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Nur Atiqah Azhari

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**BRAIN MECHANISMS OF PARENTING IN CO-PARENTING SPOUSES
AND PARENT-CHILD DYADS**

**NUR ATIQA BINTE AZHARI
SCHOOL OF SOCIAL SCIENCES**

2021

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AND PARENT-CHILD DYADS**

NUR ATIQA BINTI AZHARI

SCHOOL OF SOCIAL SCIENCES

A thesis submitted to the Nanyang Technological University in partial fulfilment of
the requirement for the degree of Doctor of Philosophy

2021

Statement of Originality

I certify that all work submitted for this thesis is my original work. I declare that no other person's work has been used without due acknowledgement. Except where it is clearly stated that I have used some of this material elsewhere, this work has not been presented by me for assessment in any other institution or University. I certify that the data collected for this project are authentic and the investigations were conducted in accordance with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Gianluca Esposito

Authorship Attribution Statement

This thesis contains material from **4 papers** published in the following peer-reviewed journal(s) / from papers accepted at conferences in which I am listed as an author.

Chapter 3 is published as **Azhari, A.**, Lim, M.Y., Bizzego, A., Gabrieli, G., Bornstein, M.H. and Esposito, G. (2020). Physical presence of spouse enhances brain-to-brain synchrony in co-parenting couples. *Scientific Reports* **10**, 7569.
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The contributions of the co-authors are as follows:

- I designed the study and directed the research team
- I conducted participant recruitment and collected fNIRS data together with Lim Mengyu
- I preprocessed all fNIRS data together with Lim Mengyu
- Andrea Bizzego and Giulio Gabrieli assisted with statistical analyses
- Prof. Marc Bornstein assisted in the interpretation of preliminary data
- I wrote the paper together with Lim Mengyu
- Prof. Gianluca Esposito and Prof. Marc Bornstein provided feedback and edited the manuscript

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The contributions of the co-authors are as follows:

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- I wrote the paper together with Leck Wan Qing
- Prof. Marc Bornstein assisted in the interpretation of preliminary data
- Prof. Peipei Setoh, Prof. Gianluca Esposito and Prof. Marc Bornstein provided feedback on the manuscript and made revisions to the paper

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- I preprocessed all fNIRS data
- I performed statistical analyses together with Giulio Gabrieli
- Andrea Bizzego conducted synchrony analyses using cross-correlations
- I wrote the manuscript
- Prof. Gianluca Esposito and Prof. Marc Bornstein provided feedback on the manuscript and made revisions to the paper

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- I performed all fNIRS preprocessing of the mother-child sample

- Justin Durnford, Jan Paolo Balagtas and I preprocessed the fNIRS data from the father-child sample
- Prof. Gianluca Esposito provided direction for the analyses of data
- Andrea Bizzego and Giulio Gabrieli assisted with statistical analyses
- Justin Durnford, Jan Paolo Balagtas and I wrote the draft of the manuscript
- Lim Mengyu assisted with editing of the manuscript
- Prof. Gianluca Esposito provided feedback on the manuscript

04/01/2021

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Nur Atiqah binte Azhari

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SUMMARY

Parenting is an integral part of human society that involves cooperation between co-parenting spouses (i.e., mother-father dyads) and bonding within parent-child dyads. Continuous exposure to a dyadic partners' behavioural repertoire in daily life will lead to rhythmic patterns of interactions that are postulated to be supported by temporally similar underlying brain signals commonly referred to as inter-brain synchrony. Within the parenting context, mother-father dyads and parent-child dyads are two attachment pairs in which inter-brain synchrony is expected to be observed. Despite the ubiquity of bi-parental rearing in humans, studies on inter-brain synchrony in mother-father dyads are scarce. Studies on parent-child dyads have yet to investigate the effects of child, parental and stimuli characteristics on a child's processing of narrative scenes during everyday joint activities like co-viewing children's movies together. Moreover, the effects of maternal psychological factors on inter-brain synchrony have been minimally investigated. This thesis comprises four functional near-infrared spectroscopy (fNIRS) studies that have examined prefrontal cortex (PFC) brain mechanisms in dyadic parenting contexts.

Study 1 investigated inter-brain synchrony in 24 mother-father dyads (N=48) who rear their infant together. In the everyday context, spouses are continually exposed to each other's physical presence and to salient infant and adult vocalisations (e.g., cry, laughter). To test the hypothesis that inter-brain synchrony would be enhanced when spouses are in each other's physical presence, each couple was presented with salient vocalisations in two conditions: together (in the same room, at the same time) and separately (in different rooms, at different times). Findings showed that co-parenting spouses displayed significantly greater synchrony when together, and that this result was observed in true couples but not in control couples. Spouses also showed greater synchrony

towards positive and neutral vocalisations, but not negative ones. These results imply that the physical presence of a spouse facilitates inter-brain synchrony in attentional brain regions, and that synchrony might be adaptive in favourable situations (i.e., exposure to laughter) but not under stressful conditions (i.e., exposure to cry).

Study 2 transitioned to parent-child dyads and investigated inter-brain synchrony in mother-child pairs during a co-viewing paradigm. 31 mother-child dyads ($N = 62$) participated in this study, which investigated the effects of maternal parenting stress and maternal anxious attachment, on inter-brain synchrony during co-viewing of three 1-minute animation scenes. To test the hypothesis that greater parenting stress would be associated with reduced synchrony, mothers' self-reported parenting stress was measured with a Parenting Stress Index (PSI) questionnaire. Findings supported this prediction as higher parenting stress was correlated with less synchrony in the medial left PFC cluster which is implicated in mentalisation processes and social cognition. This result implies that parenting stress undermines shared inter-subjective experiences between mother and child during co-viewing.

Study 2 also investigated the effects of maternal attachment-related anxiety, measured using the Attachment Style Questionnaire (ASQ), on dyadic inter-brain synchrony and maternal brain responses during co-viewing of three 1-minute animation scenes. Since anxiously-attached mothers tend to be preoccupied with their child's social cues, dyads with more anxiously-attached mothers were hypothesised to display reduced inter-brain synchrony during the co-viewing activity. Results showed that greater maternal attachment anxiety was associated with less inter-brain synchrony in the medial right cluster of the PFC which is critical for mentalisation. This finding suggests that there potentially exists a difference in the intersubjective experiences shared between a mother with anxious-related attachment and her child during everyday co-viewing

activities. The implication borne out of the findings of Study 2 is that maternal psychological variables, namely parenting stress and attachment anxiety, could undermine the quality of shared experiences when dyads engage in passive bonding activities together.

Finally, Study 3 measured children's and parental brain processing when co-viewing narrative scenes. 62 children of preschool-age (37 boys, 25 girls) and their parents (29 fathers, 33 mothers) participated in a co-viewing activity ($N = 124$) which screened three 1-minute video excerpts of children's movies of positive, neutral and negative emotional valences. Results showed that children displayed greater PFC activity when co-viewing with fathers than with mothers. Girls were also found to exhibit heightened PFC responses than boys towards the positive video stimulus. Analyses of mothers' and fathers' prefrontal responses revealed that parents from same-gendered dyads (i.e., mother-daughter, father-son) showed greater brain activation than parents from opposite-gendered dyads (i.e., mother-son, father-daughter) when watching a scene where the gender of the characters was salient. These findings suggest that social and stimuli factors in the environment influence parents' and children's processing of narrative scenes when co-viewing.

CHAPTER 1

INTRODUCTION

The Construct of Synchrony

A cadence of reciprocal behavioural exchanges typically characterise the interactions of dyadic partners nestled in an affiliative bond, such as that of a parent-child or spousal relationship (Feldman, 2012). Affiliated partners become familiarised with each other's behavioural repertoire and the configured patterns of their interactions are internalised into unique interactional rhythms over time (Beebe & Lachmann, 1988; Fogel et al., 1992; Stern, 2009; Trevarthen, 2011; Tronick & Cohn, 1989). These finely tuned temporally coordinated interactions between partners are known as synchrony and comprise micro-level signals that the two individuals sensitively perceive and respond to (Delaherche et al., 2012). Synchronous interactions indicate that dyadic partners are mutually attuned to each other's emotional states (Tourunen et al., 2019). Consequently, synchrony has been posited to be a central vehicle for the formation of selective bonds and attachments (Feldman, 2012).

The most fundamental of human attachments take root in the earliest stages of infancy, when affinity between an infant and a caregiver is fostered. In a parent-child relationship, synchrony manifests as reciprocal gazes, facial expressions, vocal qualities and bidirectional turn-taking behaviours (Feldman, 2007a; Feldman, 2012). For instance, in a face-to-face interaction between healthy mothers and their infants, the smile of the infant often elicits a corresponding smile from the mother. Synchrony is a primary predictor of greater empathy (Feldman, 2007b), attachment security (Lundy, 2002, 2003), bilateral compliance (Lindsey et al., 1997), and more developed symbolic play and internal speech (Feldman & Greenbaum, 1997). Throughout

development, the synchronous relationship in other aspects of our lives such as spousal relationships, are postulated to be modelled after the synchronous experiences we accrue from early childhood (Feldman, 2012). Indeed, synchrony in co-parenting spouses is equally important for optimal parenting (Atzil et al., 2012; Geary, 2000). Reciprocal and attuned interactions in couples have been found to enhance connectedness between partners (Thorson & West, 2018; Tourunen et al., 2019), which establishes emotional stability (Butler & Randall, 2013) and facilitates the task undertaking of co-parenting an infant together (Kinreich et al., 2017).

Regardless of the relationship in which synchrony occurs, a common finding is that synchronous behaviours are buttressed by matched underlying biological responses in the physiological domains of autonomic reactivity, hormonal fluctuations and brain activation patterns (Feldman, 2012a). These findings suggest that partners of an affiliative relationship are entrained to one another's physiological responses which enables co-regulation. For instance, mother-child synchrony in which the child exhibits calming behaviours (e.g., ceases fussing) to match the soothing responses of the mother may serve as a means to entrain physiological responses that are adaptive in stressful situations (Bazhenova et al., 2001). In a study on adult relationships, Coutinho et al. (2019) demonstrated that matched gaze patterns in couples were accompanied by harmonised shifts in electrodermal activity. As such, synchrony is conceptualised to involve biobehavioural reorganisations that align partners' signals to each other at both the behavioural and physiological levels.

Due to the plasticity of children's fledgling brain, and the flexible modifications of the parental brain in response to child-related stimuli (Atzil et al., 2011; Dapretto, 2006; Decety, 2011; Iacoboni & Strathairn, 2011), research into the neurobiology of parenting is expeditiously gaining traction (Alonzo, 2010; Corona & Lévy, 2015; Lukas & Clutton-Brock, 2013; Olazábal et al.,

2013; Pigliucci, 2005; Westneat et al., 2011). Feldman (2012) has earlier posited that the biological synchrony which surfaces along with interactive synchrony is likely to modulate reward and regulatory modules in the brain. As an offshoot of this postulation, researchers have begun to investigate synchrony between the brain signals of dyadic partners. Inter-brain synchronisation is a subdomain of physiological synchrony, intersecting at the boundaries of neuroscience and social psychology, that investigates the coordination of brain signals (Wass et al., 2020). Advances in neuroimaging have given rise to the hyperscanning technique, from which brain signals of two or more people could be recorded at the same time (Czeszumski et al., 2020). While, in the past, social neuroscience was largely limited to a “single-brain” paradigm which investigated the brain in a social vacuum, hyperscanning has shifted the field to a “two-brains” approach where inter-brain synchronisation is studied along with reciprocal interpersonal interactions in naturalistic settings. For example, brain synchrony has been found to occur between two conversing adults (Dai et al., 2018; Giraud & Poeppel, 2012; Luo & Poeppel, 2012; Zion Golumbic et al., 2013), and has been shown to be facilitated by physical touch (Goldstein et al., 2018) while active and imitative gesticulation also enhances inter-brain synchronisation (Dumas et al., 2010; Schippers et al., 2010). The present thesis narrows the scope of inter-brain synchronisation to dyads within the parenting context, namely in co-parenting spousal partners and in parent-child dyads.

The Parenting Brain

Copious findings have emerged from research on the human parenting brain. Majority of studies focused on the maternal brain (Atzil et al., 2011, 2014; Barrett et al., 2012; Bartels & Zeki, 2004; Ho et al., 2014; Kim et al., 2010; Kim et al., 2014; Landi et al., 2011; Laurent & Ablow, 2012; Leibenluft et al., 2004; Noriuchi et al., 2008; Strathearn et al., 2009; Swain et al., 2011), while some have investigated the paternal brain (Abraham et al., 2014; Atzil et al., 2012; Kim et

al., 2014; Kuo et al., 2012; Mascaro, Hackett, & Rilling, 2014). Most of the existing studies have employed a “single-brain” paradigm where a parent’s brain response is recorded upon his/her exposure to child-related cues such as infant cry and laughter. These efforts have been crucial to the mapping of a caregiving network in the brain that spans across several associated modules which underscores parental care (Feldman, 2015a). Parental care of an offspring is an evolutionary trait that is largely conserved across all mammalian species. The parenting brain in humans comprises a subcortical-limbic network (Navratilova & Porreca, 2014) that is connected to cortical regions responsible for emotional regulation, empathy and mentalisation processes (Bernhardt & Singer, 2012; Bethlehem et al., 2013; Kanat et al., 2014; Meyer-Lindenberg et al., 2011). The interconnection of these two broad circuitries allows for the more recently evolved empathy-related cortical networks to interact with the automatic and highly conserved subcortical structures that drive parenting behaviours. As a result of this integration, human parents are capable of complex parenting attributes such as deciphering a child’s needs from non-verbal cues. This ability is facilitated by mentalisation processes in the ventromedial prefrontal cortex (vmPFC) and other cortical regions like the superior temporal gyrus and temporal parietal junction (Kanat et al., 2014; Yang et al., 2015). Due to our well-developed prefrontal cortex (PFC), human parents could also tap upon executive functioning structures such as the dorsolateral prefrontal cortex (dlPFC), medial orbitofrontal cortex (mOFC), and middle frontal gyrus (MFG) to self-regulate and inhibit emotional responses, so as to select optimal caregiving actions (Menon, 2011). The integral contributions of the cortical region, and the PFC in particular, to the formation of the “social brain” (Keysers & Gazzola, 2007), serves as a pretext upon which to herein direct our focus to the PFC when adopting a “two-brains” paradigm in parent-child and co-parenting research.

Infant cry perception remains one of the most well established topics in parenting literature and therefore provides a convenient avenue to study the parenting brain (Bos et al., 2010; Kim et al., 2011; Laurent & Ablow, 2012; Mascaro et al., 2014; Riem et al., 2011; Swain et al., 2011). In a review of the extant neuroimaging literature available on infant cry perception, Rilling (2013) surmised that five circuitries are recruited. While the first three circuits - the auditory cortex, thalamo-cingulate pathway and midbrain-dopaminergic pathway - process auditory information and automate parental approach behaviours, the fourth and fifth circuits - the fronto-insular cortical pathway and the dorsomedial PFC (dmPFC) respectively - specialise in emotional empathy, mentalisation and perspective-taking (Rilling, 2013; Swain et al., 2014; Witteman et al., 2019). Based on this model, the PFC region of the “social brain” oversees processes which characterise conscious social parenting in humans. For instance, the dmPFC analyses the salience of perceived infant cues (Lima et al., 2016; Schurz et al., 2014), whereas the inferior frontal gyrus (IFG), part of the fronto-insular cortical pathway, supports mentalisation and affective evaluation (Hartwigsen et al., 2019). These multiple circuits that subserve parenting in humans evince the evolutionary malleability of the parental brain in adapting to the social demands of caregiving (Feldman, 2015a). Thus, the plasticity of the parental brain is pivotal in supporting inter-brain synchronisation between parent and child, and between co-parenting partners (Feldman, 2015b).

Inter-brain Synchronisation of Co-parenting Dyads

While the parenting landscape in humans has seen the rise of co-parenting arrangements in recent years, paternal care remains a facultative function in the 3-5 % of mammals who do partake in active caregiving (Geary, 2000). For the bi-parental human species, disseminating caregiving duties across two parents poses a challenge that requires flexibility in the social brain so as to adapt to the changing demands of parenting (Han et al., 2013). Despite our knowledge of the plasticity

of the parental brain (Atzil et al., 2011; Decety, 2011; Iacoboni & Dapretto, 2006; Strathearn, 2011), inter-brain synchronisation mechanisms between partners that coordinate co-parenting behaviours still elude us.

In Singapore, co-parenting spousal partners tend to be romantic couples who cohabit the same living space and jointly raise their children together. Such consistent daily interactions present bountiful opportunities for partners to establish behavioural reciprocity and entrain their physiological rhythms to each other (Sbarra & Hazan, 2008). Recently, Coutinho and colleagues (2019) demonstrated that couples synchronise their gaze patterns with corresponding changes observed in their electrodermal activity. Other physiological markers, including cortisol fluctuation levels (Liu et al., 2013), respiratory sinus arrhythmia (Helm et al., 2014) and brain signals (Anders et al., 2011; Hasson et al., 2004; Kinreich et al., 2017) have also been reported to be coordinated between partners. In one study, Anders et al. (2011) investigated the neural activity of heterogeneous couples' communication by having male participants perceive the emotional state displayed by their female complement. They found that the brain activity of the sender could accurately determine the neural activity of the perceiver, although these results could not be replicated in male-female pairs who were not romantic partners. These results point to the existence of inter-brain coupling in partners which are uniquely synchronised to each other's emotional experiences. In another neuroimaging study on couples, Kinreich et al. (2017) employed an EEG hyperscanning technique to measure inter-brain synchronisation of male-female couples during naturalistic interaction. They found that synchrony was linked to moments when partners gazed at each other and when positive affect was shared, whereas for strangers, synchrony was pegged to the length of duration of shared gaze. Kinreich and colleagues (2017) subsequently

posited that the human attachment between two persons, such as that shared between partners, may influence inter-brain synchrony.

Couples who are attuned to one another's emotional experiences have been found to respond to their partner's needs more optimally (Thorson & West, 2018). In co-parenting partners who jointly navigate the difficulties of rearing an infant, synchrony might be particularly important to elicit coordinated bi-parental responses. However, only one study has insofar investigated the occurrence of synchrony in co-parenting couples. Atzil et al. (2012) first recorded naturalistic videos of 4-6 month old infants during play, before presenting own and standard-infant clips to mothers and fathers in a functional magnetic resonance (fMRI) scanner. When the team examined the online coordination of brain responses in the mother-father co-parenting couple, they discovered that synchrony emerged in empathic and social cognitive regions of the brain of which the PFC was largely implicated in. Their finding once again reinforces the theory that human attachment plays a role in modulating synchrony, and that this principle is applicable to co-parenting partners.

Inter-brain Synchronisation of Parent-Child Dyads

Before the dawn of the “two-brains” paradigm, synchrony in parent-child dyads has long been observed and established on the behavioural front (Leclère et al., 2014). Described as a reciprocal interactive process between dyadic partners, behavioural synchrony encompasses mutual engagement, turn-taking behaviours and sharing of emotional states (Ambrose & Menna, 2013). The pattern of synchrony displayed by a dyad anchors upon the responsiveness and sensitivity of both the parent and child (Guedeney et al., 2014; Longhi, 2009; Thompson & Trevathan, 2009). Synchrony requires each partner to desire social engagement and have the

capacity to attune to the other's subjective emotional experiences (Crown et al., 2002; Stormark & Braarud, 2004). From the point of parturition (Hart, 2010), parents and infants are endowed with the ability to engage in reciprocal interactions across several modalities, some of which are vocalised (i.e., cries, babbles, coos) while others are non-verbal (i.e., gazes, facial expressions, smiles, matched movements) (Delaherche et al., 2012; Messinger et al., 2009; Van Puyvelde et al., 2010). Synchrony forms so robust a component of the developing parent-child bond that infants have the capacity to convey and reciprocate intent at the tender age of 2 months (Tronick et al., 1977) and display synchronous exchanges in face-to-face interactions at 3 months of age (Feldman, 2007a). These behavioural manifestations of synchrony are thought to be supported by the entrainment of biological rhythms within the dyad which occurs at the levels of hormones, autonomic, and brain systems (Feldman, 2007a, 2012b; Novembre et al., 2017). Given the biologically ingrained processes of parent-child bond maturation in infancy, it is unsurprising that biobehavioral synchrony can be traced to neural correlates (Penman et al., 1983). Synchrony that surfaces at both the behavioural and neural levels may enhance bonding, making inter-brain synchrony a potential marker in the development of parent-child affiliations (Hove & Risen, 2009; Hu et al., 2017).

Both the parental and infant brains bear great plasticity which allows the two brains to couple to each other's reciprocal inputs (Feldman, 2012a, 2012c, 2015a). Konvalinka & Roepstorff (2012) proposed that such brain-to-brain coordination within the dyadic unit is precipitated by mutual and continuous behavioural adaptations between partners. While some of these adaptations may be nonconscious and automatic, inter-brain coupling may also be regulated by interpersonal top-down socio-cognitive processes (Konvalinka & Roepstorff, 2012). For instance, Piazza et al. (2020) revealed that inter-brain synchrony between a 9 to 15-month-old infant and an adult who

is a stranger was higher when engaging in shared compared to separate activities. The authors found that infant brain activity predicted the adult's brain activity across a span of 3s in both conditions. In another study, Nguyen et al. (2020a) recruited 5-year-old children and their parents who then attempted a Tangram puzzle task either together or individually. The researchers discovered that greater behavioural synchrony during the cooperation condition predicted enhanced neural synchrony in the right frontal and temporoparietal regions of the brain. To account for the relevance of pairing the child to the parent in eliciting synchrony during the cooperative task, Reindl et al. (2018) matched 5 to 9-year-old children to either their parents or to an adult stranger, while the pair engaged in a cooperative or competitive computer task. The study demonstrated greater synchrony in the left prefrontal and frontopolar regions only between parent-child dyads in the cooperative condition. These findings reinforce the notion of inter-brain synchrony in parent-child dyads that emerge along with the engagement of similar socio-cognitive processes and the display of synchronous behaviours (Miller et al., 2019; Pan et al., 2017).

Overview of Research Gaps

In the case of co-parenting dyads, a stark research gap on real-time inter-brain synchronisation between co-parents. Since only Atzil et al. (2012) has conducted inter-brain research on co-parents, we draw upon studies that examined other physiological parameters of synchronisation (e.g., cortisol) to extrapolate possible factors that might affect inter-brain synchrony in co-parenting spouses. In one study, Saxbe & Repetti (2010) found that the physical presence of a spouse affects hormonal synchronisation, alluding to the possible effects of physical presence on synchronisation in the brain too. Moreover, synchronisation was not necessarily beneficial as it emerged during stressful and conflict situations for some couples, which surfaces

emotional valence as another factor that could possibly affect synchrony and render it as either positive or negative.

Although inter-brain synchrony has been investigated in the parent-child context, little is known regarding the factors that influence the extent of synchronisation. Thus far, majority of past studies employed active joint tasks, comparing them to individually-performed tasks, which subsequently uncovered that cooperative and synchronous behaviours tend to be accompanied by enhanced inter-brain synchrony in parent-child dyads (Miller et al., 2019; Pan et al., 2017; Reindl et al., 2018). Despite the burgeoning literature on this topic, no study has investigated inter-brain synchrony in passive joint tasks, like co-viewing of television, although such bonding activities are prevalent in today's digital age. Moreover, prior to the publication of the chapters in this thesis, the effects of parental factors on inter-brain synchrony have yet to be investigated. For instance, it remains to be seen whether parental factors like parenting stress experienced by the mother, and the attachment style of the mother, bear any relevance to the extent of inter-brain synchrony displayed by mother-child dyads.

