Physiological measures of mother–infant interactional synchrony. *Developmental Psychobiology, 62*(1), 50–61. https://doi.org/10.1002/dev.21913

Miller, J. G., Vrtička, P., Cui, X., Shrestha, S., Hosseini, S. H., Baker, J. M., & Reiss, A. L. (2019). Inter-brain synchrony in mother-child dyads during cooperation: An fNIRS hyperscanning study. *Neuropsychologia, 124*, 117–124. https://doi.org/10.1016/j.neuropsychologia.2018.12.021

Misaki, M., Kerr, K. L., Ratliff, E. L., Cosgrove, K. T., Simmons, W. K., Morris, A. S., & Bodurka, J. (2021). Beyond synchrony: The capacity of fMRI hyperscanning for the study of human social interaction. *Social Cognitive and Affective Neuroscience, 16*, 84–92. https://doi.org/10.1093/scan/nsaa143

Montague, P. R., Berns, G. S., Cohen, J. D., McClure, S. M., Pagnoni, G., Dhamala, M., ... & Fisher, R. E. (2002). Hyperscanning: simultaneous fMRI during linked social interactions. *NeuroImage, 16,* 1159-1164. https://doi.org/10.1006/nimg.2002.1150

Morawetz, C., Bode, S., Derntl, B., & Heekeren, H. R. (2017). The effect of strategies, goals and stimulus material on the neural mechanisms of emotion regulation: A meta-analysis of fMRI studies. *Neuroscience & Biobehavioral Reviews, 72*, 111–128. https://doi.org/10.1016/j.neubiorev.2016.11.014

Morris, A. S., Criss, M. M., Silk, J. S., & Houltberg, B. J. (2017). The impact of parenting on emotion regulation during childhood and adolescence. *Child Development Perspectives, 11*(4), 233–238. https://doi.org/10.1111/cdep.12238

Morris, A. S., Cui, L., Criss, M. M., & Simmons, W. K. (2018). Emotion regulation dynamics during parent-child interactions: Implications for research and practice. In P. Cole & T. Hollenstein (Eds.), *Dynamics of emotion regulation: A matter of time* (pp. 88–108). Taylor & Francis.

Morris, A. S., Silk, J. S., Morris, M. D., Steinberg, L., Aucoin, K. J., & Keyes, A. W. (2011). The influence of mother–child emotion regulation strategies on children's expression of anger and sadness. *Developmental Psychology, 47*(1), 213. https://doi.org/10.1037/a0021021

Morris, A. S., Silk, J. S., Steinberg, L., Myers, S. S., & Robinson, L. R. (2007). The role of the family context in the development of emotion regulation. *Social Development, 16*(2), 361–388. https://doi.org/10.1111/j.1467-9507.2007.00389.x

Musser, E. D., Kaiser-Laurent, H., & Ablow, J. C. (2012). The neural correlates of maternal sensitivity: An fMRI study. *Developmental Cognitive Neuroscience, 2*(4), 428–436. https://doi.org/10.1016/j.dcn.2012.04.003

Nguyen, T., Schleihauf, H., Kayhan, E., Matthes, D., Vrtička, P., & Hoehl, S. (2021a). Neural synchrony in mother-child conversation: Exploring the role of conversation patterns. *Social Cognitive and Affective Neuroscience*. https://doi.org/10.1093/scan/nsaa079

Nguyen, T., Schleihauf, H., Kayhan, E., Matthes, D., Vrtička, P., & Hoehl, S. (2020). The effects of interaction quality on neural synchrony during mother-child problem solving. *Cortex, 124*, 235–249. https://doi.org/10.1016/j.cortex.2019.11.020

Nguyen, T., Schleihauf, H., Kungl, M., Kayhan, E., Hoehl, S., & Vrtička, P. (2021b). Interpersonal neural synchrony during father-child problem solving: An fNIRS hyperscanning study. *Child Development, 92*, e565–e580. https://doi.org/10.1111/cdev.13510