Research Scope and Objective

With mounting evidence of inter-brain synchronisation in human attachment pairs, the present thesis aims to investigate its occurrence within the parenting context. Delimiting the inquiry to the parenting context narrows the scope of research to two main dyadic relationships: co-parenting partners and parent-child pairs. Thus far, we have ascertained that the flexibility of the parental and the developing brains provide fertile ground for entrainment of brain signals.

In co-parenting partners, joint rearing of a child in close proximity to each other provides opportunities for synchronised behavioural and physiological patterns in co-parents. As the

transition to caregiving in early infancy is a time that necessitates utmost coordination of effort in co-parenting partners, Study 1 (Chapter 3) investigates synchrony in mother-father couples of young infants. Two main factors, namely the physical presence (or absence) of a co-parenting spouse and the emotional valence of salient human vocalisations such as infant and adult cries and laughter, would be analysed to determine whether these factors affect inter-brain synchrony in co-parenting couples.

In parent-child dyads, the forging of the most fundamental of human attachments necessitates the advent of synchrony on multiple biological and behavioural fronts from the moment of birth. Entrainment occurs over time as the child develops his/her capacity to understand and convey intent. Inter-brain synchronisation would therefore be optimally investigated within a developmental window which has allowed for sufficient mentalisation faculties in the child to mature whilst the parent and child accumulate adequate experience in interacting with each other. Therefore, the scope of research on parent-child dyads in this thesis would be limited to preschool-aged children and their parents (Richardson et al., 2018).

The prevailing studies on parent-child inter-brain synchrony have been mostly conducted on active dyadic interaction, despite the prevalence of passive dyadic activities in parent-child dyads. For instance, in a large study which surveyed co-viewing of television across four countries, Craig and Mullan (2012) revealed that passive co-viewing is a ubiquitous shared activity in parent-child dyads, while another study by Jago et al. (2013) found that 75% of preschoolers and their parents co-viewed the television for at least two hours on a daily basis. Given the pervasiveness of co-viewing as a common bonding activity in parent-child dyads, the lack of research on inter-brain synchrony in passive dyadic contexts represents a crucial research gap, that, if addressed, would provide important insights into the role of passive bonding activities and inter-brain synchrony in

child-caregiver relationships. Hence, Study 2 (Chapter 4) would investigate parent-child synchrony during co-viewing of the television together, and would examine the effects of psychological variables, namely maternal parenting stress and maternal attachment style, on inter-brain synchrony within a co-viewing paradigm. After investigating dyadic synchronisation during co-viewing, Study 3 (Chapter 5) would further examine the social and stimuli factors that influence children's processing of narrative movie scenes when co-viewing with their mother or father.

fNIRS hyperscanning, in which the signals of two brains are recorded simultaneously, would be employed in Studies 1 and 2 to examine inter-brain synchrony whereas single scanning fNIRS, focusing on child and parental brains separately, would be employed in Study 3 of this thesis. Investigation of inter-brain synchrony and individual brain processing would be delimited to the PFC due to its integral role in attentional regulation, social cognition, and conscious parenting behaviours (Ferstl et al., 2005; Lin et al., 2015; Rossi et al., 2009; Schirmer et al., 2004). Demarcating the region of inquiry to the PFC would also direct this thesis towards the most recently evolved, thus most adaptive, part of the "social brain" which is likely implicated in inter-brain synchronisation.

CHAPTER 2

LITERATURE REVIEW

Mechanisms and Method of Inter-brain Synchronisation

Environmentally-Induced Coupling

Traditional social neuroscience was mired in an isolationist paradigm that investigated the effects of stimuli on the individual brain (Becchio et al., 2010). This egocentric model funneled our focus into investigating brains singly, which limited our understanding of how much of the world is processed similarly to form a conscious unified experience in people. Intrigued by the prospect that the brains of two individuals who are exposed to the same environmental stimuli might be activated in unison, Hasson et al. (2004) embarked on a seminal study which ultimately led to the discovery that inter-brain coupling occurred during naturalistic viewing of movie scenes. The brain regions which exhibited synchronous responses extended well beyond visual and auditory modules typically responsible for sensory processing, and into higher-order cortical regions (i.e., superior temporal sulcus, lateral sulcus, cingulate cortex). Aside from similar sensory processing of the movie due to its audiovisual properties, the fact that synchrony was observed in other brain areas drove Hasson and colleagues (2004) to conclude that the compelling narrative of the movie served as an external environmental input which elicited exceptionally similar inter-subject coherence across individuals. This finding was later replicated in several other studies which adopted comparable paradigms of either exposing participants to movie scenes or storytelling audios, further verifying the phenomenon of environmentally-induced inter-brain

synchronisation (Golland et al., 2007; Hanson et al., 2009; Hasson et al., 2004, 2008; Jääskeläinen et al., 2008; Wilson et al., 2008).

Nearly a decade later, Hasson et al. (2012) offered a possible mechanism by which inter-brain synchrony may be achieved, outlining a key distinction between stimulus-to-brain and brain-to-brain coupling. The former relies on the different manifestations of energy (e.g., mechanical, chemical) that objects in our environment discharge, which serve as stimuli that our receptors transform into neural signals. Stimulus-to-brain coupling occurs as we adjust our sensory organs (e.g., moving our eyes to sample different areas of the screen when viewing movies) to actively fetch and process information from the environment (Schroeder et al., 2010). Brain-to-brain coupling, or inter-brain synchrony, fundamentally differs from stimulus-to-brain coupling in that the signal we receive now also originates from another human or sentient life form (e.g., pets) capable of perceiving and feeling instead of objects in the environment (Nagasawa et al., 2009). Hasson et al. (2012) posited that brain-to-brain signaling is the coupling of two brains due to input from the shared physical environment, which includes (1) the stimuli and (2) the other individual. For example, when a mother and child co-view the television together, the shared physical environment consists of the television stimuli and the social partner. Even without any active social engagement, both the mother and child are aware that the partner is watching the same television show, and is experiencing the same emotion from the narrative scenes, which trigger vicarious brain activations that enable brain-to-brain coordination (Keysers & Gazzola, 2009). Essentially, the authors portrayed inter-brain coupling akin to that of a wireless transmission, where two systems communicate through a commonly shared signal that is present in the environment.

Although coherence occurred in widespread cortical brain regions, Hasson et al. (2004) reported in their seminal paper that prefrontal areas did not consistently show inter-brain

synchronisation. This observation reflects the unique variation in individual experiences which are potentially seated in the prefrontal cortex. A resounding shift from a “one-brain” to “two-brains” neuroscience approach ensued, driven by the proposition that inter-brain coupling which occurs during social interactions inherently exhibits unique interpersonal variations (Schilbach et al., 2013).

Mutual Social Attention System

Inter-brain synchronisation is posited to be an essential mechanism that expedites the conveyance of communicative signals between dyadic partners (Dumas et al., 2012; Goldstein et al., 2017, 2018; Hasson et al., 2012; Schippers et al., 2010). Corroborating with the seminal findings of Hasson et al. (2004), recent studies have uncovered that variation in inter-brain synchronisation between two partners is modulated by several general factors, namely the i) type of activity, ii) setting in which the interacting partners are in and iii) nature of the relationship between the individuals. Gvirts and Perlmutter (2020) subsequently postulated that the influence of these factors on the prefrontal cortex point to the role of the mutual attention system in regulating inter-brain synchronisation.

First, comparing between joint and individual activities, inter-brain synchronisation has been found to be more pronounced when dyadic partners engage in joint interactions. For instance, participants who engaged in cooperative tasks exhibited greater synchronisation compared to those who performed tasks in parallel (Liu et al., 2016) or who engaged in competitive tasks (Lu & Hao, 2019; Reindl et al., 2018). Enhanced inter-brain synchronisation during joint active interaction was primarily observed in the prefrontal cortex. For example, Liu et al. (2016) reported significantly greater synchrony in the dorsomedial prefrontal cortex (dmPFC) during joint playing of Jenga

compared to when the participants played Jenga individually. In the joint play condition, the authors noted that participants considered the suggestions of their partner when strategizing their next move which led the authors to propose that this goal-oriented component of social cognition could underpin the synchrony that emerges during interactions that demand joint social decision-making. Similarly, Reindl et al. (2018) showed that parent-child pairs displayed enhanced inter-brain synchronisation in the dorsolateral PFC (dlPFC) during a cooperative rather than a competitive task. Nguyen and colleagues (2020a) observed a similar finding, where higher synchrony between mother-child pairs was present in the bilateral PFC and temporo-parietal regions during the cooperative task, in contrast to the individual condition. These findings suggest that joint activity, facilitated by joint social cognitive processes (i.e., social decision-making), increases the level of inter-brain synchronisation which was primarily reflected in the PFC.

The physical setting in which interacting partners are in poses another factor that regulates the extent of inter-brain synchronisation. Previous studies have shown that participants in naturalistic social settings who are in view of each other showed greater evidence of synchronisation. In a study on joint singing, Osaka et al. (2015) demonstrated that synchrony was heightened in the left inferior frontal cortex when participants faced each other. Along a similar vein, Jiang et al. (2012) found that greater synchronisation occurred when participants conversed facing each other compared to when they talked while having their backs against each other. In another study, Piazza et al. (2020) evinced that interactions characterised by shared gazing and smiles served to enhance inter-brain synchronisation in adult-child pairs. Likewise, Leong et al. (2017) showed that direct gaze buttressed neural synchronisation in adult-child pairs. These findings also lend evidence to the postulation initially provided by Hasson et al. (2012), which emphasised that the salient social cues of another person (i.e., hearing a response, seeing changes

in posture or facial expressions) who is experiencing the same environmental stimulus served as an important signal that facilitates inter-brain synchrony.

Lastly, the nature of the relationship between the two partners affects inter-brain synchronisation. In a study by Pan et al. (2017), the authors discovered that greater inter-brain synchronisation was seen in the right SFG of opposite gender romantic partners, compared to that of opposite gender friends or strangers, when the pairs engaged in a cooperative task together. In the context of parent-child relationships, Reindl et al. (2018) revealed that greater synchrony was observed in mother-child compared to stranger-child dyads. Taken together, these results point to the importance of the nature of the dyadic relationship in facilitating inter-brain synchronisation. In line with the seminal theory on biobehavioural synchrony proposed by Feldman (2012), partners entrenched within attachment relationships are more familiar and attuned with each other's salient social signals, and thus are able to decipher and reciprocate the emotional states of their partner more accurately which allows for efficient inter-brain synchrony.

A common observation across these studies is that inter-brain synchrony emerges in the prefrontal cortex, though the degree to which synchrony is observed varies across dyads. Reindl et al. (2018) reached the conclusion that variations in synchrony across dyads is likely due to dyadic differences in a common underlying mechanism which Gvirts & Perlmutter (2020) later coined as the “mutual social attention system”. Mutual attention is a well-established mechanism that is central to social cognitive processes (O'Madagain & Tomasello, 2019) and social interactions (Babiloni & Astolfi, 2014). Casted within an integrated neural network, the mutual social attention system stretches from basal perceptual pathways to higher-order social cognitive processes such as theory of mind (TOM; Shamay-Tsoory & Aharon-Peretz, 2007) which facilitate joint attention to salient environmental (e.g., emotionally relevant content of stimuli) and social

cues (e.g., vocalisations, postures, facial expressions). The mutual attention system thus permits the interpretation of mental and emotional states, thoughts and intentions of another person (Friston & Frith, 2015; Redcay & Schilbach, 2019; Vogeley, 2017; Wade et al., 2018). Dyadic partners who are more attuned with each other's mental and emotional states have been shown to display greater inter-brain synchrony in the PFC compared to pairs of strangers (Lee et al., 2017). Thus, the prevailing literature provides ample evidence that delimit synchronisation primarily to the PFC, and supports the notion that the mutual social attention system governs inter-brain synchronisation.

Hyperscanning

The paradigm shift towards a “two-brains” neuroscience demands parallel strides in technological advancement. Inaugurated by Montague et al. (2002), hyperscanning is a technique that enables the concurrent measurement of two brains simultaneously (Babiloni & Astolfi, 2014; Dumas et al., 2010; Hari & Kujala, 2009; Hasson et al., 2012). Upon its inception, hyperscanning was primarily applied to investigate inter-brain synchronisation in adults, such as during social communication (Jiang et al., 2012), exchange of facial expressions (Anders et al., 2011), coordination of gestures (Holper et al., 2012), movement coordination (Dumas et al., 2010; Funane et al., 2011; Holper et al., 2012), production of music (Lindenberger et al., 2009) and while playing cooperative games (Liu et al., 2016; Pan et al., 2017) and singing together (Osaka et al., 2015). The first study that employed a hyperscanning setup on an adult-child pair was only conducted recently by Leong et al. (2017). The study revealed that direct gaze between an adult, who was singing nursery rhymes, and an infant, led to the confluence of neural activation patterns.

A review by Czeszumski et al. (2020) highlighted three neuroimaging methods commonly used in hyperscanning studies, namely fNIRS (functional near-infrared spectroscopy), fMRI (functional magnetic resonance imaging), and EEG (electroencephalography) (Funane et al., 2011; Koike et al., 2015; Leong et al., 2017; Liu et al., 2018). Compared to fMRI hyperscanning, which requires participants to be lying still in the artificial environment of a scanner, away from the physical presence of a social partner, fNIRS and EEG allow the brain to be imaged within an ecologically valid social context, in the physical presence of a social partner. Similar to the blood oxygen level-dependent (BOLD) response in fMRI, fNIRS hyperscanning measures the changes in oxygenation and deoxygenation levels in the blood of social partners as a proxy of brain activation (Huppert et al., 2006; Strangman et al., 2002). Both EEG and fNIRS possess lower spatial resolution when compared to fMRI and are only capable of measuring activities in the cortical regions of the brain (Scholkmann et al., 2013). When contrasted against EEG, fNIRS hyperscanning has a considerably higher spatial resolution of millimeters which enable investigation into the spatial regions where synchrony might emerge. However, fNIRS possesses lower temporal resolution than EEG, where the former has a temporal resolution of 0.1 to 1 seconds whereas the latter directly measures electrical activity on the scalp and has a higher temporal resolution of milliseconds (Quaresima & Ferrari, 2019). Compared to both EEG and fMRI, fNIRS is less susceptible to motion artifacts induced by speech and bodily movement and allows participants to remain mobile, which makes it the most optimal device to investigate social phenomena that involve free movement, gestures and speech (Boas et al., 2014; Czeszumski et al., 2020; Pinti et al., 2020). This resistance to noise induced by motion also allows fNIRS to be applied across a wide range of age groups, including young children who might not be able to keep still during long periods of experiments (Cui et al., 2012).

To deduce the most appropriate method for hyperscanning in this thesis, the first criterion that must be fulfilled is that the neuroimaging technique must allow for investigation of brain signals within an ecologically-valid social context. In the case of this thesis, social partners (i.e., co-parenting spouses and parent-child dyads) must be in each other's physical presence. This criterion automatically removes fMRI from being a potential candidate technique due to the need to keep social partners isolated in individual artificial scanners. Next, to decide between EEG and fNIRS hyperscanning, three criteria were evaluated. First, we sought a neuroimaging technique that offers some spatial investigation since it has been established that synchrony is localised in the social areas of the brain, especially in regions of the prefrontal cortex such as the medial PFC. Second, we sought a neuroimaging technique that is resistant to motion artifacts, given that child participants would be recruited for the studies in this thesis. The first two criteria greatly favour fNIRS over EEG. In fact, fNIRS hyperscanning methods have been prominently used to investigate parent-child inter-brain synchronisation (Wass et al., 2020). Finally, we considered the disadvantage of a lower temporal resolution in fNIRS compared to EEG. Despite the lower temporal resolution of fNIRS, fNIRS hyperscanning would nonetheless suffice to investigate slower events like changes in blood oxygenation when participants are presented with stimuli that last for several seconds, which would allow fluctuations in the haemodynamic response curve to be sensitively captured (e.g., Pirazzoli et al., 2019). As such, fNIRS hyperscanning would be used to measure changes in brain signals across all chapters in this thesis.

Inter-brain Synchrony in Co-parenting Spouses and Romantic Partners

Inter-brain Synchrony in Co-parenting Spouses

In the bi-parental human species, the birth of the altricial infant spurs the need for spousal partners to collaborate with each other in their joint co-parenting endeavour (McHale & Sirotkin, 2019). This ingress into parenthood triggers major alterations in parenting brain modules (Atzil et al., 2012; Franssen et al., 2011; Kinsley & Amory-Meyer, 2011). Extensive studies on maternal care have revealed modifications in two main brain circuitries, namely the subcortical motivational pathway and the social cognitive and regulatory cortical network (Atzil et al., 2011; Decety, 2011; Iacoboni & Dapretto, 2006; Strathearn, 2011). The former network includes the amygdala and the anterior cingulate cortex (ACC), while the latter implicates the medial PFC (mPFC), the inferior frontal gyrus (IFG) and the superior temporal gyrus. Comparisons between maternal and paternal brains evinced little in the way of gender differences, although mothers have been found to have a fivefold greater activation in the amygdala compared to fathers. Nonetheless, fathers who are primary caregivers exhibit heightened amygdala activity which mirrors that found in mothers (Abraham et al., 2014; Wittfoth-Schardt et al., 2012). Such evidence lends support to the notion of an adaptive parental brain (Feldman, 2015a).

Although the caregiving roles of mothers and fathers might be distinct (Kinsley & Amory-Meyer, 2011), an evolutionary standpoint argues for the possibility of similar neurobiological mechanisms underscoring parenting (Storey, 2011). Facultative fathering, in which paternal care is rendered to support infant survival even when maternal care is present, is only observed in 3-5% of all species of mammals. Moreover, most species in which facultative fathering is observed are monogamous, which points to an indubitable role of pair-bonding in fathering behaviors (Insel & Young, 2001). Support from the pair-bonded partner provides a psychological buffer in the face of novel demands which are associated with parenting (Bristol et al., 1988; Suzuki, 2010). The integral role of pair-bonding in parenting, along with evidence of a plastic parental brain,

collectively suggests that co-parenting in humans is potentially buttressed by the co-wiring of parental brain modules in spousal partners (Atzil et al., 2012; Geary, 2000). The concerted effort for spouses to care for their infant potentially presents couples with opportunities for inter-brain synchronisation between mothers and fathers to occur (Yamasue et al., 2012).

However, there is a stark paucity of research in inter-brain synchronisation of co-parenting couples. To date, only one study by Atzil et al. (2012) has insofar navigated this topic. Employing fMRI imaging, the authors aimed to elucidate whether mother-father brain synchrony served an important mechanism in facultative fathering. Mothers and fathers were individually presented with a video of their infant during solitary play and a video of an unknown infant that served as a control. Subsequent computation of inter-brain synchrony demonstrated that mothers and fathers coordinated their neural response in social cortical networks, such as the dorsomedial prefrontal cortex (dmPFC) and the inferior frontal gyrus (IFG; Decety, 2011), only in response to their own infant cues. Synchronised responses in other regions such as the motor cortex and insula were also observed. These findings suggest that co-parenting spousal partners share a coupled perception and understanding of their child's signals. The co-parental synchronisation observed in this study further strengthened earlier postulations on the links between pair-bonding mechanisms and parenting in humans.

Evidence of co-parents' synchronisation corroborated with past studies that found these brain areas to be part of a social network responsible for higher-order social cognitive functions such as empathy, mirroring, attentional and mentalisation processes (Iacoboni & Dapretto, 2006). These functions constitute a core aspect of synchrony in romantic relationships too (Bartels & Zeki, 2004; Bartels & Zeki, 2000; Xu et al., 2011, 2012). Given that cohabiting co-parenting spouses not only share a cooperative parenting relationship with each other, but tend to inhabit a

romantic affiliation as well, past studies on romantic partners would be relevant. To supplement the lack of research on co-parenting couples, the following section will draw upon the available literature on romantic couples to glean greater insight into inter-brain synchronisation in adult partners.

Inter-brain Synchrony in Romantic Partners

Romantic couples spend abundant time interacting with each other, sharing daily life events (Gable et al., 2003, 2004) and working towards a common goal together (Li et al., 2002; Li & Kenrick, 2006). Compared to other human relationships, such as family and friendship ties, romantic relationships simultaneously mobilise caregiving, sexual and affective behavioural systems (Furman et al., 2014). The integrated involvement of these systems in tandem offer favourable circumstances for partners to coordinate their emotions (Randall et al., 2013), solve problems (Assad et al., 2007) and engage in cooperative tasks (Ackerman & Kenrick, 2009; Schneiderman et al., 2012), all of which drives the development of synchronous coupled responses. Although romantic partners can either comprise of homosexual or heterosexual couples, this literature review would focus solely on heterosexual couples. Baker et al. (2016) explicated that the sex composition of adult dyads influences inter-brain synchrony during cooperative games, where mixed dyads (i.e., male/female) showed greater synchrony than female-female dyads. Given the influence of sex on inter-brain synchrony, and since spousal partners who co-parent a biologically-related child together are heterosexual couples, the literature specifically on inter-brain synchrony in heterosexual romantic couples would bear exceptional relevance in furthering our understanding of inter-brain synchrony in co-parenting spousal partners.

In presenting the literature review on synchrony in romantic couples, who could either be parents or non-parents, there are a number of caveats that should first be highlighted. Romantic couples differ from co-parenting couples in that the former might not necessarily be parents, and hence might not engage in the cooperative task of parenting an infant together. However, non-parent romantic partners commonly engage in other cooperative tasks with each other, such as managing household chores together. While co-parenting couples tend to be romantic couples, the quality of relationship in co-parenting romantic couples compared to non-parenting romantic couples typically differ. For instance, a recent study by Treter et al. (2020) demonstrated that married couples experience a decline in sexual intimacy and relationship satisfaction during the transition to parenthood. A similar study by Doss and Rhoades (2017) showed that relationship functioning in married couples decline upon having children and becoming parents. However, the same authors also note that romantic relationships of parenting and non-parenting romantic couples show similar trajectories and converge over time. These studies encourage readers to exercise caution when drawing conclusions from studies of romantic couples, most of whom are non-parents, and applying them to co-parenting romantic couples due to the subtle nuances across these populations. However, the significant overlap in relationship functioning between co-parenting couples and romantic couples, who might or might not be parents, warrant a review on inter-brain synchrony in the latter population.

Pan et al. (2017) embarked on a study to discern inter-brain synchronisation that is unique to romantic couples. To do this, the authors employed fNIRS hyperscanning to measure the extent to which behavioural and brain synchronisation was exhibited across romantic partners, friends and strangers when the pairs engaged in a cooperative task. The task entailed making concerted responses to a stimulus simultaneously, after which the quality of their reaction would be evaluated

on two factors, namely the similarity and temporal coordination of their response. Responses which were more similar to each other with less variability suggested better cooperation between partners (Funane et al., 2011). The authors revealed that romantic partners exhibited less behavioural variability and temporal differences in their responses compared to that of friends or strangers. Moreover, the coordinated responses observed in romantic partners were accompanied by greater inter-brain synchronisation in the right superior frontal cortex. This result corroborated with previous neuroimaging studies which similarly reported the recruitment of the superior frontal gyrus when participants viewed pictures of their romantic partner (Bartels & Zeki, 2004; Bartels & Zeki, 2000; Xu et al., 2011), and of the medial orbitofrontal cortex when asked to think about their romantic partner (Xu et al., 2012). These regions are integral for self-awareness (Goldberg et al., 2006), theory of mind (Cui et al., 2012; Yang et al., 2015) and implicit comprehension of intentions underlying the actions of others (Hari & Kujala, 2009). Pan et al. (2017) first rationalised their findings by postulating that romantic partners are naturally more likely to be familiar with each other, thus lending them the upper hand with the cooperative task. However, they later proposed that familiarity alone is unlikely to be the central force that led to the enhanced behavioural and brain synchrony observed. Indeed, pairs of friends who have known each other for a similar duration of time as the romantic dyads did not exhibit the same degree of synchrony. The authors argued that engaging on a task with a significant other, such as in the case of romantic partners, activates a unique set of processes that enhanced emotional attunement. Such processes possibly facilitate the sharing of emotions, intentions and joint behaviours. Given that the cooperative game demanded a high level of understanding and predicting of the partner's response, inter-brain synchronisation seems to assist partners in fulfilling cooperative tasks.

In another fNIRS hyperscanning study, Fishburn et al. (2018) investigated whether adult pairs who are not romantic partners or related by family (i.e., friends, colleagues) would exhibit inter-brain synchrony that reflects the neural underpinning of shared intentionality. Shared intentionality facilitates collaboration towards a commonly held goal. To do this, the authors tasked pairs of adult participants to a cooperative and a competitive (i.e., control) condition. In the cooperative condition, partners needed to solve a puzzle together, whereas the competitive condition required them to solve the same puzzle individually. Additionally, partners also engaged in two passive conditions, in which they watched a pair of adults complete the puzzle in person and through a video. The authors discovered that inter-brain synchrony was significantly higher in the cooperative condition compared to the competitive condition or the two passive conditions. Thus, when collaborating on a task where both partners share the same goals, inter-brain synchrony emerges.

In another study, Kinreich et al. (2017) used EEG hyperscanning to elucidate the unique inter-brain synchronisation present in romantic dyads, compared to strangers, during naturalistic interaction. They found evidence of inter-brain synchronisation of gamma waves in the temporo-parietal networks of romantic partners only. Moreover, this synchronisation was not observed during a 3-minute rest period which served as a control condition. Upon closer inspection of the data, the authors revealed that inter-brain synchronisation in the temporo-parietal region was primarily buttressed by non-verbal components of interactions, as opposed to the duration of verbal speech. As a result, Kinreich et al. (2017) propositioned that nonverbal cues were paramount to the development of social attachment and the manifestation of inter-brain coordination.

Thus far, synchronisation studies on romantic couples have uncovered the importance of shared cooperative goals and non-verbal signals in the modulation of inter-brain synchronisation.

These findings are unsurprising given the copious amount of exposure that romantic partners have to each other's non-verbal cues on a daily basis. Cohabiting romantic couples are likely to fulfill common everyday goals together (e.g., household chores, meal preparations), which necessitate synchronous behaviours (Pauly et al., 2020), thus facilitating the development of dyadic behavioural rhythms which inter-brain synchronisation is postulated to be built upon (Feldman, 2012; Kinreich et al., 2017). Although these studies have demonstrated that inter-brain synchronisation can be observed in romantic partners, it is not known whether it persists in the absence of the romantic partner. To date, no study has investigated the effects of physical presence on inter-brain synchronisation in romantic partners, although there have been studies that explored the effects of physical presence on the mood states and cortisol synchronisation of spousal partners, which would be elaborated in the next section (Papp et al., 2013; Saxbe & Repetti, 2010).

Physical Presence and Physiological Synchrony in Romantic Partners

Cohabiting romantic partners or spouses live in close proximity to each other and are hence considerably exposed to each other's behavioural and biological rhythms. However, their day likely consists of time spent together and other periods spent apart (e.g., at work) and our understanding of the biological concomitants of such living arrangements remain limited. The literature on physiological synchrony in spousal partners is currently divided as to whether the physical presence of a partner facilitates physiological synchrony or whether such synchrony naturally persists in couples even when they are not in each other's immediate presence.

Saxbe and Repetti (2010) demonstrated that synchrony of mood states and cortisol levels of cohabiting couples was indeed dependent on physical presence. The authors measured salivary cortisol concentration and self-reported mood states of 30 married spousal partners 4 times each

day for a period of 3 days. They found that husband's and wife's cortisol levels significantly correlated with each other across the span of several days. When examining within-day fluctuations, the authors demonstrated that dyadic coregulation of both negative mood states and cortisol levels were heightened when partners were physically together at home, compared to when they were apart during the day, whilst at work. Findings from this seminal paper suggests that physiological synchrony is unique to couples and follows a synchronised trajectory over several days, and that synchrony over smaller within-day time frames hinges upon each other's physical presence.

Aside from demonstrating the importance of physical presence in enhancing cortisol synchrony, Saxbe and Repetti (2010) also evinced that physiological synchrony was not always beneficial to romantic partners. They showed that synchrony of negative mood states was moderated by marital satisfaction, wherein couples who are more dissatisfied with their marriage tend to share a stronger correlation in negative mood states, and wives who reported less marital satisfaction synchronised more with their husband's temporal cortisol fluctuations. As exemplified by their finding, physiological synchrony should not be misconstrued as an invariably positive marker of dyadic relationship. In fact, their results suggest that physiological synchronisation towards a negative mood state is indicative of partners who continue to engage with each other's negative affect, thereby intensifying animosity. Conversely, the ability to remain calm and not synchronise with a partner's negative mood state would prevent spouses from getting entrapped in a pernicious pattern of interactions.

Papp et al. (2013) continued to investigate the effect of spousal physical presence on cortisol synchronisation, which led to the converse finding that coordinated cortisol level was determined by the total amount of time that partners spend together, rather than being dependent

on the presence of the spouse. These findings were deduced from 47 pairs of married cohabiting couples whose salivary cortisol levels were monitored 7 times a day over two working days. Similar to Saxbe and Repetti (2010), dyadic partners were found to significantly synchronise their cortisol levels with each other which further supports the notion of within-couple synchronisation. However, unlike Saxbe and Repetti (2010), Papp and colleagues (2013) did not find within-day variations in cortisol synchrony that would have indicated differences in cortisol synchronisation when partners are together (i.e., at home in the evening) and apart (i.e., at work, during the day). Instead, they revealed that couples who spent more time together in general showed greater cortisol synchronisation across the two days, which suggests that momentary physical presence and absence does not affect physiological synchrony as much as the general time spent together does.

Taken together, both the studies of Saxbe and Repetti (2010) and Papp et al. (2013) testify to the unique phenomenon of physiological synchrony in romantic couples. Although both studies emphasise the importance of physical presence of the partner, their findings varied as to whether momentary physical presence of the partner is associated with visibly heightened physiological synchrony. Given that co-parenting spousal partners also inhabit the same household, these contradicting results serve as an important research gap to be addressed in the co-parenting literature too.

Research Gap in Co-parenting Synchrony Literature

Drawing upon the literature on inter-brain and physiological synchronisation in co-parenting and romantic couples, several main findings ought to be highlighted. First, unique inter-brain and physiological synchronisation can be observed in co-parenting and romantic couples. Second, inter-brain synchronisation in romantic partners is enhanced during cooperative tasks and

exposure to non-verbal signals of the partner. Third, the physical presence of a spouse enhances physiological synchrony in romantic couples, although the importance of the momentary presence of the spouse in enhancing synchrony is yet to be ascertained. Fourth, from the study of Saxbe and Repetti (2010), synchronisation towards negative and stressful mood states might be detrimental to the dyadic relationship.

However, several research gaps remain. First, besides the study on Atzil et al. (2012), the other findings that have been discussed were extrapolated from literature on romantic couples. While spousal co-parenting partners do typically inhabit a romantic relationship, their relationship significantly differs from that of romantic partners due to the added responsibility of jointly raising a child together. Hence, while inter-brain synchrony in naturalistic settings has been found to occur in romantic couples, the same has yet to be observed in co-parenting couples. Second, although the importance of physical presence on the physiological synchrony of romantic couples has been shown, no study has insofar investigated whether the momentary physical presence of a co-parenting partner enhances inter-brain synchronisation of the couple. Third, little is known as to whether inter-brain synchronisation serves to support or hinder the cooperative rearing of an infant during stressful parenting situations, such as when they are exposed to infant cry signals and need to quickly soothe their distressed infant. Addressing these research gaps would lend a greater understanding to how the physical presence of a co-parenting spousal partner facilitates efficient joint parenting endeavours.

Research Questions and Hypotheses

To address these research gaps, Study 1 (Chapter 3) of this thesis would employ fNIRS hyperscanning to measure the PFC responses of co-parenting partners when they are exposed to

salient infant and adult vocalisations (i.e., cry and laughter) in the physical presence of their partner (in the same room, at the same time), and in the absence of the partner (in different rooms, at staggered times). Based on the research gaps identified in the previous section, the following research questions (RQ) have been proposed:

RQ 1. Do co-parenting partners exhibit greater inter-brain synchronisation when together (together-condition; TOG) compared to when they are apart (separate-condition; SEP)?

RQ 2. Is the enhanced synchrony in co-parenting partners (in both TOG and SEP) due to the unique pairing of partners with each other which is significantly higher than the synchrony index derived from the random pairing of brain signals of men and women who are not partners?

RQ 3. Does the emotional valence of the vocalisation (i.e., cry vs laughter) and the speaker of the vocalisation (i.e., infant vs adult) have an effect on inter-brain synchronisation of co-parenting partners?

RQ 4. Do the following parental characteristics (i) the ratio of mother to father taking the lead in attending to the child, (ii) parental status (i.e. primiparous or multiparous), and (iii) age of parents affect inter-brain synchronisation?

Research questions 1-3 are the main questions to be addressed, whereas RQ 4 is an exploratory RQ. As little is known about RQ 4, no specific hypothesis is attached to it. The following three hypotheses (H) are formulated to test RQ 1-3:

H1. Since the sample in Chapter 3 consisted of married co-parenting couples who cohabited, we drew upon the findings from Saxbe & Repetti (2010) on cohabiting romantic partners, and posited that greater inter-brain synchronisation would be observed in the couples in the TOG compared to the SEP condition.

H2. Similar to the findings of inter-brain synchrony in romantic partners (Kinreich et al., 2017; Pan et al., 2017), we hypothesised that unique synchrony would be observed in true co-parenting dyads compared to randomly paired signals.

H3. A recent study by Chen and colleagues (2020) discovered that married couples synchronised their physiological signals (i.e., measures of peripheral nervous activity such as heart rate and skin conductance) more significantly during positive conversations compared to conflictual conversations, and that greater synchrony during the positive condition was associated with higher relationship quality. Extrapolating these findings to the present inter-brain synchrony study on co-parenting married couples, we hypothesise that co-parents are less likely to synchronise their brain signals in response to negative vocalisations, and would instead synchronise their responses to positive vocalisations. Of the vocalisations that would be presented to participants, infant cry is particularly negative and stressful (Soltis, 2004), triggering prompt caregiver proximity and eliciting an immediate behavioural response (Venuti et al., 2012; Messina et al., 2016). Albeit to a lesser extent, adult cry has also been demonstrated to signal distress and induce pro-social behavioural responses from others (Hendriks et al., 2008).

Inter-Brain Synchrony in Parent-Child Dyads

This section would review the prevailing studies on inter-brain synchrony in parent-child dyads. It would begin by introducing the ubiquity and significance co-viewing of the television, which is the social context in which synchrony of parent-child dyads would be investigated in this thesis. Following that, the limited research on inter-brain synchrony during passive co-viewing would be reviewed before the more extensive literature review on inter-brain synchrony during social interaction would be discussed.

Co-viewing of Television

At the turn of the century, leisure time shared between parents and their children was beginning to be considered as an important ingredient for a mutually fulfilling dyadic relationship (Daly, 2001). Within the first decade, a clear trend started to emerge that revealed an increase in time that both mothers and fathers spent with their children (Coltrane & Adams, 2008). Co-viewing of the television comprises a common passive joint activity that is regarded as relaxing whilst still allowing parent-child dyads to share quality time together (Craig & Mullan, 2012). In fact, in a study by Craig and Mullan (2012) which investigated the pervasiveness of co-viewing of television across USA, Denmark, Australia and France, co-viewing was consistently represented as a leisure activity across the four countries. In a related study conducted in the UK on 252 families, Jago et al. (2013) similarly demonstrated that two-thirds of 3-to-5-year old children, and three-quarters of parents, spent more than two hours watching television together every day. Along the same vein, a study on 2,326 parents with children under the age of 8 years from a US sample showed that parents typically co-view the television with their children (Connell et al., 2015). In another study, Lavigne et al. (2015) found that, across the span of a week, parents and their children spend 9.2 hours watching television in the foreground and 9.5 hours interacting with the television in the background. More recently, Carter et al. (2016) reported that most children, upon reaching preschool age, would be more savvy with viewing screen media before reading books. These findings testify to the pervasiveness of co-viewing between parents and their children.

The ubiquity of co-viewing has been met with an equivocal mix of scorn and support by the research community. While some ardently argue that media is detrimental to family life (Turkle, 2017), others acknowledge the potential benefits and pitfalls that are associated with media use (Gee et al., 2017; Hoover, 2012; Jordan et al., 2006). Proponents posit that co-viewing

of the television occurs as a function of parental availability (Connell et al., 2015) and translates to greater dyadic bonding (Padilla-Walker et al., 2012). Parent-child engagement during co-viewing of media has also been shown to exert positive effects on the child's linguistic development (Mendelsohn et al., 2010). For example, mothers' mental state talk affects children's emotional processing (Baptista et al., 2017), which renders the parent as an external regulator of the child's emotions during co-viewing. These emerging studies attest to the importance of parental presence for optimal processing of narrative scenes during co-viewing. Due to these emerging findings on the benefits of co-viewing, the American Academy of Pediatrics has revised their policy from restricting viewing of media for young children to supporting co-viewing of media for parents and their children (American Academy of Pediatrics, 2013).

Even in the absence of any social engagement, co-viewing of the television has been shown to lend a positive impact on familial well-being. In a study by Jones, Hill and Miller (2018) on 623 married parents and their children in Singapore, co-viewing of the television was found to have the strongest relationship with family satisfaction, and was ranked higher than other family routines, including family meals, active leisure, and religious worship. Although common wisdom would anticipate co-viewing of the television to displace more quality interactions, the findings by Jones and colleagues (2018) were in fact replicating an earlier study by Crouter et al. (2004) which similarly found co-viewing to be predictive of positive family functioning. Jones and colleagues (2018) also argued that the smaller apartments in Singapore could underpin the frequency of TV watching as a family. Moreover, the long working hours in Singapore, averaging at 48 hours per week (Hill, 2007), might further explain families' choice of opting for a passive joint activity frequently. The ubiquity and significance of television co-viewing demands further inquiry into the brain mechanisms that transpire during this activity.

Inter-brain Synchronisation During Co-viewing of Television

To date, no study has investigated parent-child inter-brain synchrony during dyadic co-viewing of television, although one study did examine inter-brain synchronisation between arbitrary groups of adults and children in general. In an fMRI study, Moraczewski et al. (2018) measured brain synchrony of adult and child participants who were watching movie clips individually in an fMRI scanner. To obtain an index of inter-subject correlation, the authors compared the similarity between the brain responses of child participants to the adult sample, which revealed that synchrony differed as a function of the child's age. The older the child, the more the temporo-parietal junction, a brain implicated in TOM and attention, responded to movies in a manner that is similar to that of an adult.

In another study, Levy et al. (2017) used magnetoencephalography (MEG) to examine inter-brain synchrony between mothers and their school-aged children during a passive activity of watching video vignettes individually. The vignettes presented to them were videos of the mother-child dyads themselves as they engaged in positive and negative interactions at home. Prior to the MEG experiment, dyadic interaction was videotaped at home and microcoded for moments of behavioural synchrony (i.e., positive) and non-synchrony (i.e., negative/conflictual). Upon analysing mother's and child's brain responses to both positive and negative videos of dyadic interaction, it was discovered that mother-child inter-brain synchronisation in the superior temporal sulcus was tightly linked to moments of synchronous behaviours, which was consistent with previous findings that likewise showed that inter-brain synchrony in mother-child dyads is anchored in positive behavioural synchrony (Atzil et al., 2011, 2014; Levy et al., 2016). Moreover, Levy et al. (2017) showed that dyads did not exhibit synchrony to positive social interactions of

other dyads, which further supports the notion of unique parent-child inter-brain coupling that exists within an attachment relationship.

Although the two studies described above had examined parent- and adult-child inter-brain synchrony during viewing of video stimuli, a common limitation shared between them is that brain responses were measured when the adult and the child viewed the video stimuli individually which did not replicate real-life events of co-viewing together. This limits the ecological validity of these findings as parent-child dyads often engage in tasks in each other's physical presence, during which they continue to receive social signals from each other. Given the dearth of research in the context of parent-child co-viewing, the following section seeks to derive insights from the literature on parent-child inter-brain synchrony in interactive contexts.

Inter-brain Synchrony During Interactions

Cooperation

Majority of studies focusing on parent-child inter-brain synchrony have done so within the context of social interactions. Cooperation between parent-child dyads, as opposed to engaging in tasks competitively or individually, is one of the most researched topics thus far. In an fNIRS hyperscanning study, Reindl et al. (2018) compared inter-brain synchrony in a cooperative condition with a competitive control condition. In the cooperative condition, parent-child dyads were tasked to respond to a signal at the same time, whereas in the competitive condition, they were challenged to respond to the signal faster than their partner. Inter-brain synchronisation was only evident during the cooperative condition, where temporal alignment of behavioural responses was required of the dyadic partners. However, in a dyadic control condition when parent and child were paired with strangers, inter-brain synchrony no longer emerged in the cooperative condition,

which attests to the unique synchrony that develops in attachment relationships. During the cooperative condition, Reindl et al. (2018) reported synchrony in the dorsolateral PFC and frontopolar cortex (FPC) that significantly predicted the dyad's performance during the game.

The importance of cooperation was further supported by another fNIRS hyperscanning study. Nguyen et al. (2020a) employed a similar research paradigm where 42 mothers and their preschool children participated in a cooperative Tangram puzzle task and a competitive (control) task in which they have to solve the puzzle individually. Similar to the findings by Reindl et al. (2018), increased inter-brain synchronisation in the bilateral PFC and temporal areas emerged in the cooperative condition. Enhanced inter-brain synchrony in these regions was also associated with a higher incidence of reciprocal behaviours during the cooperative condition. During cooperative tasks, mothers and their children engaged in mentalisation and TOM processes in the prefrontal and temporal areas in order to predict one another's goal (Baimel et al., 2015). Synchrony in the PFC in particular has been associated with efficient communication and decision making between partners (Zhang et al., 2017). Subsequently, the authors reasoned that inter-brain synchrony, during which brain signals are temporally aligned, might reduce the cognitive effort required to understand the other partner's intention and make decisions together (Keller et al., 2014; Koban et al., 2019). These findings also corroborate with that of Cui et al. (2012), who found increased inter-brain synchrony in parents and their school-aged children in the frontal and temporal areas during a cooperative reaction time task, compared to the competitive condition.

Taking the literature on inter-brain synchrony and cooperation further, Miller et al. (2019) investigated whether synchronisation differed between mother-daughter and mother-son dyads during a cooperative dual-player game compared to an independent single-player game. The researchers revealed right-lateralised synchrony in the dorsolateral PFC and the frontopolar PFC

during the cooperative game. Mother-son dyads were found to exhibit greater inter-brain synchrony than mother-daughter dyads during the cooperation task. Overall, these studies consistently point to the role of inter-brain synchrony in the prefrontal and temporal areas, and their importance in cooperative tasks.

Behavioural Synchrony

Whereas studies on cooperation emphasised the need for active collaboration for inter-brain synchrony to emerge, other studies have shown that inter-brain synchrony also occurs during synchronous behaviours that involve direct gaze, joint attention, and matched speech prosody. The first hyperscanning study on an adult-infant pair, conducted by Leong et al. (2017), employed a dual-EEG paradigm to investigate whether direct gaze during live interaction and through a video facilitates inter-brain synchrony. Across both modalities, direct gaze, compared to indirect gaze, elicited greater inter-brain synchrony of the alpha and theta frequency waves which reflects the influence of direct gaze on aligning brain signals of adult-child pairs.

However, the study by Leong et al. (2017) was conducted in a laboratory setting and did not reflect natural variations in gazes that occur during free interactions. Recently, Piazza et al. (2020) employed an fNIRS hyperscanning technique to measure inter-brain synchrony between an adult experimenter and infant participants during naturalistic interaction. The experimenter-infant pairs experienced a together-condition, when the experimenter interacted with the infant, and a separate-condition, when the experimenter ignored the infant. Analyses from the study revealed a robust increase in inter-brain synchrony in the PFC when adult-child pairs were interacting. Inter-brain coupling occurred during instances of direct gaze, joint attention to objects like toys and when the adult engaged in infant-directed speech characterised by extreme pitch changes. Taken

together, these two studies demonstrated the importance of synchronous behaviours in eliciting inter-brain synchrony.

Emotional Valence of Interaction

Another emerging factor that has been shown to influence parent-child inter-brain synchrony is the emotional quality of the interaction, wherein social interactions characterised by positive emotional valences tend to elicit greater synchrony. In a dual-EEG study on 12 month old infants and their parents during joint and individual play, Wass et al. (2018) showed that positive instances of interactions, compared to negative ones, were associated with greater inter-brain synchrony. Moreover, parents' theta frequency wave was found to change in response to the child's level of attention, with longer sustained attention by the infant shown to be associated with greater theta wave responsiveness by the parent.

Emotional valence of parent-child interaction was once again found to modulate inter-brain synchrony in another dual-EEG study by Santamaria et al. (2020). In this study, 15 mother-infant dyads displayed positive and negative interactions with their infants during joint play. Their analyses revealed that greater inter-brain synchrony of the alpha band was observed during the positive interaction compared to the negative interaction, corroborating with the findings of Wass et al. (2018).

Parental Factors Affect Parent-child Synchrony

From the previous sections, it is apparent that studies on parent-child inter-brain synchrony within both the interactional and co-viewing contexts placed little emphasis on parental factors. Parental factors refer to variables that the parent introduces into the parent-child relationship. Two

parental factors that have been consistently shown to affect the quality of the parent-child relationship are parenting stress and maternal attachment style.

Parenting Stress

Parenting Stress and the Parent-Child Relationship

Although parenthood brings a deluge of joy to parents, many would nonetheless concur that the parenting experience comes with a unique set of challenges and stressors. Parenting stress is a multidimensional construct defined as the psychological, emotional and mental strain experienced by a parent when the demands of parenting exceed the coping resources that the parent perceives to be available to him/her (Deater-Deckard & Scarr, 1996). While a moderate dose of parenting stress is typical, excessive parenting stress may incite antipathetic emotions towards the parenting role (Deater-Deckard, 2004) which poses a hurdle to optimal caregiving (Abidin, 1992).

The theoretical model of parenting stress posits this construct to comprise two fundamental domains, namely the parental (i.e., personal) and child rearing dimensions of parenting stress (Abidin, 2011; Abidin, 1983; Deater-Deckard, 1998). While this model acknowledges the two central sources of parenting stress, it lacks a quantifiable and operational definition that would facilitate research investigations. Parenting Stress Index - Short Form (PSI-SF; Abidin, 1995) is an instrument designed to measure parenting stress with a three-factor solution. The three subscales of the PSI are the parental distress, difficult child and the parent-child dysfunctional interaction subscales. The parenting distress subscale reflects the affliction, in the form of incompetence, restriction and depression, that parents personally experience due to the role they have acquired as a parent. The difficult child subscale measures whether a parent perceives the child to be easy or challenging to rear, whereas the parent-child dysfunctional interaction subscale

quantifies how satisfied parents are with their relationship and interactions with the child. Finally, the sum of all three subscales generates a total parenting stress score, which gives an indication of the stress that a parent undergoes.