Pechtel, P., Murray, L. M., Brumariu, L. E., & Lyons-Ruth, K. (2013). Reactivity, regulation, and reward responses to infant cues among mothers with and without psychopathology: An fMRI review. *Translational Developmental Psychiatry, 1*(1), 19673. https://doi.org/10.3402/tdp.v1i0.19673

Pozzi, E., Simmons, J. G., Bousman, C. A., Vijayakumar, N., Bray, K. O., Dandash, O., & Whittle, S. L. (2020). The influence of maternal parenting style on the neural correlates of emotion processing in children. *Journal of the American Academy of Child & Adolescent Psychiatry, 59*(2), 274–282. https://doi.org/10.1016/j.jaac.2019.01.018

Pozzi, E., Vijayakumar, N., Byrne, M. L., Bray, K. O., Seal, M., Richmond, S., ... & Whittle, S. L. (2021). Maternal parenting behavior and functional connectivity development in children: A longitudinal fMRI study. *Developmental Cognitive Neuroscience*, *48*, 100946. https://doi.org/10.1016/j.dcn.2021.100946

Quiñones-Camacho, L. E., Fishburn, F. A., Camacho, M. C., Hlutkowsky, C. O., Huppert, T. J., Wakschlag, L. S., & Perlman, S. B. (2020). Parent–child neural synchrony: A novel approach to elucidating dyadic correlates of preschool irritability. *Journal of Child Psychology and Psychiatry, 61*(11), 1213–1223. https://doi.org/10.1111/jcpp.13165

Quiñones-Camacho, L. E., Hoyniak, C. P., Wakschlag, L. S., & Perlman, S. B. (2021). Getting in synch: Unpacking the role of parent–child synchrony in the development of internalizing and externalizing behaviors. *Development and Psychopathology,*. https://doi.org/10.1017/S0954579421000468

Ratliff, E.L., Cosgrove, K.T., Kerr, K.L., Deville, D.C., Burrows, K., Moore, A.J., Bodurka, J., Simmons, W.K., & Morris, A.S. (2018, November). *Parental involvement predicts posterior insula hemodynamic activation in response to child's costly error.* Poster presented at the Society for Neuroscience Conference, San Diego, CA

Ratliff, E. L. (2019). *Role of Cross-Brain Connectivity in Emotion Regulation Within the Parent-Adolescent Dyad* (Master's thesis - Oklahoma State University)

Ratliff, E. L., Kerr, K. L., Misaki, M., Cosgrove, K. T., Moore, A. J., DeVille, D. C., ... & Morris, A. S. (2021). Into the unknown: Examining neural representations of parent–adolescent interactions. *Child Development*. https://doi.org/10.1111/cdev.13635

Redcay, E., & Schilbach, L. (2019). Using second-person neuroscience to elucidate the mechanisms of social interaction. *Nature Reviews Neuroscience, 20*(8), 495–505. https://doi.org/10.1038/s41583-019-0179-4

Reindl, V., Gerloff, C., Scharke, W., & Konrad, K. (2018). Brain-to-brain synchrony in parent-child dyads and the relationship with emotion regulation revealed by fNIRS-based hyperscanning. *NeuroImage, 178*, 493–502. https://doi.org/10.1016/j.neuroimage.2018.05.060

Romund, L., Raufelder, D., Flemming, E., Lorenz, R. C., Pelz, P., Gleich, T., Heinz, A., & Beck, A. (2016). Maternal parenting behavior and emotion processing in adolescents: An fMRI study. *Biological Psychology, 120*, 120–125. https://doi.org/10.1016/j.biopsycho.2016.09.003

Rothbart, M. K., Sheese, B. E., Rueda, M. R., & Posner, M. I. (2011). Developing mechanisms of self-regulation in early life. *Emotion Review, 3*(2), 207–213. https://doi.org/10.1177/1754073910387943

Rutherford, H. J., Wallace, N. S., Laurent, H. K., & Mayes, L. C. (2015). Emotion regulation in parenthood. *Developmental Review, 36*, 1–14. https://doi.org/10.1016/j.dr.2014.12.008