Parenting stress has long been established to impair parent-child interactions (McCarty et al., 2005; Molfese et al., 2010). Studies on maternal stress specifically has elucidated the detrimental effects that parenting stress has on maternal sensitivity, warmth and responsiveness (Pereira et al., 2012). Moreover, parenting stress has been found to further aggravate adverse parenting behaviours such as intrusiveness and punitive parenting (Kang, 2011; Whiteside-Mansell et al., 2007). As parenting stress may vary over time, longitudinal studies have also been conducted on the effects of parenting stress on the quality of parent-child interactions. For instance, in a longitudinal study on parenting stress and maternal interaction, Spinelli et al. (2013) measured the quality of parent-child play when infants were 4, 24 and 36 months old. An increase in self-reported parenting stress throughout the duration of the study was associated with a diminished quality of interaction, whereas reduced parenting stress scores over time correlated with an enhanced quality of interaction. In a similar study that spanned from infancy to toddlerhood, Le et al. (2017) measured the effects of personal distress and child rearing stress on parents' negative affect and harsh parenting behaviours. Both domains of parenting stress were found to moderate the association between negative affect and harsh parenting throughout the longitudinal duration.

Regrettably, persistent parenting stress may leave enduring adverse effects on the child's social, cognitive and emotional development (Harewood et al., 2017). An impaired parent-child interaction in early childhood, as a result of aggravating parenting stress, renders the child with fewer opportunities to be cognitively stimulated (Nievar et al., 2006), to engage in prosocial behaviours, and to exercise their newly acquired linguistic skills (Farver et al., 2006). Children

who experienced poorer parent-child interactions tend to have reduced cognitive processing capacity (Thompson & Trevathan, 2009), difficulties in acquiring object-word relations (Matatyaho & Gogate, 2008), school maladjustment (Harrist et al., 1994) and lower IQ scores (Feldman, 2007b; Feldman et al., 1996). These children are also placed at greater risk of temperamental behaviours (Booth, Lyons & Barnard, 1984) and internalizing conditions (Church, 2000). Given the multitude of detrimental outcomes that parenting stress has on a child's development, emerging studies have taken to neuroimaging methods to investigate the mechanisms through which parenting stress exerts its effects on the parent-child relationship.

Parenting Stress and Inter-brain Synchrony

Recent efforts to isolate brain regions modulated by parenting stress have made promising discoveries. Employing an fMRI paradigm, Noriuchi et al. (2019) examined the brain activation patterns of 28 mothers of typical preschool children when they were presented with vignettes of the feeding behaviours of their own children and other children. When brain responses were compared with mothers' self-reported parenting stress levels, the researchers found that brain areas responsible for maternal motivation and identification of their own child's emotional state surfaced. These regions include the orbitofrontal cortex (OFC), ventral pallidum, periaqueductal gray (PAG), anterior insular cortex (AIC) and cerebellum. The OFC, in particular, showed greater activation in parents who reported less parenting stress stemming from their sense of competence within their parenting role. Moreover, dual activation of both the OFC together with the PAG and AIC was observed in parents who reported lesser parenting stress associated with their child's difficult traits. These findings suggest that the effects of parenting stress can be observed in mothers during passive observations of their child.

The authors broached that adaptive parenting responses may hinge upon the OFC, which serves as a central hub that maintains well-regulated brain responses due to its essential function in the reward system related to maternal love (Bartels & Zeki, 2004; Noriuchi et al., 2008; Swain et al., 2014; Zeki, 2007). Nestled within the PFC, the OFC plays a critical role in evaluating the value of a reward (O'Doherty et al., 2001; Schoenbaum et al., 1998). The finding that lesser parenting stress in the parental domain, which reflects a greater sense of competence within the parenting role, is associated with greater OFC activation, suggests that activation in this area may be necessary for maternal motivation and functioning. At the same time, co-activation of the OFC together with the AIC and DRN in mothers with lesser parenting stress in the child domain demonstrates that the OFC operates in conjunction with brain areas responsible for interoception to facilitate mothers' ability to understand her child's feelings and perspectives. Conversely, diminished OFC activation may impede maternal motivation and functioning which may further aggravate parenting stress.

Only one study thus far has investigated parenting stress within the context of parent-child inter-brain synchrony. Shortly after the publication of Study 2 (Chapter 4) of this thesis (Azhari et al., 2019), Nguyen et al. (2020a) examined inter-brain synchrony amongst 42 mother-child dyads who engaged in a cooperative and a competitive tangram puzzle task. Upon examining the effects of self-reported maternal stress, the authors showed that parenting stress reduced inter-brain synchronisation and altered the mother's brain responses in areas implicated in self-awareness and decision-making networks. Taken together, these two studies demonstrated the possibility for parenting stress to be observed in the parent's brain, as well as in the inter-brain synchronisation of mother-child dyads.

Maternal Adult Attachment Style

Maternal Adult Attachment and the Parent-child Relationship

Another enduring parental factor that affects the parent-child relationship is adult attachment style, which refers to stable patterns through which adults foster emotional connectedness with attachment figures such as with their romantic partner (Hazan & Shaver, 1987). Adult attachment styles are generally divided into two main classifications: secure and insecure attachment (Mikulincer & Shaver, 2010a). Secure attachments develop when an attachment figure is available to provide a stable base which one can rely on to regain emotional stability during a distressing event. Insecure attachments are further classified into avoidant or anxious types (Mikulincer & Shaver, 2010b), where an individual with the former type refrains from seeking an attachment figure whereas the latter exhibits enhanced proximity-seeking behaviours due to a perceived deficiency to regulate his/her emotions independently (Mikulincer & Shaver, 2010c; Vrtička & Vuilleumier, 2012). As a result, individuals with anxious attachment tend to be hypervigilant toward social cues (Bartholomew, 1990; Bartholomew & Horowitz, 1991; Griffin & Bartholomew, 1994; Mikulincer & Shaver, 2010c).

In the context of parenting, an insecure maternal adult attachment style has been shown to impair caregiving behaviours and undermine the mother-child relationship. Insecurely attached mothers exhibit a higher likelihood of being emotionally unavailable (Licata et al., 2016a), insensitive (Jones et al., 2018; van IJzendoorn, 1995), and harsh to their children (Jones et al., 2014). They also experience difficulties in regulating their own emotions which impedes their ability to engage in optimal caregiving behaviours (Jones et al., 2014). Insecure anxious and avoidant adult attachment styles also manifest as distinct patterns of mother-child interactions

(Edelstein et al., 2004; Rholes et al., 1995; Selcuk et al., 2010a). Maternal avoidant attachment is typically associated with reduced sensitivity during dyadic interactions whereas anxiously attached mothers need inordinately close levels of proximity with their children (Buehler, 2017). Mothers with anxious adult attachment also tend to miss salient social signals from their child (Selcuk et al., 2010a), which has been attributed to the mother's preoccupation with being accepted at the expense of attending sensitively to her child. In fulfilling their own attachment needs, anxiously attached mothers may employ a narrow focus on her own emotions which impairs the mother's capacity to identify and respond to her child's needs (Feeney & Collins, 2001; Mikulincer & Shaver, 2007). Overall, an insecure maternal adult attachment style certainly diminishes the quality of interaction within a parent-child relationship (Licata et al., 2016b).

Maternal Adult Attachment and Parent-child Synchrony

The notion of behavioural and physiological synchrony as a construct that underpins affiliative relationships has been perpetuated since it was first conceived (Feldman, 2012b). To uncover the link between maternal adult attachment style and behavioural synchrony, Selcuk et al. (2010b) analysed the association between mothers' self-reported adult attachment styles and naturalistic mother-child interactions of 85 mother-child dyads, which was conducted at home and lasted for 3 hours. The authors demonstrated that maternal avoidant attachment was correlated with non-synchronous interactions that featured mother's psychological distance, emotional inaccessibility, discomfort with close proximity, and missing salient cues from the child. Their findings were in line with past studies that reported a tendency for avoidant mothers to assign little weight to the importance of attachment and intimacy, which might have underscored the lack of behavioural synchrony (Collins, Guichard, Ford, & Feeney, 2004; Schachner et al., 2005). Meanwhile, dyads with anxiously-attached mothers also exhibited reduced synchrony that was

mostly precipitated by mothers' inability to detect and respond to the child's signals. Although anxiously-attached mothers maintain close contact with their children, their predominant self-focus, marked by egotistical needs to reduce their own anxiety (Feeney & Collins, 2001), together with their chronic preoccupation with being accepted (Mikulincer & Shaver, 2007) and exhibiting unrealistic standards of care (Snell et al., 2005), might obscure their ability to focus on their child's needs. The anxiously-attached mother's inability to fulfill her child's needs might set in motion a vicious cycle of frustration that in turn further aggravates her chronic worries, and may lead to feelings of anger towards the child.

Maternal Adult Attachment and Inter-brain Synchrony

Since synchrony traditionally denotes shared emotional and mental states between dyadic partners, mentalisation processes play an important role in facilitating synchrony. Fonagy & Luyten (2009a) proposed that mentalisation processes can be classified into either emotional or cognitive mentalisation processes, and that these mentalisation processes are preferentially adopted depending on one's adult attachment style. Emotional mentalisation relies on implicit and automatic processing of emotions based on another person's observable attributes, such as changes in facial expressions. Cognitive mentalisation, by comparison, involves conscious and voluntary processing that interprets internal attributes, including feelings, perspectives and intentions (Fonagy & Luyten, 2009b; Lieberman, 2007). An anxious attachment profile typically exhibits hypervigilance to social signals of acceptance and rejection, which renders individuals who are anxiously-attached more likely to adopt emotional mentalisation processes, which focus on the physical attributes of others (Fonagy & Luyten, 2009b).

Advances in social neuroscience have seeded a wont for identifying brain regions responsible for different attachment styles. In a recent review, Long et al. (2020) presented a functional neuro-anatomical model of attachment (NAMA) which proposed that attachment styles are underpinned by mentalisation brain modules that bear activation patterns characteristic of different attachments. The authors posited that inter-individual differences in attachment-related security, anxiety and avoidance are reflected in differentiated blood-oxygen-level-dependent (BOLD) signal changes in cognitive and emotional mentalisation modules. These mentalisation modules are nested within a densely connected circuitry called the mental state representation network which stretches from the prefrontal to temporal areas. Over time, as the individual forges and develops social attachments (Mikulincer & Shaver, 2007), the mental state representation network becomes progressively more established. Within this network, medial prefrontal areas are predominantly implicated in mentalisation processes (Andrews-Hanna et al., 2014) and exhibit differential BOLD patterns depending on attachment style (Long et al., 2020).

Two studies have previously investigated the relationship between attachment and inter-brain synchrony. In one study that examined mother-child synchrony within a cooperation paradigm, Miller et al. (2019) revealed preliminary findings which demonstrated that children's avoidant attachment style was associated with reduced inter-brain synchrony in the right frontopolar prefrontal area. In another study, Nguyen and colleagues (2020a) similarly adopted a dyadic cooperation paradigm, in which mother-child pairs were tasked to complete tangram puzzles. Their inquiry as to the possible association between maternal attachment style and inter-brain synchrony did not reveal significant associations between the two constructs.

Maternal Anxious Attachment and Synchrony

While some studies point to an impairment of synchrony amongst insecurely-attached mothers and their children, recent studies on behavioural synchrony of anxious mothers suggest that anxious maternal characteristics may also be linked to maladaptively high levels of behavioural synchrony. In fact, excessive behavioural coupling is quickly emerging as a trait of anxious mothers and their children during dyadic interactions. For instance, in a study on anxious and depressed mothers, Granat et al. (2017) discovered that anxious mothers exhibited high levels of gaze and touch synchrony while depressed mothers showed reduced behavioural synchrony. Although the study was conducted on anxious maternal traits rather than attachment constructs, these preliminary results suggest that excessive behavioural synchrony may be a detrimental attribute of anxious mothers.

Recent studies on physiological synchrony further suggests that excessive coupling may serve as a marker of hypervigilance and maternal anxiety. For example, Pratt et al. (2017) evinced that parents who are hypervigilant towards their child exhibit dyadic adrenocortical synchrony to an atypically high degree. Such emerging studies posit that there exists an optimal adaptive range of dyadic synchrony, beyond which too much coordination is a hallmark of parental hypervigilance and renders behavioural coupling maladaptive (Beebe et al., 2011). In another recent study, Smith et al. (2019) examined the moment-to-moment changes in autonomic activity of mother-child dyads along with vocalisations of both the mother and the child. The researchers recorded the vocalisations and autonomic activity of the mothers and infants throughout the day in their natural home setting. Upon comparing how non-anxious and anxious mothers reacted to small- and large-scale physiological changes in their children, the authors discovered that non-anxious mothers exhibited changes in physiological arousal which was coupled to their child's peak arousal

activities only. Children whose mothers react specifically to peak events were found to have a faster rate of recovery from negative emotions. In comparison, anxious mothers were more reactive and showed changes in arousal that matched even the miniscule fluctuations in their child's arousal levels, in addition to large-scale peak physiological events. These findings suggest that anxious mothers did not differentiate between moments of peak arousal from natural physiological variations in their child, which led the authors to posit that anxious mothers tend to be hyper-reactive. Moreover, their discovery is in line with the profile of an overly stimulating anxious mother previously described by Feldman (2007a). Due to the hyper-reactivity of anxious mothers to small-scale changes in their child, the child might be left with little opportunity to feel calm and engage in self-regulation. However, it should be noted that the recent studies by Granat et al. (2017) and Smith et al. (2019) focused on anxious mothers, rather than anxiously-attached mothers.

The literature on maternal anxious attachment and mother-child inter-brain synchrony remains scarce, with only one fNIRS study by Nguyen et al. (2018) showing that greater synchrony was observed in the PFC of dyads with mothers of higher anxious attachment, but not with those of higher avoidant attachment, when dyads engaged in a cooperative tangram puzzle task together. In a related study that used fMRI to measure mothers' individual brain responses to videos of their own interaction with their child, Atzil, Hendler and Feldman (2011) demonstrated that intrusive anxiously-attached mothers displayed greater neural disorganisation compared to their securely-attached counterparts. Although we have ascertained that differences in the neural responsivity of anxiously- and securely-attached mothers exist, the current literature is divided as to whether synchrony in the context of maternal anxious attachment is an adaptive or maladaptive trait. The emerging hypothesis that greater synchrony, instead of less synchrony, is observed especially

among dyads of anxiously-attached mothers warrant further investigation given that it runs contrary to the prevailing hypothesis that connotes greater mother-child synchrony to be adaptive.

Research Gap in Parent-child Inter-brain Synchrony Literature

A review of the literature on parent-child inter-brain synchrony has revealed several research gaps that ought to be addressed. First, studies on inter-brain synchrony have been predominantly conducted in an interactive setting. Social interactions are indubitably crucial to affiliative bonding between parent and child, and facilitates the child's cognitive and social development, making investigations into this developmental area paramount. However, in an increasingly digital age, parents often engage with their children through a screen medium, and such social activities are rendered more passive in nature. Despite the extensive prevalence of co-viewing of television shows, no study has employed a passive paradigm when investigating inter-brain synchrony.

Second, there is a paucity of research on the impact of parental factors on inter-brain synchrony. To date, only Nguyen et al. (2020a) has investigated both the effect of maternal parenting stress and maternal adult attachment style on inter-brain synchrony, despite the prominence of these two parental factors in affecting the parent-child relationship. Both parenting stress and insecure maternal anxious attachment are known to undermine the quality of the parent-child relationship, which thus demand further inspection as to their roles in modulating inter-brain synchrony.

Third, the long-held predominant view of synchrony as an inherently adaptive trait in parent-child relationships, marking the coordination of shared internal states between a parent and child (Feldman, 2007), has been placed under scrutiny in recent years. Emerging studies have

demonstrated that excessive synchrony might in fact be a symptom of maladaptive relationships (Smith et al. , 2019). Such discrepancy within the existing literature should be addressed before a clear argument can be presented about the clinical applications of synchrony within the parent-child context.

Research Questions and Hypotheses

To address these research gaps, Study 2 (Chapter 4) would employ fNIRS hyperscanning to measure prefrontal cortical (PFC) responses of mother-child dyads during co-viewing of children's animation shows together. Dyadic inter-brain synchrony would be computed and assessed in relation to parenting stress scores and maternal anxious attachment style. These two analyses would fulfil the lack of investigation on inter-brain synchrony in passive dyadic contexts alongside launching an inquiry as to the possible roles of parental psychological factors in modulating synchrony. The indubitably maladaptive nature of the two maternal factors in question would lend more clarity to the interpretation of findings. For instance, should less inter-brain synchrony be found with increasing parenting stress, it is likely that greater synchrony during co-viewing is adaptive.

Although previous studies have predominantly examined inter-brain synchrony within an interactive context, there is ground to postulate that synchrony would be observed in a passive task like co-viewing of animation scenes together (Hasson et al., 2012). To understand the emotions and perspectives of characters in a movie, and the plot of a narrative excerpt as a whole, socio-cognitive processes in the PFC which are associated with mentalisation are recruited (Lyons et al., 2019; Yeshurun et al., 2017). Since the mother and child would be presented with the same

videos, inter-brain synchrony is expected to be observed in a passive co-viewing paradigm, particularly in medial regions of the brain which are responsible for mentalisation.

However, there is also ground to posit that maternal parenting stress and maternal anxious attachment would influence the degree to which inter-brain synchrony in the PFC would be observed. One previous fMRI study by Noriuchi et al. (2019) examined the brain responses of 28 mothers while passively watching video vignettes of their own preschool children and other preschool children being fed. The authors found that mothers with higher parenting stress showed lower activation of the orbitofrontal cortex (OFC), a brain area which lies within the mPFC and is responsible for the recognition of social cues (Dal Monte et al., 2013, Willis et al., 2014). Likewise, women with an anxious attachment orientation have been demonstrated to display a disproportionately greater brain activation when passively viewing pictures of crying infants (Ma et al., 2017). Donges et al. (2012) have also previously shown that persons with anxious-related attachment displayed greater brain activities in several brain regions, including the PFC. These studies suggest that individuals with higher levels of parenting stress and attachment anxiety exercise fundamentally different cognitive processes compared to their less stressed and anxiously attached counterparts, and that these differences can be observed in brain signals during passive paradigms. It has yet to be determined, however, whether maternal parenting stress and maternal anxious attachment can be captured with a measure of inter-brain synchrony. A potential association between maternal variables and inter-brain synchrony during a passive co-viewing paradigm points to the possibility of a pre-existing “default” mismatch in the cognitive processes of these mother-child pairs even prior to the production of any behavioural output. Nonetheless, subsequent studies would need to be conducted to further verify the robustness of this hypothesis and replicate the findings arising from this thesis.

We postulated one research question (RQ) and hypothesis (H) specific to parenting stress:

RQ . Do dyads with mothers who report more parenting stress exhibit less parent-child inter-brain synchrony in the PFC when co-viewing children's shows together?

H1. We expected dyads of mothers who reported greater parenting stress to exhibit reduced inter-brain synchrony during co-viewing, as parenting stress has been shown to impede parent-child behavioural synchrony in general. To rule out the alternate explanation that a difference in inter-brain synchrony is solely due to more stressed mothers displaying different patterns of social cognitive responses to the emotional content of the videos compared to less stressed mothers, a general linear model on maternal brain responses and parenting stress score would also be conducted. A lack of significant result from this preliminary analysis would lend support to the hypothesis that dyads with more stressed mothers have greater mismatches in brain signals, therefore reduced inter-brain synchrony.

Due to an emerging discrepancy as to the adaptive function of synchrony especially in mothers with an anxious attachment style, this chapter focuses only on maternal attachment anxiety. The following RQs and hypotheses were formulated for maternal anxious attachment:

RQ1. Do dyads with mothers who scored higher on anxious adult attachment show less parent-child inter-brain synchrony in the PFC when co-viewing children's shows together?

H1. We hypothesised that less inter-brain synchrony would be observed in dyads with anxiously-attached mothers. This hypothesis was informed by the mentalisation models previously proposed (Fonagy & Luyten, 2009b; Lieberman, 2007), which described how an anxious attachment style is associated with reliance on social cues to interpret the mental states of others

(i.e., emotional mentalisation). Thus, anxiously-attached mothers are likely to be more preoccupied with their child's cues which potentially detracts their attention away from the stimuli, thereby impeding inter-brain synchrony in joint processing of narrative scenes together. To rule out the alternate explanation that a difference in inter-brain synchrony is solely due to more anxiously-attached mothers displaying different patterns of social cognitive responses towards the videos compared to less anxiously-attached mothers, a general linear model on maternal brain responses and maternal anxiety score would also be conducted. A lack of significant result from this preliminary analysis would lend support to the hypothesis that dyads with more stressed mothers have greater mismatches in brain signals, therefore reduced inter-brain synchrony.

Findings from this chapter would uncover how parenting stress and maternal attachment style modulate the joint processing of narrative scenes during a common activity of co-viewing narrative scenes together.

Co-viewing in Preschoolers, Mothers and Fathers

Preschoolers' Developmental Processing of the Television

Theory of Mind (TOM) processes allow humans to reason about the mental states of others and, in the context of television-viewing, serve to facilitate children's abilities to understand and interpret character's mental states as well as their verbal and non-verbal cues. These complex integrations reside primarily in the medial prefrontal region, along with the temporal parietal junction and the precuneus (Naci et al., 2014; Yeshurun et al., 2017). Seminal studies have uncovered that TOM emerges in infancy and develops sufficiently enough to be detected in the child's first year (Kovács et al., 2010; Southgate & Verneti, 2014) and second year of life (e.g., Onishi & Baillargeon, 2005; Southgate et al., 2007; Surian & Geraci, 2012). At around the

developmental age of 3 years old, children have developed a distinct TOM network (Richardson et al., 2018). Children's TOM matures in parallel to their comprehension of narrative television scenes. At the tender age of 6 months, infants develop the capacity to attend to a television screen. Comprehension of child-directed television, however, only starts to emerge at 2 years of age (Anderson & Hanson, 2010). By the age of 3, children's comprehension of narrative television scenes have much improved due to their wider knowledge base and the life experiences they have accumulated (Anderson et al., 2017).

In an fMRI study that presented 65 3-to-6-year old children with a short excerpt of a child-directed movie, Pixar's "Partly Cloudy", Richardson et al. (2018) compared children's brain responses during snippets when the main characters exhibited physical pain to when the characters implied that they were feeling emotional. The authors found that even children who failed false-belief tasks activated the TOM network when characters were emotional, and that this network was found to be functionally distinct from pain pathways. The authors reasoned that such activation reflects a young child's ability to consider the current events in a movie and mentalise emotions which might not be explicitly described. Their seminal finding suggests that at 3 years old, children are able to comprehend movie stimulus and engage in TOM processes to mentalise characters in narrative scenes, although TOM continues to develop as the child grows up (Dumontheil et al., 2010; Richardson et al., 2018). Parallel findings were reported by Lyons et al. (2019), who recently demonstrated that the lateral prefrontal cortex region of the TOM network played a pertinent role in following a narrative plot. Kirkorian and Anderson (2018) has likewise shown that 4-year old children are capable of comprehending short narrative plots. Adults employ the same TOM network to mentalise about the beliefs and emotions of others (Gallagher et al., 2000; Jacoby et al., 2016; Kobayashi et al., 2007; Schneider et al., 2014), although there is

increased variability in the neural processing of movies in children, compared to adults, due to their less developed functional brain specialisation (Moraczewski et al., 2018).

Aside from their rapidly developing TOM, preschool-age children have also amassed knowledge of the world which allows them to interpret scene transitions in movies (Smith et al., 1985). For instance, understanding that a change in camera angle implies a change in point-of-view from one character to another relies on a child's TOM processes whereas interpreting a scene that transits from an indoor to an outdoor environment requires the child to tap upon his/her previous life experiences of leaving the house and venturing the outdoors. Not all life experiences are accrued at a similar rate in children, and this might have implications on the efficiency and ease with which screen stimuli with different emotional valences are processed. Emotional valence refers to the affective quality of a stimulus (Frijda, 1986). A stimulus with positive valence denotes that it conveys happiness and pleasure whereas that with a negative valence expresses emotions such as sadness and anger. Preschoolers typically acquire sheltered life experiences which have been posited to underpin their selective processing of positively-valenced stimuli (Gao et al., 2010; Kauschke et al., 2019; Leppänen & Hietanen, 2004). Prior to reaching schooling age, children exhibit a proclivity to process positively-valenced stimuli, such as faces and words, disproportionately more efficiently than those with a neutral or negative valence (Gao et al., 2010; Kauschke et al., 2019; Leppänen & Hietanen, 2004). Similarly, it may be possible for preschoolers to process positively-valenced narrative scenes more easily than negatively- or neutrally-valenced scenes.

The gender of the child has also been demonstrated to be pivotal in influencing the processing of stimuli. In a meta-analysis of developmental studies spanning infancy to adolescence, McClure (2000) revealed how girls possess a slight, yet significant, advantage over

boys in processing different facial expressions. Several years later, Charman et al. (2002) and Walker (2005) showed in separate experiments that the child's gender influences his/her success in TOM tasks. One commonly administered TOM task is the false-belief task, in which children must deduce that another individual does not have the same knowledge that the child has. For instance, a child could be shown a jar of candies that contains coins and they would be asked what another person would expect to find in the jar. Charman et al. (2002) and Walker (2005) demonstrated that preschool-aged girls perform significantly better than their male counterparts in the understanding of emotions and in false belief tasks, respectively. These studies generally point to the existence of gender differences in emotional processing at the preschool age, with girls having a slight advantage over boys in this particular domain. Likewise, the child's gender might play a role in the processing of narrative scenes.

Co-viewing Impacts the Parent-child Relationship

Although co-viewing is a typical parent-child activity, there is a stark paucity of research on its effects on the parent-child relationship. As Connell et al. (2015) eloquently argued, if a significant amount of time that parents spend with their children occur in front of the television, and if the presence of media influences parent-child interactions differently than when media is absent, then co-viewing might have important effects on the quality of dyadic interaction and on the child's cognitive and social development. Co-viewing provides opportunities for parents to interact with their children (Masur & Flynn, 2008; Schmitt et al., 2003). Masur and Flynn (2008) found that more than half of parents reported that they played with their young children while co-viewing television programmes, and 90% of parents reported that the television was switched on for at least some time when they interacted with their young children.

Pempek et al. (2011) investigated the behavioural events that transpired between parents and their children when co-viewing the television together. The authors found that longer looking time by either the parent or the child predicted longer looking time of the other member when dyads were presented with child-directed programmes. Moreover, if the parent or child initiated a look at the screen, the other member was likely to look as well, which suggests that parent-child dyads exhibit behavioural synchrony in gaze patterns when co-viewing the television. Previous studies have demonstrated that longer looking time in children is associated with enhanced comprehension (Anderson & Hanson, 2010; Anderson, & Kirkorian, 2006). Thus, co-viewing may be a medium through which the child ultimately develops attentional strategies. Co-viewing of child-directed programmes, in particular, offers opportune moments for parents to scaffold their children's comprehension (Barr et al., 2008) and has been shown to be an effective intervention that enhanced father-child interaction and quality of dyadic bonding (Barr et al., 2014).

Research Gap in Processing of Narrative Scenes When Co-viewing

Greater accessibility to screen media necessitates a more in-depth understanding of how children process narrative scenes. However, there is a paucity of research on this topic which leaves many research gaps to be addressed. First, although several studies have uncovered the role of the parent in regulating children's emotional processing of screen media, these studies have yet to employ a neuroimaging approach in a co-viewing paradigm, where the child's brain activity is examined. Such an investigation would lend significant ecologically valid insights into the central processing that occurs in children during everyday co-viewing of the television. Second, a majority of these studies are skewed towards examining mother-child dyads. With an ever increasing participation of the father in child rearing (Cabrera et al., 2000), it would be of great import to compare the effects of co-viewing with a father against that of a mother. Third, despite burgeoning

studies that point to children's gender differences in processing emotional stimuli, no study has investigated gender differences within a co-viewing paradigm. Researchers have yet to determine if girls would process video stimuli differently from boys in the presence of their parents. Fourth, with the knowledge that preschoolers process positively-valenced stimuli efficiently, it should be examined whether a distinction in prefrontal processing of positive narrative scenes, compared to neutral or negative ones, can be detected during co-viewing.

Beyond the child's processing of narrative scenes, no study has examined differences in how mothers compared to fathers process positive, neutral and negative scenes when co-viewing naturalistically with their sons and daughters. Proponents of differential parenting between mothers and fathers have provided behavioural evidence dating back to the turn of the millennium. Parents often encourage gender-stereotyped socialisation of children in regard to the type of play and household chores the child engages in (Lytton & Romney, 1991; McIntyre & Edwards, 2009; Paquette & Dumont, 2013). For example, mothers have been found to exercise more restriction with their daughters during risky physical activities (Morrongiello & Hogg, 2004) while fathers assert gender stereotypes when speaking with their child regarding emotional expression (van der Pol et al., 2015). Recently, studies have begun to trace the neurobiological mechanisms that might underpin differences in parenting behaviours in relation to the child's gender. For instance, one study by Mascaro et al. (2017) employed an fMRI paradigm to compare between mothers' and fathers' brain processing of their child's positive, neutral and negative emotional expressions. The researchers found that fathers exhibited heightened brain response in the mPFC when viewing their daughters happy facial expressions, whereas they display greater medial orbitofrontal cortex (mOFC) activity when viewing their sons' neutral expressions. The authors posit that these observations in brain responses might translate to real-world differences in how fathers and

mothers behave with their sons and daughters. Despite such significant strides made to examine parental brain responses in relation to child's gender in different emotional conditions, no study has done so within an everyday ecologically-valid context such as co-viewing.

Research Questions and Hypotheses

The research gaps outlined in this section would be addressed in Study 3 (Chapter 5) by examining the prefrontal cortical activity of preschool-aged children, mothers and fathers using fNIRS single-scanning approach as they co-view positive, neutral and negative video clip excerpts of animation movies.

Three research questions (RQ) have been formulated according to the research gaps that have been identified:

RQ 1. Do preschool-age children show different prefrontal processing when watching narrative scenes with their fathers compared to their mothers?

RQ 2. Do girls exhibit stronger prefrontal activation towards positive stimulus compared to boys?

RQ3. Are there distinct PFC activities in response to positive, neutral and negative narrative scenes?

RQ4. Do mothers and fathers exhibit different PFC activity when co-viewing positive, neutral and negative narrative scenes with their sons compared to daughters?

The following hypotheses (H) were conjectured for each of the three research questions:

H1. Given that the majority of the existing studies have found that mothers play an integral regulatory role to children (Baptista et al., 2017; Kiel & Kalomiris, 2015), we predict that children would need to employ less PFC activity to regulate their own emotions when co-viewing a movie with mothers compared to fathers. Thus, it is hypothesised that greater PFC activity would be observed in father-child compared to mother-child dyads who engaged in the same co-viewing paradigm.

H2. Since girls at the preschool-age have been found to have an advantage over boys in processing emotions (Charman et al., 2002; McClure, 2000), and that preschoolers possess an inclination to process positively-valenced stimuli (Gao et al., 2010; Kauschke et al., 2019; Leppänen & Hietanen, 2004), we predict that girls would show greater PFC activity than boys when viewing the positive movie excerpt.

H3. Since children have been found to process positive stimuli more efficiently than negative or neutral ones (Gao et al., 2010; Kauschke et al., 2019; Leppänen & Hietanen, 2004), we expect to observe distinct PFC activity in response to each of the three video stimuli.

H4. Parental brain responses have previously been found to be related to emotional condition and child's gender (e.g., Macaro et al., 2017). In line with this observation, we likewise predict that fathers will differ from mothers in their PFC responses across emotional conditions of video stimuli and child's gender.

CHAPTER 3

INTER-BRAIN SYNCHRONY IN CO-PARENTING SPOUSES

Methods

Participant Recruitment

27 pairs of heterosexual couples ($N = 54$, Mean age = 33.6, $SD = 5.65$) comprising 27 mothers (Mean age = 32.8, $SD = 5.65$) and 27 fathers (Mean age = 34.4, $SD = 5.67$) were recruited for this study through online platforms, namely parenting forums and Facebook groups. However, data files from 3 couples were omitted from subsequent analyses as their children were either present in the room (2 couples) or cried during the experiment such that the participants' attention was detracted from the stimuli (1 couple). The final sample of 24 parents were included for analyses. The data and materials for this study may be found here: <https://doi.org/10.21979/N9/KF1JOG>.

Participants' suitability to partake in the study was assessed via the following inclusion criteria: i) both members of the couple must be at least 21 years old, ii) couples need to be cohabiting together, iii) couples must be co-parenting a young child under the age of 4 years old ($N = 27$, 15 males and 12 females; Mean age = 17.28 months, $SD = 9.43$ months), iv) couples should not have any known psychological conditions, v) couples should not have medical conditions that impair or otherwise alter oxygen-carrying functions of their blood. Prior approval of all empirical protocols was obtained from the ethics committee of the Psychology department of Nanyang Technological University, Singapore. Participants provided their informed consent

before commencing with the study. As a token of appreciation for volunteering their time, monetary reimbursement was given to each couple at the end of the study.

The above inclusion criteria were specifically selected for several relevant reasons. First, couples need to be cohabiting to allow for co-parenting opportunities and for co-regulation of physiological signals on a daily basis. Second, couples with younger children were recruited as infant vocalisations was one of the experimental stimuli used in the study (see **Table 1**). As such, parents with younger children were selected for as they would have an increased tendency to attend to these vocalisations (Kail, 2002). Third, the device used in this study, fNIRS, measures blood oxygenation and deoxygenation levels as a proxy of brain activation (Villringer et al., 1993). Therefore, persons with blood-related medical conditions that affect normal oxygenation concentration in the blood (e.g., G6PD) were excluded from the study (Beutler, 1994).

To ascertain that the sample size was adequate enough to detect the effects of together-condition (TOG) and separate-condition (SEP) in each channel of the 20-channel fNIRS montage, a power analysis (G*Power version 3.1.9.4, Windows 64bit; Erdfelder et al., 1996) was conducted with an $\alpha = 0.0025$ (corrected for 20 independent tests, i.e., the number of channels in the fNIRS montage). From the analyses, a total of 260 channels ($N_{SEP} = 130$ channels, $N_{TOG} = 130$ channels) were required to observe moderate ($d = 0.5$) and strong ($d = 0.7$) effect sizes with a high power of 0.83 and 0.99 respectively.

Questionnaire

Prior to the fNIRS empirical paradigm, couples completed an online questionnaire which recorded the following sociodemographic information: 1) parental status (i.e., whether parents were primiparous or multiparous), 2) age of their youngest child, and 3) the parenting response

ratio, which is the ratio in which mother: father takes the lead in attending to their child. Each partner was asked the following question: “When you and your partner are together and you hear your child(ren) cry, what is the ratio of mother:father taking the lead in attending to the child(ren)?”. Each parent responded by choosing one of the following answers: 0:5, 1:4, 2:3, 3:2, 4:1 and 5:0. These responses were then coded on a 0 to 1 scale, where 0 denotes mother never taking the lead and father always taking the lead, and 1 indicates that mother always takes the lead and father never takes the lead. Since the ratios provided by the two co-parents might differ, the scores were averaged between them to form the Average Parent Ratio score.

Audio Stimuli

Table 1.

Audio frequency of experimental stimuli

S/No.	Stimulus	Frequency (Hz)
1	Adult female laughter	348.9
2	Infant laughter	331.2
3	Infant cry (low-pitched)	354.3
4	Infant cry (high-pitched)	554.3
5	Adult female cry	318.2
6	Static	Not Applicable

Table 2.

Distress rating of low- and high-pitched infant cry

Stimulus	Gender	Mean	S.D.
Infant cry (low-pitched)	Mothers	2.21	0.885
	Fathers	1.83	0.874
	Combined	1.96	0.876
Infant cry (high-pitched)	Mothers	2.88	1.09
	Fathers	2.29	1.09
	Combined	2.58	1.08

Six audio stimuli were downloaded from a free online public database of sounds (see **Table 1**; Source: Soundcloud social sound platform [sound library]; Ljung, 2008). Of these six stimuli, two reflected negatively-valenced crying vocalisations (Wilkie & Ames, 1986), while another two stimuli represented positively-valenced laughing vocalisations (Provine, 1992). For a control stimulus, a static sound was modified to adopt the temporal structure of an infant cry.

Praat software (version 6.1.08, Macintosh 64bit) was used to trim the sounds to a duration 15s and to modify the frequency of sounds to be between the range of 300Hz and 400Hz. Only Stimulus 4 did not fall within this frequency range as it was specifically adjusted to be 200Hz higher than Stimulus 3 to provide a vocalisation that is more distressing (Zeskind & Marshall, 1988). Aside from Stimulus 4, the rest of the stimuli have been used and validated in two previous studies by Azhari et al. (2018) and Azhari et al. (2020a) which used ECG and fNIRS devices, respectively, to examine non-parents' responses to salient vocalisations.

Stimuli 3 and 4 provided a distinction between less and more distressing infant cry vocalisations. Participants were asked to report the amount of distress they experienced when exposed to the low- and high-pitched infant cries on a 5-point Likert scale, where 1 denoted “not distressing at all” and 5 denoted “extremely distressing” (see **Table 2**). Paired t-test analyses between the two sounds revealed that the high-pitched cry induced significantly greater distress compared to the lower pitched cry ($t(95) = -4.09$, $p < 0.05$, $d = 0.561$).

Auditory stimuli were presented to participants in a randomised order using NIRStim (NIRx Medical Technologies LLC, 2000, Version 4.0, Windows 64bit). In the separate-condition, auditory stimuli were played to participants through headphones set at a volume of 27.5dB so as to simulate the experience of listening to the sound stimuli individually, whereas in the together-condition, auditory stimuli were presented aloud at 44dB to emphasise the shared experience of listening to sounds together.

Each of the six sound stimuli was presented thrice for a period of 15s each. An inter-stimulus interval (ISI) in the form of a white fixation cross against a black background was screened to participants via a 38-cm Acer Laptop for 10s between every two sound stimuli. The fixation cross was only present when no sound was being presented to the participants. The laptop was positioned about 40cm in front of the participants.

Experimental Procedure

This study consisted of a home-based online questionnaire and an fNIRS empirical component. Upon completing the online questionnaire, participants were invited to Nanyang Technological University (NTU) to partake in two fNIRS sessions, within the same laboratory visit, which were counterbalanced across different couples: together-condition (TOG) and

separate-condition (SEP). In the SEP condition, each partner listened to auditory stimuli individually and at staggered times. When one partner participates in the SEP condition, the other partner waits outside the fNIRS testing room, in the reception area. The order in which the SEP condition was conducted was also counterbalanced across couples such that the father might undergo the SEP condition first for one couple, whereas the mother might undergo the SEP condition first for another couple.

Conversely, the TOG condition required spouses to listen to auditory stimuli together, whilst being in the same room (**Figure 1**). Couples were requested not to engage in physical touch as touch could confound the result of inter-brain synchrony (Chatel-Goldman et al., 2014). Participants were instructed to attend to the sounds, refrain from verbal communication and fixate their gaze on the fixation cross when it appears, so as to prevent eye contact between partners.

Figure 1. Experimental set-up in together (left) and separated (right) conditions.

fNIRS Recording

Brain activity of the PFC was obtained at a sampling rate of 7.81Hz using the NIRSport system (NIRSport, NIRx Medical Technologies LLC). Near-infrared LED lights of 760nm and

850nm wavelengths were shone onto the scalp of participants via optodes to collect optical density data which is reflected differently by oxygenated (oxyHB) compared to deoxygenated haemoglobin (deoxyHB) (Ferrari & Quaresima, 2012). The concentration of oxyHB, which served as a proxy of localised brain activation, and deoxyHB, which indicated brain deactivation, could then be computed. Brain activity of couples were collected simultaneously in hyperscanning mode during the TOG condition, whereas in the SEP condition, fNIRS recording was conducted individually using the single scanning mode.

As the present study focuses on the PFC region, a 20-channel PFC montage comprising 8 sources and 7 detectors was used (**Figure 2**). This channel configuration was analogous to the PFC setup of the international 10-20 system used in electroencephalogram (EEG) experiments (Homan et al., 1987). The channels were configured using the NIRStar software (v15.2, Windows 64bit). Similar channel setups were used in previous fNIRS studies (Azhari et al., 2019; Azhari et al., 2020c; Meszlényi et al., 2017; Yamauchi et al., 2015).

Figure 2. fNIRS montage used in the experiment. 8 sources (grey dots) and 7 detectors (black dots) were used to form the 20-channel configuration (bold lines). Brain areas are marked by different colours. *Note: Superior Frontal Gyrus (SFG), Middle Frontal Gyrus (MFG), Inferior Frontal Gyrus (IFG) and anterior Prefrontal Cortex (aPFC).*

fNIRS Data Preprocessing

Preprocessing of fNIRS data was performed using NIRXlab software (NIRx Medical Technologies LLC, v2016.01, Windows 64bit) to remove noise and motion artifacts from the signals. Signals with a gain of more than 8 and a coefficient of variation which exceeds 7.5 were identified as noisy and these channels were subsequently omitted from further analyses (Blasi et

al., 2014; Pfeifer et al., 2018; Piper et al., 2014). Due to the removal of noisy channels, each channel and condition had a different sample size.

Signals which are usable might still possess spike artifacts, which are marked by abnormally large changes in amplitude of signals. These artifacts are usually caused by motion such as head movements (Xu et al., 2014). In this dataset, artifacts were replaced with the nearest surrounding signals. Discontinuities, which refer to intermittent signal components lacking in continuity due to diminished contact between the optode and the scalp, were also removed. Subsequently, a band pass filter (0.01 Hz - 0.2 Hz) was used on the signal to remove slow and baseline shift variations. The modified Beer-Lambert law was used to convert preprocessed optical signals to haemoglobin concentrations.

Lastly, the oxyHB and deoxyHB signals were visually inspected by two independent coders for validation. An inter-rater agreement of at least 80% was achieved for each subject. Time-series oxyHB signals were exported from NIRSLab for each subject, channel and condition for further analyses.

Computation of Synchrony

Cross-correlations were used to calculate a metric of synchrony between the brain activation patterns of spouses based on their oxyHB signals. This analytical technique computes the degree to which two time-series signals vary with respect to each other (Kettunen et al., 2000; Kettunen & Ravaja, 2000; Mauss et al., 2005). As spousal partners might exhibit slight variations in brain responses, cross-correlation was computed by shifting copies of one signal within a window of -2 to 2s, with step-wise increments of 0.125s each time, an index which is referred to as the Maximum Cross Correlation within a window of 2 s (MCC2). A 2s maximum delay prior

to and after a signal was adopted to account for the temporal delay in the haemodynamic response function in responding to stimuli (Arichi et al., 2012). An MCC2 synchrony index was obtained from true dyads for each of the three trials of each stimulus and then averaged to generate a measure of synchrony for each auditory stimulus. As a control measure, MCC2 indexes were also calculated between randomly paired signals of non-spousal mothers and fathers (e.g., mother 1 with father 2) for each stimulus, channel and SEP and TOG conditions. Since experiencing the inputs from the presence of another individual constitutes an essential component of synchrony, the MCC2 index generated by control dyads do not fulfill the technical definition of synchrony as dyadic control partners did not experience each other's physical presence. To highlight this important distinction, the MCC2 index generated from control dyads would be referred to as similarity indexes whereas the MCC2 indexes generated by true dyads would be referred to as synchrony indexes. The MCC2 method has been used in past studies to measure synchrony across different physiological input and experimental conditions (Bizzego, Azhari, et al., 2019a; Golland et al., 2014a, 2015a). A custom code using pyphysio (Bizzego, Battisti, et al., 2019) and physynch packages (Bizzego et al., 2019) were used for cross-correlations computations.

Analytic Plan

We embarked on Chapter 3 of this thesis with three hypotheses. To test the first hypothesis, that spouses would evince greater inter-brain synchrony in the TOG compared to the SEP condition, Analysis of Variance (ANOVA) was used to compare the distributions of MCC2 synchrony metrics across the two conditions for all auditory stimuli. Since we investigated the effect of spousal copresence in each of the 20 channels, p-values were corrected using Benjamini and Hochberg False Discovery Rate (FDR) correction with $\alpha = 0.05$, across 20 independent tests corresponding to the 20 channels (Benjamini & Hochberg, 1995). As the number of spouses

in SEP compared to TOG conditions differed due to more stringent quality checks necessary in the TOG condition (i.e., the channels of both spousal partners must be acceptable before that channel is analysed), a two-sided Mann-Whitney test was used.

To test the second hypothesis, that synchrony would be unique to co-parenting spouses compared (ie. true couple) to non-spousal partners (i.e., control couple), similarity indexes of randomly paired mother-father brain signals who are not spousal partners served as a control and compared against that of true couples. Similar to how the distribution of synchrony index in TOG and SEP conditions were compared in true couples, the two conditions were also compared in control couples.

To test the third hypothesis that co-parenting spouses are less likely to exhibit inter-brain synchrony towards negative vocalisations, and more likely to synchronise towards positive sounds, the third part of the analyses investigated whether the emotional valence of the auditory stimulus (i.e., positive or negative) is associated with synchrony in spouses. Only channels in which the presence of the spouse was associated with greater synchrony were further investigated with a Mann-Whitney one-sided test to compare the synchrony index across the six stimuli in both SEP and TOG. Similarly, p-values were corrected using Benjamini-Hochberg FDR (Benjamini & Hochberg, 1995), with $\alpha = 0.05$, across 6 independent tests which corresponded to the six auditory stimuli.

Finally, we engaged in exploratory analyses regarding the impact of the following parental variables on inter-brain synchrony: (i) ratio of mother to father attending to their child, (ii) parental status (i.e., primiparous compared to multiparous) and (iii) parents' age. A Mann-Whitney two-sided test was employed to compare between primiparous and multiparous spouses, whereas

Spearman correlations were conducted to examine the role of mother:father caretaking ratio and the age of the parents. Each test conducted on parental variables was first done on all channels together, before they were conducted separately only on the channels which emerged to be significantly different in the SEP compared to TOG conditions. As only 4 channels showed significant difference between SEP and TOG, p-value correction using Benjamini-Hochberg FDR (Benjamini & Hochberg, 1995) was used to correct for $\alpha = 0.05$, across 4 independent tests. Tests that were conducted on true dyads were also performed on control dyads. All analyses were conducted on Python software (python v3.x).