Sheeber, L. B., Davis, B., Hops, H., and Leve, C. (2005). *Mother and father socialization of adolescent emotion regulation: Influence on depressive symptomatology*. Paper presented at The Biennial Meeting of the Society for Research in Child Development, Atlanta, GA

Silk, J. S., Steinberg, L., & Morris, A. S. (2003). Adolescents' emotion regulation in daily life: Links to depressive symptoms and problem behavior. *Child Development, 74*(6), 1869–1880. https://doi.org/10.1046/j.1467-8624.2003.00643.x

Somers, J. A., Luecken, L. J., McNeish, D., Lemery-Chalfant, K., & Spinrad, T. L. (2021). Second-by-second infant and mother emotion regulation and coregulation processes. *Development and Psychopathology,*. https://doi.org/10.1017/S0954579421000389

Suveg, C., Shaffer, A., & Davis, M. (2016). Family stress moderates relations between physiological and behavioral synchrony and child self-regulation in mother–preschooler dyads. *Developmental Psychobiology, 58*(1), 83–97. https://doi.org/10.1002/dev.21358

Swain, J. E., Konrath, S., Brown, S. L., Finegood, E. D., Akce, L. B., Dayton, C. J., & Ho, S. S. (2012). Parenting and beyond: Common neurocircuits underlying parental and altruistic caregiving. *Parenting, 12*(2–3), 115–123. https://doi.org/10.1080/15295192.2012.680409

Swain, J. E. (2011). The human parental brain: In vivo neuroimaging. *Progress in Neuro-Psychopharmacology and Biological Psychiatry, 35*(5), 1242–1254. https://doi.org/10.1016/j.pnpbp.2010.10.017

Tan, P. Z., Oppenheimer, C. W., Ladouceur, C. D., Butterfield, R. D., & Silk, J. S. (2020). A review of associations between parental emotion socialization behaviors and the neural substrates of emotional reactivity and regulation in youth. *Developmental Psychology, 56*(3), 516. https://doi.org/10.1037/dev0000893

Tortella-Feliu, M., Balle, M., & Sesé, A. (2010). Relationships between negative affectivity, emotion regulation, anxiety, and depressive symptoms in adolescents as examined through structural equation modeling. *Journal of Anxiety Disorders, 24*(7), 686–693. https://doi.org/10.1016/j.janxdis.2010.04.012

Valencia, A. L., & Froese, T. (2020). What binds us? Inter-brain neural synchronization and its implications for theories of human consciousness. *Neuroscience of Consciousness*, Doi: https://doi.org/10.1093/nc/niaa010

Whittle, S., Dennison, M., Vijayakumar, N., Simmons, J. G., Yücel, M., Lubman, D. I., ... & Allen, N. B. (2013). Childhood maltreatment and psychopathology affect brain development during adolescence. *Journal of the American Academy of Child & Adolescent Psychiatry*, *52*(9), 940–952. https://doi.org/10.1016/j.jaac.2013.06.007

Whittle, S., Simmons, J. G., Dennison, M., Vijayakumar, N., Schwartz, O., Yap, M. B., Sheeber, L., & Allen, N. B. (2014). Positive parenting predicts the development of adolescent brain structure: A longitudinal study. *Developmental Cognitive Neuroscience, 8*, 7–17. https://doi.org/10.1016/j.dcn.2013.10.006

Yap, M. B., Allen, N. B., & Ladouceur, C. D. (2008). Maternal socialization of positive affect: The impact of invalidation on adolescent emotion regulation and depressive symptomatology. *Child Development, 79*(5), 1415–1431. https://doi.org/10.1111/j.1467-8624.2008.01196.x

Zeman, J., Shipman, K., & Suveg, C. (2002). Anger and sadness regulation: Predictions to internalizing and externalizing symptoms in children. *Journal of Clinical Child and Adolescent Psychology, 31*(3), 393–398. https://doi.org/10.1207/S15374424JCCP3103_11