Results

The first hypothesis was that couples would demonstrate greater inter-brain synchrony in the together-condition (TOG) compared to the separate-condition (SEP). From the ANOVA analyses that were conducted, 4 channels emerged to have significantly differed between TOG and SEP conditions: channel 3 (CH3), CH7, CH11 and CH13. Across these 4 channels, the TOG condition elicited greater synchrony compared to the SEP condition (see **Table 3**). These channels corresponded to the left inferior frontal gyrus (IFG), left middle frontal gyrus (MFG) and bilateral anterior PFC (aPFC). See **Table 4** for results on all channels.

The second hypothesis was formulated to test whether the increased synchrony observed in true couples was due to the unique presence of the co-parenting spousal partner. To do this, ANOVA analysis was also conducted on control dyads to determine if any channel was significantly different in TOG compared to SEP conditions. The results revealed that no channel showed an increase in similarity index in TOG, compared to SEP, amongst control couples. From

these results, it can be concluded that TOG elicited enhanced inter-brain synchrony only among true couples, but not in control couples.

Table 3.

Synchrony values in true couples in together and separate conditions.

Channel	Area	SEP			TOG			p-uncorr	p-corr	d
		Mean	SD	N	Mean	SD	N			
3	IFG	0.007	0.025	141	0.031	0.083	138	0.00221	0.015	0.4
7	MFG	0.009	0.025	135	0.024	0.045	132	0.00041	0.004	0.4
11	aPFC	0.013	0.064	135	0.062	0.119	138	0.00003	0.001	0.5
13	aPFC	0.026	0.109	135	0.043	0.090	138	0.00484	0.024	0.2

Note. Table depicting MCC2 synchrony values in true couples in TOG and SEP conditions in CH3, CH7 CH11 and CH13, which are channels that are found to be significantly different between TOG and SEP in true couples. IFG = inferior frontal gyrus, MFG = middle frontal gyrus, aPFC = anterior prefrontal cortex, p-uncorr = uncorrected p-value, p-corr = corrected p-value.

Table 4.

Comparison of synchrony values between SEP and TOG conditions in all 20 channels.

Channel	SEP			TOG			p-uncorr
	Mean	SD	N	Mean	SD	N	
1	0.006	0.046	135	0.033	0.107	132	0.028

2	0.021	0.048	141	0.047	0.105	126	0.091
3	0.007	0.025	141	0.031	0.083	138	0.002
4	0.015	0.051	141	0.041	0.095	120	0.022
5	0.040	0.178	141	0.021	0.300	138	0.547
6	0.010	0.035	141	0.016	0.039	132	0.140
7	0.009	0.025	135	0.024	0.045	132	0.00041
8	0.024	0.064	135	0.045	0.087	132	0.190
9	0.015	0.054	141	0.037	0.116	138	0.096
10	0.011	0.047	135	0.031	0.065	126	0.044
11	0.013	0.064	135	0.062	0.119	138	0.00003
12	0.010	0.029	135	0.021	0.039	138	0.038
13	0.026	0.109	135	0.043	0.090	138	0.005
14	0.008	0.019	141	0.012	0.024	132	0.341
15	0.039	0.168	135	0.021	0.118	138	0.735
16	0.001	0.362	135	0.022	0.060	138	0.032
17	0.019	0.050	135	0.095	0.291	126	0.343
18	0.011	0.034	141	0.020	0.046	138	0.498
19	0.006	0.069	135	0.023	0.048	126	0.093

20	0.012	0.034	141	0.024	0.085	120	0.419
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Note. p-uncorr = uncorrected p-value.

The third hypothesis predicted that couples would show greater inter-brain synchronisation when presented with positive, compared to negative auditory stimuli. When analysing the effect of sound across the 4 channels which significantly varied between TOG and SEP conditions, we found that infant laughter, adult laughter and static sound elicited greater synchrony in TOG than SEP (see **Figure 3**). Out of the 4 channels, only CH13, corresponding to the right aPFC, showed no significant difference across sound stimuli. CH3, CH7 and CH11, which mapped to the left IFG, left MFG and left aPFC, showed increased synchrony towards infant laughter compared to the other sound stimuli. CH7 and CH11 also evinced increased synchrony towards adult laughter and static sounds. However, no significant differences were found for infant cry (both high- and low-pitched) and adult cry.

Finally, we embarked on exploratory analyses to determine whether the following parental variables modulated the effects of physical presence of spousal partner: (i) the ratio of the mother: father attending to the child, as measured by the Average Co-parenting Ratio Score, (ii) the parental status of the parents (i.e., primiparous or multiparous) and (iii) the age of the parents. Since our aim is to examine the modulating effect of these variables on the effect of spousal presence, analyses were only conducted on CH3, CH7, CH11 and CH13.

Figure 3. MCC2 indexes between SEP (red) and TOG (blue) conditions across the 6 auditory stimuli in CH3, CH7, CH11 and CH13 in which the effect of physical presence of a spousal partner was found to be significant.

(i) *Average Co-parenting Ratio Score*

Analysis of the 4 pooled channels revealed an overall increase in synchrony with a higher Average Co-parenting Ratio score in which mother takes the lead more so than father in caretaking activities ($\rho = 0.18$, $p = 0.00003$). Subsequent analyses of the 4 individual channels (see **Table 5**) generated significant positive correlations in CH7 (MFG, $\rho = 0.29$, $p = 0.004$) and CH11 (left aPFC, $\rho = 0.23$, $p = 0.015$) between MCC2 synchrony and Average Co-parenting Ratio score. See **Table 6** for results on all channels.

Table 5.

Correlations statistics between synchrony values and Average Parenting Ratio score in TOG and SEP conditions for pooled channels, CH3, CH7, CH11 and CH13 wherein the significant effect of physical presence of partner was observed.

Channel	Area	SEP		TOG	
		rho	p-corr	rho	p-corr
All	PFC	0.00	0.974	0.18	0.00003
3	IFG	0.01	0.894	0.06	0.478 [^]
7	MFG	0.07	0.801	0.29	0.004 [^]
11	aPFC	-0.07	0.801	0.23	0.015 [^]
13	aPFC	0.04	0.833	0.18	0.053 [^]

Note. p-corr = corrected p-value, [^] corrected for multiple comparisons (FDR B-H Method, 4 independent tests corresponding to the 4 channels).

Table 6.

Correlations of synchrony values and Average Parenting Ratio score in SEP condition in all 20 channels. Rows in bold indicate significant results.

Channel	N	rho	p-corr
1	132	0.259	0.014
2	126	0.269	0.014
3	138	0.061	0.531
4	120	0.149	0.173
5	138	0.141	0.173
6	132	0.102	0.328
7	132	0.286	0.009
8	132	0.302	0.009
9	138	0.113	0.269
10	126	0.179	0.100
11	138	0.226	0.030
12	138	0.123	0.230
13	138	0.175	0.100
14	132	0.192	0.077
15	138	0.139	0.173

16	138	0.084	0.387
17	126	0.228	0.034
18	138	0.090	0.365
19	126	0.011	0.901
20	120	-0.029	0.796

Note. p-corr = corrected p-value. All results were corrected for multiple comparisons (FDR B-H Method, 20 independent tests to the 20 channels).

(ii) Parental status of the parents (i.e., primiparous or multiparous)

Investigations on the moderating effect of parental status evinced that significantly greater synchrony was present in primiparous couples, compared to their multiparous counterparts ($p = 0.00066$, $\text{Mean}_{\text{primiparous}} = 0.117$, $\text{Mean}_{\text{multiparous}} = 0.028$) in the together condition, when the 4 channels were pooled together. Upon analysing individual channels, CH7 emerged to be significantly more synchronous in primiparous compared to multiparous couples ($p = 0.036$, $\text{Mean}_{\text{primiparous}} = 0.041$, $\text{Mean}_{\text{multiparous}} = 0.014$; see **Table 7**) in the together condition. Since none of the 4 channels showed a significant difference between multiparous and primiparous couples in the separate condition, **Table 8** depicts the results on the comparison between primiparous and multiparous couples in all channels in the separate condition.

(iii) Parental age

Analysis of parental age and synchrony found a negative association between the two factors when the 4 channels were pooled together for average parent's age ($\rho = -0.11$, $p=0.01$),

mother's age ($\rho = -0.10$, $p = 0.01$) and father's age ($\rho = -0.14$, $p = 0.001$). When individual channels were investigated, CH13 was found to show a significant negative correlation between father's age and synchrony ($\rho = -0.22$, $p = 0.03$, **Table 9**). All the associations with parental age showed that younger parents displayed more synchrony. See **Table 10** for results on all channels. None of the tests conducted on true dyads were found to be significant in control dyads.

Table 7.

Comparisons between synchrony values of primiparous and multiparous couples in TOG and SEP conditions for pooled channels, CH3, CH7, CH11 and CH13 wherein the significant effect of physical presence of partner was observed.

		SEP					TOG				
		Primiparous			Multiparous		Primiparous			Multiparous	
Channel	Area	Mean	SD	p-corr	Mean	SD	Mean	SD	p-corr	Mean	SD
All	PFC	0.017	0.094	0.453	0.011	0.034	0.060	0.117	0.0006	0.028	0.065
3	IFG	0.003	0.023	0.307^	0.010	0.027	0.036	0.089	0.310^	0.027	0.079
7	MFG	0.010	0.033	0.444^	0.008	0.018	0.041	0.059	0.004^	0.014	0.031
11	aPFC	0.009	0.082	0.444^	0.016	0.046	0.094	0.166	0.092^	0.042	0.069
13	aPFC	0.045	0.161	0.307^	0.012	0.037	0.067	0.114	0.069^	0.028	0.067

Note. p-corr = corrected p-value. ^ corrected for multiple comparisons (FDR B-H Method, 4 independent tests corresponding to the 4 channels). Rows in bold indicate significant results.

Table 8.

Comparison of synchrony values between primiparous and multiparous couples in SEP condition across all channels. Rows in bold indicate significant results.

Channel	Multiparous			Primiparous			Mann-Whitney Statistics	
	N	Mean	SD	N	Mean	SD	U	p-corr
1	54	0.047	0.122	78	0.024	0.093	1994	0.388
2	48	0.065	0.124	78	0.035	0.090	1627	0.199
3	54	0.036	0.089	84	0.027	0.079	2154	0.388
4	54	0.052	0.108	66	0.032	0.081	1738	0.431
5	54	0.015	0.472	84	0.025	0.066	2196	0.419
6	48	0.028	0.042	84	0.009	0.035	1425	0.022
7	48	0.041	0.059	84	0.014	0.031	1354	0.018
8	54	0.058	0.113	78	0.037	0.061	2031	0.419
9	54	0.036	0.122	84	0.038	0.112	1832	0,096
10	54	0.046	0.085	72	0.021	0.040	1505	0.061
11	54	0.094	0.166	84	0.042	0.069	1927	0.172
12	54	0.028	0.034	84	0.016	0.041	1645	0.022
13	54	0.067	0.114	84	0.028	0.067	1850	0.098
14	54	0.017	0.027	78	0.009	0.022	1579	0.037

15	54	0.035	0.170	84	0.011	0.065	1960	0.180
16	54	0.032	0.079	84	0.015	0.041	1960	0.180
17	48	0.186	0.443	78	0.039	0.085	1856	0.469
18	54	0.020	0.049	84	0.020	0.043	2127	0.388
19	48	0.029	0.053	78	0.020	0.044	1751	0.388
20	42	0.008	0.057	78	0.033	0.096	1519	0.388

Note. p-corr = corrected p-value. All results were corrected for multiple comparisons (FDR B-H Method, 20 independent tests corresponding to 20 channels).

Table 9.

Correlations statistics between synchrony values and parental age in TOG and SEP conditions for pooled channels, CH3, CH7, CH11 and CH13 wherein the significant effect of physical presence of partner was observed.

Channel	Area	Average Parent's Age				Mother's Age				Father's Age			
		SEP		TOG		SEP		TOG		SEP		TOG	
		rho	p-corr	rho	p-corr	rho	p-corr	rho	p-corr	rho	p-corr	rho	p-corr
all	PFC	0.03	0.436^	-0.11	0.019	0.02	0.683	-0.10	0.015	0.04	0.307	-0.14	0.001
3	IFG	0.03	0.9^	-0.04	0.635^	-0.02	0.919^	-0.01	0.902^	0.12	0.697^	-0.11	0.28^
7	MFG	0.04	0.9^	-0.07	0.582^	0.03	0.919^	-0.10	0.324^	0.02	0.843^	-0.03	0.733^

11	aPFC	0.07	0.9^	-0.13	0.265^	0.06	0.919^	-0.11	0.324^	0.08	0.767^	-0.17	0.081^
13	aPFC	-0.01	0.9^	-0.21	0.057^	-0.01	0.919^	-0.20	0.073^	-0.04	0.843	-0.22	0.032

Note. p-corr = corrected p-value. ^: corrected for multiple comparisons (FDR B-H Method, 4 independent tests corresponding to the 4 channels). Rows in bold indicate significant results.

Table 10.

Correlations between synchrony values and parental age in SEP and TOG conditions across all channels. Rows in bold indicate significant results.

Channel	N	Average Parent's Age		Mother's Age		Father's Age	
		rho	p-corr	rho	p-corr	rho	p-corr
1	132	-0.159	0.198	-0.196	0.083	-0.114	0.295
2	126	-0.186	0.123	-0.188	0.087	-0.203	0.090
3	138	-0.041	0.668	-0.011	0.902	-0.107	0.297
4	120	-0.227	0.071	-0.205	0.083	-0.272	0.018
5	138	-0.035	0.688	-0.028	0.827	-0.054	0.591
6	132	-0.100	0.361	-0.038	0.781	-0.168	0.119
7	132	-0.068	0.537	-0.102	0.347	-0.030	0.772
8	132	-0.105	0.352	-0.196	0.083	-0.007	0.934
9	138	-0.122	0.278	-0.176	0.087	-0.074	0.463
10	126	-0.137	0.265	-0.131	0.263	-0.150	0.169

11	138	-0.129	0.265	-0.114	0.307	-0.175	0.119
12	138	-0.262	0.019	-0.234	0.058	-0.256	0.018
13	138	-0.208	0.071	-0.201	0.083	-0.225	0.040
14	132	-0.338	0.001	-0.283	0.020	-0.377	0.000
15	138	-0.187	0.111	-0.176	0.087	-0.157	0.131
16	138	-0.064	0.537	-0.052	0.679	-0.105	0.297
17	126	-0.143	0.265	-0.142	0.225	-0.173	0.119
18	138	0.072	0.533	0.094	0.364	0.073	0.463
19	126	-0.121	0.293	-0.113	0.319	-0.145	0.175
20	120	0.064	0.543	-0.020	0.870	0.177	0.119

Note. p-corr = corrected p-value. All results have been corrected for multiple comparisons (FDR B-H Method, 20 independent tests corresponding to 20 channels).

Discussion

Co-parenting an infant naturally invokes the perception that partners need to harmonise their caregiving responses with each other. This chapter aimed to examine whether the physical presence of a spousal partner affects inter-brain synchrony between co-parents when they are exposed to salient human vocalisations. Three predictive hypotheses and one exploratory hypothesis were tested. The first hypothesis aimed to show that co-parenting partners exhibited greater synchrony towards the salient vocalisations in the together-condition (i.e., TOG), when they were in each other's presence, compared to when they engaged in the task individually in the

separate-condition (i.e., SEP). This hypothesis was fulfilled as synchrony in the left inferior frontal gyrus (IFG), left middle frontal gyrus (MFG) and bilateral anterior PFC (aPFC) was found to be significantly greater in TOG compared to SEP conditions. These implicated PFC regions are part of the attentional and cognitive control network in the brain (Lin et al., 2015; Rossi et al., 2009). The second hypothesis aimed to demonstrate that the effect of physical co-presence was specific to co-parenting partners and would not be observed in randomly paired brain signals. This hypothesis was supported too as we found that only true couples showed an increase in synchrony in the TOG compared to the SEP condition, whereas control couples did not show an increase in similarity index in TOG compared to SEP. From the first hypothesis, physical presence of a co-parenting spousal partner elicited significantly greater synchrony in only four channels. From these identified channels, the third aim was to test if the emotional valence of auditory stimuli modulated synchrony. Of the six sounds, only infant laughter, adult laughter, and static sounds generated enhanced synchrony in TOG compared to SEP. From this finding, it could be observed that positively-valenced and neutral sound stimuli, but not negatively-valenced sounds, were associated with synchrony, thus fulfilling the third hypothesis. Finally, we tested an exploratory hypothesis to ascertain whether parents' characteristics influenced synchrony between spousal partners. Analyses of parental characteristics revealed that when the mother, rather than the father, led in caretaking activities, synchrony within the couple was greater in the left MFG and aPFC. Moreover, first-time parents (i.e., primiparous couples) also showed more synchrony compared to their experienced (i.e., multiparous) counterparts. The age of parents was also found to be associated with synchrony, with younger parents exhibiting greater synchrony. Overall, the findings from this study suggest that the physical presence of a co-parenting spousal partner

increases inter-brain synchrony that is unique to the couple, and that stimuli factors and social characteristics might further influence this effect.

The primary finding from this chapter is that the physical presence of a spouse facilitates the enhancement of inter-brain synchrony in attentional and cognitive control networks. These networks span the dual dorsal and ventral prefrontal streams (Corbetta & Shulman, 2002) which are activated upon exposure to emotive human vocalisations like cry and laughter (Koch et al., 2008). These two pathways inhabit specialised functions, where the dorsal route oversees voluntary endogenous (i.e., top-down) attention, whereas the ventral route regulates involuntary exogenous (i.e., bottom-up) attention, such as that initiated by a cued shift in attention from an environmental stimulus. In spite of their respective specialisations, these two streams communicate to enact flexibility between endogenous and exogenous modes of attention (Buschman & Miller, 2007; Weissman & Prado, 2012). In particular, the MFG serves as the point of contact between the attentional streams, thus serving as a “circuit-breaker” in the network (Corbetta et al., 2008; Fox et al., 2006; He et al., 2007). Straddling the two attentional pathways, the MFG thus allows for flexible switching between endogenous and exogenous attention (Rossi et al., 2014). The present study had participants focusing on the fixation cross in the absence of auditory stimuli, thereby inducing top-down attention, while the subsequent disappearance of the fixation cross along with exposure to sounds triggered bottom-up attentional processing. This experimental design hence captures attentional switching processes which is primarily facilitated by the MFG. Along the same vein, inter-brain synchrony in the area that implicates the MFG suggests that co-parenting spouses exhibit coupled attentional switching processes when they are in each other’s physical presence.

Additionally, synchronous brain activation also occurred in the IFG, which, together with the MFG, govern attentional regulation towards salient emotional information (Ferstl et al., 2005; Schirmer et al., 2004). Beyond attentional pathways, synchrony was also evident in the bilateral PFC, which is an area of the brain that is implicated in the frontoparietal control network (Choi et al., 2012; Lin et al., 2015; Vincent et al., 2008) which facilitates decision-making (Spreng et al., 2010) and executive control (Dosenbach et al., 2006). The emergence of synchrony in the IFG, MFG and bilateral PFC cumulatively suggest that the physical presence of a co-parenting spouse enhances the coordination of attentional and executive processes in the couples which could potentially facilitate subsequent concerted behaviours. Previous studies have demonstrated the occurrence of physiological co-regulation in couples (e.g., Diamond et al., 2008; Saxbe & Repetti, 2010), which further supports our observation of synchrony at the neurophysiological level that is unique to co-parenting couples.

The absence of any observed inter-brain synchrony in response to negatively-valenced auditory stimuli might be beneficial, and indeed even adaptive, to co-parenting spouses. In the extant literature, synchrony is commonly portrayed as a positive phenomenon. However, several studies have revealed that synchrony might not always be advantageous for the spousal relationship, with some showing that synchrony might reflect maladaptive emotional co-regulation (Liu et al., 2013; Wilson et al., 2018). For instance, studies that investigated couples who undergo high degrees of conflict found associations between these maladaptive relationships and synchrony in heart rate variability (Wilson et al., 2018) as well as in cortisol fluctuations (Liu et al., 2013). From these observations, the authors postulated that physiological synchrony in such cases could be interpreted as an inclination for partners to be reflexively influenced by each other during negative, stressful and conflict-ridden situations. Within the co-parenting context, synchrony in

response to aversive and stressful cry stimuli might similarly signify maladaptive co-regulatory processes between spouses which hinder optimal caregiving behaviours. In this particular study, inter-brain synchrony in attentional and cognitive control networks was not observed for cry stimuli which is arguably adaptive since these networks are critical in supporting a parent's ability to effectively respond to a crying child, manage his/her own personal distress, engage in flexible parenting (Kienhuis et al., 2010) and execute daily caregiving behaviours (Barrett & Fleming, 2011; Kienhuis et al., 2010). Likewise, if a parent is easily affected by the stress felt by his/her spouse when their infant is crying, co-parenting partners may be less effective in coordinating optimal caregiving responses to soothe their child. Although there is still much debate about whether synchrony serves as a positive or negative marker of spousal and parenting relationships, the findings brought to light from this chapter suggests that inter-brain synchrony in attentional and cognitive control regions serve as adaptive mechanisms overall, but may turn maladaptive in conflictual situations.

One possible explanation for the increased synchrony towards static noise in TOG compared to SEP is that synchrony is enhanced in non-negative emotional conditions, which encompasses neutral stimuli. According to a physiological synchrony study by Wilson et al. (2018) on married couples, partners tend to avoid synchronising with each other during stressful situations. On the contrary, partners tend to synchronise to situations that do not elicit distress so as to remain socially attuned to each other's emotional states. In another study, Bizzego et al. (2020) examined the degree of physiological synchrony across romantic partners, friends and strangers when each pair was presented with video vignettes which elicited different emotional conditions (i.e., fear, embarrassment, romance, pride, sadness, calmness/neutral). They demonstrated that romantic partners displayed significantly greater synchrony towards the neutral

non-social stimulus which depicted a scene of waves rolling onto the beach. These studies support the argument that co-parenting partners synchronised with each other towards the non-social static stimulus as a way to establish social connectedness when together.

Several parental characteristics, namely the ratio of mother to father taking the lead in caregiving activities, primiparous or multiparous parental status, and the age of parents, emerged as factors that modulate inter-brain synchrony between co-parenting spouses. However, these parental variables were largely found to be statistically significant in TOG, but not in SEP, which leads to the postulation that the physical presence of a spouse lends an additional social element to partners' brain responses to salient auditory stimuli. First, we found that enhanced inter-brain synchrony was related to a higher ratio of mother to father responding to the needs of the child. To interpret this result, we draw upon long-established family systems theories which propose gender role differences between mothers and fathers in the family. In particular, primarily the mother plays the role of mediator and peacemaker in the family when faced with stressful situations, such as during exposure to a distressed infant (Vuchinich et al., 1988). Since mothers, compared to fathers, are generally more inclined to adopt mediation approaches, they are likely to adjust their reaction to salient vocalisations depending on the emotional cues presented by their partner which hence explains the greater weight that a mother's parenting responses lends to the resultant synchrony in the co-parenting couple. Next, primiparous couples were also found to exhibit enhanced synchrony compared to their multiparous counterparts. Since caring for an infant is a highly demanding task that is fundamentally distinct from other life experiences (Deater-Deckard, 1998; Ostberg & Hagekull, 2013), first-time parents might need to co-regulate themselves to each other more so than multiparous parents who have amassed significantly more co-parenting experiences together. Thus, primiparous and multiparous parents might show different adjustment

patterns (Gameiro et al., 2009) upon exposure to salient infant vocalisations. Additionally, infant vocalisations, especially cries, have been found to elicit a stronger physiological reaction in first-time parents compared to multiparous parents (Boukydis & Burgess, 1982). As such, more pronounced synchrony in primiparous parents might reflect their first concern to coordinate their decision-making processes amidst their heightened reaction in stressful caregiving situations.

Finally, synchrony was negatively correlated to the ages of parents, with less synchrony observed in older parents compared to their younger counterparts. Employing a life-span perspective, aging unlocks new heights of maturity, stability and sense of competence (Bing & Coleman, 1982; Daniels & Weingarten, 1983; Heath, 1994; Roosa, 1988). Frankel and Wise (1982) posited that older parents have developed greater security in their role as parents and partners due to the maturity they have acquired from their broader life experiences. Therefore, diminished synchrony in older spouses might indicate reduced necessity to match their responses to each other as they have established a greater sense of security in their individual caregiving capacity. These observed differences across primiparous and multiparous parental status and age of parents lend support to the notion of a malleable adult brain which becomes modified by parenting experiences in different life stages. At present, existing studies have only uncovered the malleability of the maternal brain (Kim et al., 2010, 2016), though it is probable that a similar process occurs in fathers too. However, as this chapter was not designed in a longitudinal manner, further research has to be conducted to verify these possibilities and elucidate the manner in which these parental variables modulate inter-brain synchrony in co-parenting spouses over time.

Several limitations ought to be highlighted from this study. First, we did not measure brain activation at baseline in the absence of any auditory stimuli which would have given an indication of inter-brain synchrony at resting state. Obtaining this measure would have provided a greater

understanding of the extent to which synchrony was stimulated by the sounds or which was otherwise inherent in the couple even in the absence of any stimulus. Second, we exposed participants to standard infant vocalisations, instead of cry and laughter vocalisations recorded from their own child. Contrasting inter-brain synchrony in a couple's response to their own child, with standard infant vocalisations, could have provided insight to whether synchrony could be elicited specifically in response to the child that the spouses co-parented. Thus, our results might underestimate synchrony in co-parenting couples. Third, our study did not employ a longitudinal design, which would have allowed for observations of changes in inter-brain synchrony over time as the partners accumulated more parenting experiences. Such a design would better reflect differences in the trajectory of synchrony development across different couples. Fourth, this study is limited in its brain area of investigation. By focusing only on the prefrontal cortex (PFC), other implicated regions of the brain such as the amygdala (Atzil et al., 2012) was not examined in our study, although synchrony might be present in these areas too. Fifth, the study did not investigate inter-brain synchrony in relation to parenting competence, which could have played a significant role in eliciting variance in synchrony across different couples. Perceived competence acquired over time in the couple's or individual's parenting abilities could potentially influence inter-brain synchrony of the couple. Sixth, despite having achieved sufficient statistical power to detect differences between SEP and TOG conditions, subsequent investigations could recruit a greater sample size so that more in-depth analyses of auditory and social factors could be conducted. Seventh, the control couples in this study were generated from the arbitrary matching of brain signals between male-female participants who were not couples. This approach introduces a confounding factor where the synchrony generated from the control couple confounds with the physical absence of the control partner. Future studies can employ a different approach in

controlling for this study by matching pairs of male-female strangers together. Eighth, information on the length of the couple's relationship was not obtained. Future studies could analyse the length of couple's relationships to lend more nuance as to how duration of relationship may affect mechanisms of inter-brain synchrony. Lastly, the sample in this study comprised couples with children spanning 0-4 years of age, at various stages of development. This diversity could have been associated with differences in couples' responses to infant vocalisations. For example, compared to couples with older children, their counterparts with younger infants might perceive infant cries and laughter to be more salient as these sounds are more relatable to their immediate parenting experiences. Subsequent studies could opt to distinguish sub-populations of parents from each other.

In conclusion, Chapter 3 has demonstrated how the physical presence of a co-parenting spousal partner enhances inter-brain synchrony in couples, and that synchrony in co-parenting partners are unique. Couples also showed enhanced synchrony in response to positive and neutral sounds, but not towards auditory stimuli with negative valence (i.e., infant cries), in spite of its social salience.

CHAPTER 4

INTER-BRAIN SYNCHRONY IN MOTHER-CHILD DYADS

Methods

Participants

33 mother-child dyads participated in this study, of which 14 of the children were girls (Mean age_{mothers} = 34.7 years, $\pm$ 4.1 years; Mean age_{children} = 41.9 months, $\pm$ 6.1 months). Mother-child dyads were recruited for this study through online platforms such as forums and Facebook groups. Prior to this study, we calculated the adequate sample size for a one-group analytic study to detect a moderate correlation ($r=0.5$) using the formula by Hulley et al. (2018) which generated a minimum sample size of 29. As young children belong to a vulnerable category of participants, we collected data from only a necessary number of participants. Previous inter-brain hyperscanning studies on parent-child dyads have likewise recruited a similar or even smaller number of participants. For example, Miller et al. (2019) recruited 28 dyads, Reindl et al. (2018) recruited 33 dyads, Leong et al. (2017) recruited 17 and 19 dyads in two separate experiments, Piazza et al. (2018) recruited 18 dyads, and Levy et al. (2017) recruited 25 dyads.

To be eligible for the study, the inclusion criteria were as follows: (i) mothers needed to be at least 21 years old, (ii) children must be the biological offspring of mothers within the age range of 36 and 48 months upon testing, (iii) both mother and child should not have any known psychological conditions, (iv) both mother and child must be residing together and (v) both mother and child should not have any known cognitive, visual or hearing impairments that might undermine their ability to understand the video stimuli presented to them. Informed consent was

obtained from mothers, and mothers provided their consent on behalf of their children before the study ensued. Each pair of participants was remunerated with monetary compensation at the end of the study. All protocol in this study have been approved by the Institutional Review Board of Nanyang Technological University.

Study Design

Mothers were requested to complete a home-based online questionnaire that consisted of a parenting stress survey, the Parenting Stress Index- Short Form (PSI-SF), and an Attachment Style Questionnaire (ASQ). After submitting the questionnaire, participants were invited to attend the fNIRS session which was conducted at the Nanyang Technological University (NTU) LifeSpan facility.

The experimental set-up required the child to be seated on the mother's lap during the presentation of video stimuli (**Figure 4**). Mother-child pairs engaged in a passive task of watching 3 video clip stimuli together, each of which lasted for a duration of 1 minute. The prefrontal brain activity of mother and child were recorded simultaneously using fNIRS hyperscanning.

Figure 4. Experimental set-up where the child sat on the mother during the presentation of video stimuli, while their brain activity was simultaneously recorded with fNIRS hyperscanning.

Parenting Stress Index - Short Form (PSI-SF)

Mothers' perceived parenting stress was evaluated using the Parenting Stress Index - Short Form (PSI-SF) questionnaire (Abidin, 2012). The PSI-SF was formed by extracting items from the Parenting Stress Index - Fourth Edition (PSI-4) (Abidin, 2012), which is a well-established instrument used to measure parenting stress in parents of children between the ages of 1 month and 12 years old. The short version of the PSI-4, the PSI-SF, has shown to have high reliability (alpha coefficient = 0.98; Johnson, 2015) as well as high validity (Barroso et al., 2016; Brobst et al., 2009; Reitman et al., 2002). It consists of 36 items in the form of statements which parents

respond to on a 5-point Likert scale, where 1 denotes strongly disagree and 5 denotes strongly agree. In this study, the alpha coefficient was also found to be high at 0.90.

The PSI-SF comprises three sub-scales: (i) Parenting Distress, (ii) Parent-child Dysfunctional Interaction and (iii) Difficult Child. The Parenting Distress subscale computes how restricted or stressed the parent feels from having to inhabit the parental role. One such example is 'Since having my child I have been unable to try new and different things.'. Unlike the Parenting Distress subscale which is concerned with intrapersonal perceptions, the Parent-child Dysfunctional Interaction subscale measures the degree to which the child fulfills the parent's expectations and whether the parent derives satisfaction from her interactions with her child (e.g., 'My child is not able to do as much as I expected.'). Finally, the Difficult Child subscale indicates whether the parent perceives the child to be challenging to rear. An example of an item in this subscale is 'My child generally wakes up in a bad mood'. The sum of scores from the three subscales forms the total parenting stress score, where higher scores indicate more perceived parenting stress.

Attachment Style Questionnaire (ASQ)

The Attachment Style Questionnaire (ASQ; Feeney et al., 2014) is an instrument that assesses an adult's attachment style in their general relationships. Comprising 40 items, participants responded to each of these items on a 6-point Likert scale where 1 = totally disagree and 6 = totally agree.

The 40 items are categorised into 5 subscales: Confidence, Discomfort with closeness, Relationships as secondary, Need for approval, and Preoccupation with relationships. These subscales can be further classified into anxious, avoidant and secure attachment styles. The

Confidence subscale reflects secure attachment, whereas Discomfort with closeness and Relationships as secondary indicate avoidant attachment. Finally, Need for approval and Preoccupation with relationships indicate anxious attachment (Stein et al., 2002). To evaluate the reliability of this questionnaire on our specific sample, Cronbach's alpha analysis was conducted and revealed an acceptable alpha value of 0.77.

Maternal Anxious Attachment (MA)

Since the hypotheses in this study were in regard to maternal anxious attachment, only the Need for approval and Preoccupation with relationships subscales were used for subsequent analyses. To compute a measure of maternal anxious attachment (MA) from the Need for approval (NFA) and Preoccupation with relationships (PREOP) subscales, a Principal Component Analysis (PCA) with one component (following the method used by Pedregosa et al. (2011) (v0.22.1) was employed to generate MA from the scores of these two subscales. Bartlett test of sphericity ($\chi^2=5.89$, $ddl=1.0$, p value=0.009) and KMO test of sampling adequacy (overall=0.5, NFA=0.5, PREOP=0.5) were conducted to verify that the assumptions of the PCA test were fulfilled.

Figure 5: TOP: Correlation scatter plot of Maternal Anxious Attachment (MA) component and the Need for Approval (NFA; left) and Preoccupation (PREOP; right) subscales of the Attachment Style Questionnaire (ASQ). BOTTOM: Correlation scatter plot of MA and synchrony.

The MA component derived from the PCA was negatively associated with both NFA ($r_s = -0.86$, $p < 0.001$) and PREOP ($r_s = -0.79$, $p < 0.001$), which suggested that higher scores were correlated with reduced MA. To allow for a more intuitive interpretation of the results, the estimated MA was inverted such that the final MA positively correlated with NFA and PREOP.

Therefore, greater MA reflected higher maternal anxious attachment (see **Figure 5**).

Video Stimuli

The narrative scenes were excerpted from *Brave*, *Peppa Pig* and *The Incredibles* animation movies, which were specifically selected due to variations in their audio-visual complexities and emotional valences (i.e., positive, neutral and negative) which allowed for the generalisation of the co-viewing task. All three clips showed scenes of a family. The 1-minute clip from *Brave* depicted a positive scene of a family reunion which occurred towards the end of the movie, where the mother, father, daughter and three little brothers smiled and engaged in a hug before proceeding to dance together. The 1-minute neutral clip from *Peppa Pig* showed a neutral scene of the Peppa Pig family was walking through a forest. The father, Daddy Pig, was speaking in a calm and didactic manner to his children. Finally, the 1-minute negative scene from *The Incredibles* showed an intense conflict spectacle between the mother and the father which started as a quarrel before escalating into shouts exchanged between the characters.

Since it would take at least 30 minutes to set-up and calibrate the fNIRS hyperscanning devices on both the mother and child, there was a possibility that the preschool-aged child would grow restless during the experiment. As with all developmental neuroscience studies, excessive motion in child participants poses a significant barrier to collecting clean signals and completing a study in its entirety. As such, it was important that the duration of the video task be kept to a minimum. To determine if differences in emotional valences across clips can be captured if each video was screened for a duration of 1 minute each, a pilot study was conducted. In the pilot study, an online visual analogue scale (VAS) was distributed to 12 participants where they were asked to assess the positivity of each video stimuli by selecting a facial expression that reflects the positivity

of each clip watching after watching the clips. The VAS presented a neutral face in the middle of a graphic slider but became more negative when the slider was moved one step to the left, and became most negative when the slider was moved to steps to the left. However, the facial expression became more positive when the slider was moved one step to the right, and became most positive when the slider was moved two steps to the right. The facial expressions were coded on a 5-point scale, with 1 denoting the most negative facial expression and 5 denoting the most positive facial expression. The excerpt from *Brave* had the most positive score of 2.75, while *Peppa Pig* had a neutral score of 1.5 and *The Incredibles* had a negative score of -2. With these preliminary results, we proceeded with the main empirical study using three video clips of 1 minute each. Further analyses on the emotional valence and audio-visual properties of each video clip were subsequently conducted.

Emotional valence can be largely categorised into positive and negative valences. For instance, anger, fear and sadness are typically regarded as negative emotional valences whereas pleasure and joy are positive emotional valences (Frijda, 1986). To account for differences in emotional valence across the three video stimuli, two independent coders – graduate researchers who have received previous training in microanalytic behavioural analyses – engaged in a second-by-second coding of each clip, where they rated whether each second of the clip was positively valenced. Subsequently, the sum of positive codings across the entire video clip was computed and used as a positivity score. To ensure consistency in coding, inter-rater agreement between the independent coders was measured with the “irr” package in RStudio (Gamer, Lemon, Fellows & Singh, 2012). The computation derived an inter-rater agreement of at least 80% for each of the three videos. The narrative scene excerpts from *Brave*, *Peppa Pig* and *The Incredibles* were found to have a positive, neutral and negative emotional valence respectively.

Each of the video stimuli was also analysed for their audio and visual properties using Praat (v. 6.0.46) and FFmpeg command (v. 3.4.4) on Python. Audio complexity reflects differences in acoustic energy which is indicated by the root mean square (RMS) amplitude of the signal (Denison et al., 2012). The audio signal was first extracted using FFmpeg before information on amplitude and fundamental frequencies were derived from the video clip. Conversely, video complexity is concerned with the degree of information density (i.e., visual cluttering) within a specific scene (Bucy, Lang, Potter, & Grabe, 1999). To analyse video complexity, each clip was extracted at 12 frames per second (FPS) before visual cluttering was computed. Video complexity, audio fundamentals and audio intensity are described in **Table 11**. Finally, the video clips were edited to control for volume and brightness.

At the start of the task, a 5-second fixation cross “+” preceded the first clip, after which a 10-second fixation cross was added between two clips (see **Figure 6**). The three video clips were arranged differently to create six different sequences (e.g., Incredibles-Peppa-Brave, Brave-Incredibles-Peppa), after which participants were assigned to one of six sequences to control for potential order effects. All video stimuli were presented to dyads on a 15-inch Acer laptop, with the brightness and volume set at 165nits and 44dB respectively.

Table 11.

Video complexity, audio fundamentals and audio intensity values for each of the three video stimuli.

Video Stimulus	Video Complexity [^] (bytes)	Audio Fundamentals (Hz)	Audio Intensity [#] (W/m ²)
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Brave	658119.31	245.26	59.89
Peppa Pig	468369.81	218.37	62.50
The Incredibles	423005.66	271.64	56.30

Note. ^ Bytes is a unit of memory size. # W/m² is a measure of sound energy

Figure 6. Schematic diagram of video stimuli screened to participants. Prior to the start of the first clip, a fixation cross “+” was presented for 5 seconds. Each clip lasted for 1 minute, with a fixation cross which lasted for 10 seconds between two clips. The order of the three video clips was randomised to form six stimuli sequences, and dyads were randomly assigned to one of the six sequences.

Functional Near-Infrared Spectroscopy (fNIRS)

fNIRS data was preprocessed using NIRSLab software (NIRSLab v.205). Stimulus markers were first added to identify the onset and offset of each video clip. Then, optical signals were inspected for noise which was indicated by gain and coefficient of variation (CV) of each channel. Channels with significant noise (i.e., gain>8, CV>7.5) were omitted from further preprocessing. Subsequently, channels were visually inspected and discontinuities and spike artifacts, which usually occur due to motion, were manually removed. Next, a band-pass filter of 0.01-0.2 Hz was applied to eliminate physiological slow signals and baseline shift variations. Finally, haemodynamic signals were computed from optical signals using the modified Beer-Lambert law. The resulting haemodynamic signals were further inspected by two independent coders to detect and remove any remaining signal artifact.

Since there were 33 pairs of mother-child dyads, the total number of channels prior to omission of any channel was 3960 (66 participants * 3 videos * 20 channels = 3960). From this total, 1283 channels (32.4%) were discarded. Only oxyHB signals are subsequently analysed in this study.

Analytic Plan for Parenting Stress: Beta Analyses

Generating Beta Coefficients

Although the objective of this chapter was to uncover the effects of maternal parenting stress on inter-brain synchrony, analyses were first conducted to investigate the effects of parenting stress on mothers and children separately. Beta analyses, which generated beta-coefficients from mothers and children, were conducted to measure individual oxyHB patterns.

Following the conversion of optical to haemodynamic signals, a haemodynamic response function (HRF) was specified to the signal. The three video stimuli were plotted against the time axis within a convolution design matrix to ensure the correct stimuli sequence for each participant. Thereafter, a Discrete Cosine Transformation (DCT) parameter with a 128-second high-pass cut-off was applied. A Gaussian Full Width at Half Maximum (FWHM) 4 model was subsequently applied and a general linear model (GLM) was formulated for each participant from which 3 beta-coefficients, corresponding to the oxyHB beta-coefficients of each of the three video stimuli, were obtained. The beta-coefficients were then aggregated to form an averaged beta-coefficient for each participant.

Preliminary Analyses

R studio (version 1.0.153, R-core 3.4.2) was used for all analyses in this chapter. Since the brain functions within interconnected networks, investigating broader regions of interest instead of single channels would lend greater practicality when interpreting the results from this study. Hence, the channels were grouped based on their proximity to each other, thus forming four clusters of the PFC, which were labelled as the frontal left, frontal right, medial left and medial right clusters. Beta-coefficients of the oxyHB signals were derived for each PFC cluster. The frontal left PFC cluster (channels 4, 6, 7, 11) maps to the left anterior PFC, middle frontal gyrus and inferior frontal cortex (IFC) and Brodmann Areas (BA)47L, BA10L and BA46L, whereas the frontal right cluster maps to the right anterior PFC, middle frontal gyrus and inferior frontal cortex (IFC) and Brodmann Areas (BA)47R, BA10R and BA46R. The medial left cluster maps to the left dorsolateral PFC (DLPFC), lateral PFC, IFC, lateral DLPFC and the superior frontal gyrus which are BA46L, BA45L, BA09L and BA08L. Finally, the medial right cluster maps to the right dorsolateral PFC (DLPFC), lateral PFC, IFC, lateral DLPFC and the superior frontal gyrus which

are BA46R, BA45R, BA09R and BA08R. Preliminary analyses aimed to investigate whether there were any prevailing effects of child's gender, mother's age and video's emotional valence on beta-coefficient values of mothers and children in each cluster. To do this, three separate GLMs were conducted for each cluster, where these factors were individually fitted as factors, beta-coefficient values were the dependent variables and audio intensity and fundamentals were included as covariates (i.e., $\text{Beta}_{\text{frontal left}} \sim \text{Parenting Stress} + (\text{Child's gender} + \text{Video complexity} + \text{Audio intensity})$). These beta analyses were run separately for mothers and for children.

Descriptive Analyses

The mean and standard deviation of averaged beta-coefficient values for each PFC cluster, for both mothers and children, would be reported in the results section.

Inferential Analyses

Following the preliminary analyses, the inferential analyses incorporated parenting stress as an independent variable in the GLM of each PFC cluster for both mothers and children, whereas beta-coefficient remained the dependent variables and video complexity and audio intensity and fundamentals were included as covariates (i.e., $\text{Beta}_{\text{frontal left}} \sim \text{Parenting Stress} + (\text{Video Complexity} + \text{Audio Fundamentals})$). False Discovery Rate (FDR) correction was applied to correct p-values for multiple comparisons across clusters. This set of analyses was performed once for mothers and then again for children.

Any significant finding between parenting stress and beta-coefficient in a PFC cluster suggests that parenting stress might be associated with brain activation of mothers or children in that cluster when they engage in the passive joint task of co-viewing narrative scenes together.

Analytic Plan for Parenting Stress: Synchrony

Synchrony Approach: Dynamic Time Warping (DTW)

Dynamic Time Warping (DTW) algorithm from the dtw package (Giorgino, 2009) in R studio (ver.1.0.153) was used to quantify inter-brain synchrony between mother and child time-series signals. In DTW calculation, the greater the distance between the time series signals, the lower the synchrony between mother and child. Distance index of each channel was then normalised so that scores ranged from 0 to 1. DTW was chosen as a means to determine synchrony because it allows matching similar but out-of-phase contours of signals within the same time window (Keogh & Ratanamahatana, 2005), thereby optimising signal alignment (Senin, 2008). Additionally, DTW has been widely used in the research literature (Rath & Manmatha, 2003; Tuzcu & Nas, 2005).

Preliminary Analyses

For each synchrony approach, similarity metrics were averaged across channels that fall within a particular cluster to generate a distance index for each of the four clusters. Similar to the beta-coefficient analyses, preliminary analyses aimed to investigate whether a child's gender, mother's age and video's emotional valence influenced synchrony index in dyads in each cluster. Likewise, three separate GLMs were conducted for each cluster, where these factors were individually fitted as factors, distance index was the dependent variable and video complexity and audio intensity and fundamentals were included as covariates (i.e., Distance Index_{frontal left} ~ Child's gender + Video complexity + Audio intensity).

Descriptive Analyses

The mean and standard deviation values of synchrony for each of the 4 clusters would be reported.

Inferential Analyses

Similar to beta-coefficient inferential analyses, GLMs were conducted for each cluster, where parenting stress was fitted as the independent variable, distance index was the dependent variable and video complexity and audio intensity and fundamentals were included as covariates (i.e., Distance Index_{frontal left} ~ Parenting Stress + (Video Complexity + Audio Fundamentals)). False Discovery Rate (FDR) correction was applied to correct p-values for multiple comparisons across clusters.

Any significant finding between parenting stress and distance index in a cluster implies that parenting stress is associated with inter-brain synchrony in that region when mother-child dyads engage in a passive task of co-viewing narrative scenes together.

Analytic Plan for Maternal Anxious Attachment: Beta Analyses

To rule out the alternate explanation that differences in inter-brain synchrony is driven only by enhanced brain activity in more anxiously-attached mothers, analyses on maternal oxyHB signals and maternal anxiety score would be conducted. Another analytical model would be conducted for children's oxyHB signals and maternal anxiety score.

A Gaussian Full Width at Half Maximum (FWHM) 4 model was applied to oxyHB data of each participant, individually. At the within-participants level, a general linear model (GLM) was subsequently applied to these oxyHB data to derive beta coefficients of each of the three video

stimuli. The beta-coefficient values were then averaged to produce the beta-coefficient value of each mother in each PFC cluster.

Following the extraction of beta-coefficient values, one linear regression model was conducted for maternal brain activity and another was run separately to investigate children's brain activity. Each regression model featured the beta-coefficient as the dependent variable and MA as a covariate, whilst video complexity, audio complexity and video positivity were added as controls (i.e., $\text{Beta-coefficient}_{\text{mothers}} \sim \text{MA} + [\text{Video Complexity} + \text{Audio Complexity} + \text{Video Positivity}]$ and $\text{Beta-coefficient}_{\text{children}} \sim \text{MA} + [\text{Video Complexity} + \text{Audio Complexity} + \text{Video Positivity}]$). All analyses were conducted on Python software (python v3.x).

Analytic Plan for Maternal Anxious Attachment: Synchrony

Synchrony Approach: Cross-Correlations

Detrending is usually applied to non-stationary time-series signals when computing cross-correlations so as to mitigate the potential effects of shared time-series structures. The time-series structure in this particular study is determined by the three narrative video stimuli such that different segments of the signal could be entrained to each of the three scenes. Therefore, a linear regression model was applied to the fNIRS dataset so as to detrend each segment of the signal and filter any slow physiological drift (Quinones-Camacho et al., 2019; Czescumski et al., 2020).

Cross-correlation analyses of mother's and child's normalised oxyHB cluster signals with a delay of 2 seconds (Azhari et al., 2020b; Bizzego, Azhari, et al., 2019b; Golland et al., 2014b, 2015b) was calculated for each dyad, prefrontal cluster and video stimuli. This computation was conducted with lags of -2 and +2 s (steps of 0.2 s) to generate cross-correlation values that

accounted for a lagged duration of 2 seconds for both the mother's and child's signals. Similar to method reported by Golland et al. (2014), the maximum cross-correlation score across all computed lags was used as a measure of synchrony. Hence, the lag which was associated to the maximum value differed across dyads. Cross-correlation analyses were based on the *physynch* library (Bizzego et al., 2019).

Preliminary Analyses

Synchrony measures from real mother-child dyads are referred to as True Dyads. To investigate the effects of the co-presence of mother-child dyads, cross-correlation was also computed between randomly paired mother-child signals which was referred to as Control Dyads. Similar to Chapter 3, the cross-correlations values generated from Control dyads would be referred to as similarity indexes, whereas the cross-correlations value generated from True dyads would be referred to as synchrony indexes. The mean and standard deviations of synchrony and similarity values for each cluster would be reported for of True and Control Dyads, respectively.

Synchrony from True Dyads and Similarity from Control Dyads were contrasted with a Mann-Whitney test to investigate if the co-presence of a mother and child played a significant role in influencing synchrony, or whether all participants entrained to the video stimuli, in which case no specific differences would be observed between True and Control Dyads.

Inferential Analyses

To evaluate the first hypothesis on the effect of MA on inter-brain synchrony in True Dyads, a linear regression analysis was conducted for each prefrontal cluster, with MA as an independent variable and synchrony as a dependent variable. Audio fundamentals and video

complexity were included as covariates to account for the potential influence of varying stimuli properties on synchrony (i.e., $\text{Synchrony} \sim \text{MA} + [\text{Video Complexity} + \text{Audio Complexity} + \text{Video Positivity}]$). False Discovery Rate (FDR) correction was applied to the four clusters to correct for multiple comparisons across clusters.

Results: Parenting Stress

Results from Beta Analyses

Preliminary Results

Three general linear models (GLMs) were conducted for mothers and another three for children, where mother's age, child's gender and video's emotional valence were individually fitted as factors. In all three models, video complexity and audio fundamentals were incorporated as covariates.

The GLMs on mothers did not generate any significant finding in any cluster that survived p-value correction. However, the GLMs on children elicited a significant finding in the frontal left cluster when mother's age was a factor ($R^2 = 0.058$, $F(3,245) = 5.045$, $p < 0.01$) and when child's gender was a factor ($R^2 = 0.058$, $F(3,245) = 5.043$, $p < 0.01$), even after p-value correction. However, the only variable that was found to be significant across all three GLMs was the video complexity covariate (see **Table 12**). Mother's age and child's gender were excluded from inferential analyses as there were no significant findings associated with these factors. Since video complexity was significant, it was included as a control in subsequent inferential analyses.

Furthermore, the GLMs on children showed that models with video's emotional valence as a factor were significant in the frontal left ($R^2 = 0.058$, $F(3,246) = 7.595$, $p < 0.01$) and frontal

right ($R^2 = 0.030$, $F(2, 259) = 3.988$, $p < 0.05$) clusters. In the former, the video complexity covariate was found to be the only significant variable in the model, and since it was already controlled for in the inferential models, video's emotional valence could be excluded from inferential analyses of the frontal left cluster. In the latter, video's emotional valence was found to be significant, and hence was included in inferential analyses only for the frontal right cluster (see **Table 13**).

Descriptive Results

The mean and standard deviation of averaged beta-coefficient values for each PFC cluster for mothers and children are reported in **Table 14** and **Table 15**, respectively.

Inferential Results

GLMs were conducted to investigate if parenting stress was significantly associated with brain activation in any of the four prefrontal clusters for either mothers or children. For mothers, no significant finding was found. For children, the statistical model for the frontal left cluster was found to be significant ($R^2 = 0.058$, $F(3, 245) = 0.008$, $p < 0.05$). However, only video complexity emerged to be significant in the model ($\beta = 31.036e-09$, $p < 0.01$). Since video complexity was a control variable across all models, it was concluded that parenting stress was not significantly related to any PFC cluster activity in mothers and children.

Table 12.

Beta coefficient values of the video complexity covariate for the three regression models in the frontal left PFC.

Models	b	SE	t	p-corr
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Mother's Age	-1.04e-09	2.68e-10	-3.87	0.000139
Children's Gender	-1.04e-09	2.68e-10	-3.87	0.000139
Video Emotional Valence	-1.14e-09	3.02e-10	-3.79	0.000190

Note. p-corr = corrected p-value. Mother's age, children's gender and video emotional valence were fitted as factors

Table 13.

Beta coefficient values of the video complexity covariate for the three regression models in the frontal right PFC.

Variable	b	SE	t	p-corr
Video Emotional Valence	- 3.24e-06	1.40e-06	2.31	0.0214
Video Complexity	-8.88e-10	3.49e-10	-2.55	0.0114

Note. p-corr = corrected p-value. Mother's age, children's gender and video emotional valence were fitted as factors.

Table 14.

Mean and standard deviation of beta values for all clusters for mothers.

Clusters	Mean beta values	Standard Deviation
Frontal left	-5.25E-07	2.11E-06
Frontal right	8.82E-07	2.92E-06
Medial left	1.07E-06	6.35E-06

Medial right	4.09E-06	6.971E-06
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Table 15.

Mean and standard deviation of beta values for all clusters for children.

Clusters	Mean beta values	Standard Deviation
Frontal left	-2.71E-06	2.74E-06
Frontal right	-1.02E-06	1.22E-06
Medial left	-2.79E-06	2.62E-06
Medial right	-1.55E-06	5.00E-06

Results from Synchrony Analyses

Preliminary Results

No significant finding emerged for mother's age, child's gender and video positivity with distance index in any of the four clusters.

Descriptive Results

Mean and standard deviation of the distance indices for each of the four clusters are reported in **Table 16**.

Inferential Results

GLMs were conducted to examine if parenting stress was associated with inter-brain synchrony in any of the four PFC clusters. No significant finding emerged in the frontal left ($R^2=0.016$, $F(3, 226)=1.226$, $p>0.05$), medial right ($R^2=0.017$, $F(3, 261)=1.472$, $p>0.05$) and frontal

right ($R^2 = 0.034$, $F(3, 231) = 2.738$, $p > 0.05$) clusters. However, parenting stress was found to be significantly associated with synchrony in the medial left PFC cluster ($R^2 = 3.730 \times 10^{-6}$, $p < 0.01$). The medial left cluster is composed of the frontal eye field (FEF), the left inferior frontal gyrus (IFG) and the dorsolateral PFC. Subsequently, Pearson's correlation test revealed that parenting stress was positively associated with distance index ($r = 0.556$, $p = .0032$), which conversely suggests that parenting stress is negatively associated with synchrony (i.e., $1 - \text{distance index}$) in the medial left cluster ($r = -0.556$, $p = .0032$) (**Figure 7**).

Table 16.

Distance indexes in the four PFC clusters, along with the channels found in each cluster and corresponding sample size and demographic information.

Cluster	Channels	Brain Areas	Brodmann Areas	N	Mother's age	Child's age	Child's gender (male, female)	Mean Distance Indexes	Standard Deviation
Frontal left	4, 6, 7, 11	Anterior PFC, Middle frontal gyrus, Pars orbitalis of Inferior frontal cortex (IFC)	BA47L, BA10L, BA46L	31	35.2 ± 4.3	41.6 ± 6.1	18, 13	0.000208	0.000232
Frontal right	13, 14, 16, 19	Anterior PFC, Middle frontal gyrus, Pars orbitalis of Inferior frontal cortex (IFC)	BA10R, BA46R, BA47R	30	35.2 ± 4.3	41.7 ± 6.1	18, 12	0.000208	0.000193
Medial left	1, 2, 3, 5, 8	Dorsolateral PFC (DLPFC), Lateral PFC, Broca's area of IFC, Lateral DLPFC, Superior frontal gyrus	BA46L, BA45L, BA09L, BA08L	27	35.4 ± 4.5	41.1 ± 5.4	15, 12	0.000300	0.000360
Medial right	10, 15, 17, 18, 20	DLPFC, Superior frontal gyrus, Lateral DLPFC, Lateral PFC, Intermediate frontal cortex, Pars triangularis of IFC	BA08R, BA09R, BA46R, BA45R	29	35.3 ± 4.3	41.2 ± 5.7	16, 13	0.000257	0.000230

Figure 7. Scatterplot showing the negative correlation between parenting stress and Dynamic Time Warping (DTW) synchrony ($r=-0.556$, $p=.0032$) in the left medial cluster.

Results: Maternal Anxious Attachment

Preliminary Results

The linear regression analysis which was conducted to detrend the dataset did not generate any significant findings.

Results from the Mann-Whitney analyses which compared synchrony between True and

Control Dyads revealed that True dyads exhibited greater synchrony than the similarity indexes of their Control counterparts in the frontal left cluster (Median of *Control* coupling = 0.156, $U=77947$, $p=0.019$) and when all four clusters were pooled together (Median of *Control* coupling = 0.16, $U=763629$, $p=0.013$). Upon p-value correction with Benjamini-Hochberg's multiple comparisons method, however, these results no longer survived. The results of the Mann-Whitney test both True and Control Dyads are reported in **Table 17**.

Table 17.

Mann-Whitney analyses of control and true dyads in each of the four PFC clusters.

		Control		True				
Cluster	N	Mean	SD	Mean	SD	U	p-uncorr	p-corr
Medial Left	71	0.158	0.260	0.169	0.306	29458.0	0.333	0.333
Medial Right	68	0.145	0.268	0.189	0.253	27658.0	0.078	0.156
Frontal Left	95	0.156	0.255	0.200	0.264	77947.0	0.019	0.078
Frontal Right	92	0.151	0.266	0.169	0.277	64792.0	0.304	0.333
All	326	0.153	0.262	0.182	0.275	763629.0	0.013	

Note. p-uncorr = uncorrected p-value, p-corr = corrected p-value.

Table 18.

Correlations of the medial left, medial right, frontal left and frontal right clusters with Maternal Attachment Anxiety (MA).

	Maternal Attachment Anxiety (MA)
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Cluster	r^2	p-corr
Medial Left	0.076	0.949
Medial Right	0.163	0.029
Frontal Left	0.019	0.949
Frontal Right	0.026	0.949

Note. p-corr = corrected p-value.

Inferential Results

Beta analyses: The analyses on beta-coefficient values did not elicit any significant finding between brain activation in any cluster and MA, in both mothers and children.

Synchrony analyses: The general linear model (GLM) that investigated the association between MA and inter-brain synchrony elicited a significant finding in the medial right cluster in True Dyads ($R^2=-0.163$, p-corrected=0.029, see **Figure 7**). Following that, Spearman's correlation test showed that greater MA was correlated with less synchrony ($r_s = 0.251$, $p=0.043$). No other cluster showed a significant relationship between MA and synchrony (see **Table 18**).

Discussion

Chapter 4 investigated the effects of parenting stress and maternal anxious attachment on the inter-brain synchrony of mother-child dyads. Parenting stress has been shown to hinder behavioural synchrony in dyads that might, in the long-term, compromise the quality of the parent-child relationship. In this chapter, we tested one central hypothesis which was that dyads in which mothers reported higher levels of parenting stress would exhibit diminished inter-brain synchrony.

This hypothesis was only partially fulfilled as greater parenting stress was significantly associated with reduced synchrony in the left medial prefrontal cortex (PFC) cluster. This chapter also examined the association between maternal attachment style and inter-brain synchrony in the mother-child dyad when the pair partook in a typical shared activity of co-viewing narrative animation scenes together. Our hypothesis was that dyads with more anxiously-attached mothers would exhibit reduced synchrony. This hypothesis was partially supported as higher self-reported maternal attachment anxiety was found to be associated with diminished dyadic synchrony in the medial right PFC cluster. However, no significant difference was found between true and control dyads, and so these findings should be taken as preliminary. One possibility for this lack of difference could be that dyads were entrained to the video clips. Since the presentation of all video stimuli were coordinated with the onset of fNIRS recording, participants could have entrained to the videos which engendered similarities between true and control dyads (Hasson et al., 2004).

Parenting Stress and Inter-Brain Synchrony

The medial PFC is a region in the brain that is specialised in making mental inferences (Frith, 1999; Frith & Frith, 2000; Frith & Frith, 2001). Of these processes, making inferences of another person's mental states fall under a specific mentalisation construct known as Theory of Mind (ToM) (Gallagher et al., 2000). The medial PFC houses two Brodmann Areas (BA) that are known to be implicated in ToM, namely BA 8 and BA 9. Less synchrony observed in the medial PFC might hence indicate reduced similarities in ToM processes adopted by stressed mothers and their respective children during the shared activity of co-viewing animation shows together. To interpret this finding, we postulate that mothers who experienced greater parenting stress might have found it more difficult to enjoy joint activities with their child. In the context of this study, highly stressed mothers were perhaps not fully engaged in watching the movie stimuli which

hindered their ability to mentalise with the characters in the movies. This reduced ability to mentalise with characters could have led to mismatches in temporal brain responses exhibited by the mother and child in the mentalisation domain of the brain, which reflects differences in inter-subjective experiences on the part of the stressed mother and the child during co-viewing of movies. These differences in inter-subjective experiences of mother and child during shared activities might undermine the quality of bonding during dyadic activities.

Another potential interpretation of our result is that mothers who experienced more parenting stress were less attuned to their child, and this was reflected in the reduced inter-brain synchrony that these dyads showed during the co-viewing activity. Mothers and their children enjoy consistent interactions with each other, and these accrued experiences serve as rich opportunities for them to understand each other's emotional repertoire (Curci & Rimé, 2012). Over time, mother-child dyads develop coupled emotional organisation that could lead to them experiencing social situations in a similar manner (Anderson & Keltner, 2004). Parenting stress undermines the quality of open interaction which is paramount to the bidirectional expression of emotions that facilitates dyadic emotional coordination (Ponnet et al., 2013). Besides its central role in mentalisation processes, the medial PFC is also known to be implicated in emotional processing, including emotional regulation (Buchanan et al., 2010; Cerqueira et al., 2008; Wang & Saudino, 2011) and context-specific memory retrieval of emotional experiences (Euston et al., 2012). In the present study, co-viewing of video stimuli could have elicited similar event-specific emotional reactions in mothers and their children, hence driving synchronous brain responses. However, for mothers who reported greater parenting stress, less coordinated dyadic emotional responses could have occurred which was reflected in reduced inter-brain synchrony.

While the relationship between parenting stress and synchrony is interesting, we cannot prematurely rule out the possibility of mediating third variables underlying the relationship between higher parenting stress and lower inter-brain synchrony. Mothers' emotional regulation ability, that is, the ability to navigate emotional stressors and respond to aversive emotional experiences effectively, is one potential mechanism through which parenting stress exerts observable effects on synchrony in mentalisation modules of the brain. A large study by Hafshah and Pratiwi (2021) on 111 parents of preschool-aged children demonstrated that mothers who scored higher on the Emotional Regulation Questionnaire (ERQ) scale, a measure of emotional regulation, reported lower parenting stress. Likewise, a study by Hu et al. (2019) showed that parents who struggled less with emotional regulation experienced less parenting stress. In turn, mothers with ineffective emotional regulation abilities have also been found to engage in less mentalisation and display diminished emotional awareness of their child's mental state (Schultheis, Mayes & Rutherford, 2019). Thus, higher emotional regulation capacity amongst mothers with lower parenting stress would have enabled them to be more aware of their own and their child's emotional states during co-viewing of the animation scenes, which would have driven greater coordination in brain responses of mother and child that underpinned inter-brain synchrony.

Shortly after this chapter was published (Azhari et al., 2019), two studies similarly pointed to the effects of maternal parenting stress on inter-brain synchrony and on the maternal brain. In one study on 5-year-old children and their mothers, Nguyen et al. (2020a) found that greater parenting stress reduced inter-brain synchrony when dyads engaged in a joint activity of solving a Tangram puzzle task together. Along the same vein, Noriuchi et al. (2019) employed an fMRI paradigm on 28 mothers of preschool-aged children to demonstrate that greater parenting stress

was associated with less orbitofrontal cortex activation in response to videos of their own children. These studies lend support to the notion that maternal psychological variables like parenting stress possess neural correlates that can be traced to the maternal brain and observed through parameters of inter-brain synchrony.

Maternal Anxious Attachment and Inter-Brain Synchrony

The medial right cluster, where reduced synchrony was observed with greater maternal attachment anxiety, houses Brodmann areas (BA) 8, 9, 45 and 46 in which mentalisation processes take place (Atique et al., 2011; Barbas & Zikopoulos, 2007; Corradi-Dell'Acqua et al., 2014; Medalla et al., 2007; Van Overwalle, 2009; Van Overwalle & Baetens, 2009). Previously, Fonagy & Luyten (2009b) and Lieberman (2007) revealed that more anxiously-attached individuals employ disproportionately more emotional mentalisation strategies. These strategies depend on automatic processes such as attending to social signals (e.g., facial expressions, gestures) to interpret others' mental states. Typically, the anxiously-attached mother covets emotional proximity with her child, and her preoccupation with maintaining a high level of proximity renders her inclined to attend to her child's faintest social signals (Feeney & Collins, 2001; Mikulincer & Shaver, 2007). In the context of this study, placing too much attention on her child so as to detect cues of social acceptance or disapproval could have possibly detracted an anxiously-attached mother's attention from the videos. Hence, while the child attended to the videos and generally matched his/her mental state to that of the characters being screened, the anxiously-attached mother might not have devoted sufficient attention to the stimuli which undermined her ability to fully mentalise with the characters in the shows. As such, a misalignment in the brain responses of mother and child was observed amongst more anxiously-attached mothers which manifested in reduced inter-brain synchrony.

Reduced synchrony in the medial PFC of dyads with anxiously-attached mothers likely reflects differences in the perceptual processing and intersubjective experiences of the mother and child (Gvirts & Perlmutter, 2020). Future studies investigating inter-brain synchrony should determine whether synchrony sensitively reflects the degree to which mother and child report parallel subjective qualities of shared experiences. Applying this finding to the real world, the lack of similar joint experiences during co-viewing of television shows could limit the mother's ability to provide mental state comments regarding the characters in the show during subsequent interactions. Indeed, supplementing joint activities with mental state comments have been shown to scaffold the development of the child's mentalising abilities (Laranjo et al., 2010; Meins et al., 2002).

Beta analyses of brain activity lent no significant evidence to support the link between maternal attachment anxiety and the prefrontal activity of neither mothers nor their children during passive co-viewing. The absence of a significant association mirrors the observation of Chapter 4 (Azhari et al., 2019a), wherein parenting stress was not found to be related to maternal and child brain activity either. Collectively, these results seem to indicate that the effects of maternal psychological variables, such as attachment anxiety and parenting stress, are likely detected at the dyadic inter-brain level, where the degree to which a mother and child synchronise their cerebral responses are quantified. However, since this conjecture has yet to be demonstrated, more studies are required to provide further verification.

Finally, we observed a lateralisation effect, where parenting stress was associated with the medial left cluster of the brain whereas attachment anxiety was associated with the medial right cluster of the brain. Lateralisation of prefrontal functions have been demonstrated in regard to emotional regulation and decision-making processes, where the former transpires predominantly

in the left hemisphere of the PFC whereas the latter occurs in the right lateralised PFC. The left PFC, especially left ventromedial areas, is typically implicated in the downregulation of negative emotions such as stress and depressive symptoms (Johnstone et al., 2007). The study by Johnstone et al. (2007) has also demonstrated that the activation of the left PFC, during the downregulation of negative affect, correlated with a decrease in activity of the amygdala. Applying this finding to the first part of Study 2, a potential explanation for the diminished synchrony observed in the left medial cluster of the PFC is that mothers with heightened parenting stress required greater cognitive effort to regulate their stress when engaging in a joint activity with their child, who also served as a main source of stress to them. In directing cognitive resources to regulate their emotions, mothers could have exhibited less temporal similarities in brain signals with their child which was reflected as less brain-to-brain synchrony in the left medial cluster of the PFC. On the other hand, decision-making capacities which are known to be a hallmark of prefrontal functions are conducted primarily in the right lateralised areas of the PFC (Clark and Manes, 2004; Damasio, 2000; Neal and Gable, 2017; Lv et al., 2019). In the second part of Study 2, decision-making processes might have been linked to the trait of attachment anxiety due to the need amongst mothers with attachment anxiety to exercise greater inhibitory control and refrain from attending to the behavioural cues of their child for signs of rejection, so as to focus on the video stimuli being presented to them.

Limitations

Like all studies, it is important to consider the findings from Chapter 4 within the context of its limitations. First, the empirical paradigm of this study was such that children were seated on their parents' lap to minimise any stress incurred from being in a novel setting. However, this sitting arrangement also introduced the potentially confounding factor of physical touch between

mother and child, which could have also co-regulated the dyad's emotional responses. Subsequent studies should add another condition where mother and child are seated separately so as to distinguish the effects of touch on inter-brain synchrony. Second, parenting stress and maternal anxious attachment experienced by the mother were measured using a self-reported instrument which is prone to social desirability bias. Mothers could have provided answers that exaggerated or underrated the extent to which they experienced parenting stress or insecure attachment. However, since parenting stress is an inherently subjective construct, the use of a self-report measure in this study is viable. Subsequent studies could also obtain reports from people who are closest to the mother to confirm that the attachment inclinations reported by the mother are verified. Third, anxiety was only measured within the context of attachment, although maternal trait anxiety is a factor that could have also influenced inter-brain synchrony. For instance, mothers who are more anxious in general might have found the co-viewing task more anxiety-inducing due to the evaluative component inherent in psychological research. Fourth, similar to Chapter 3, the use of randomly paired adult-child brain signals who are not mother-child dyads presents a limitation since the synchrony measured for these control dyads confound with the absence of the "control partner". Future studies should derive synchrony metrics from non-dyadic adult-child pairs who engaged in the co-viewing task together. Fifth, since the investigation on parenting stress and maternal anxious attachment stems from the same sample of participants, there could be some overlap in the two constructs. Future studies should be done on independent samples to replicate the findings. Sixth, as there is no standardised approach to computing synchrony at present, the use of different computational methods of computing synchrony across and within chapters could be a limitation, and future studies could compare between several approaches of measuring synchrony and assess the appropriateness of different approaches for different types of

hyperscanning paradigms and research questions. Finally, this study recorded brain responses of the prefrontal regions of the brain only which might present an incomplete depiction of inter-brain synchrony mechanisms that could be occurring in other subcortical and cortical brain areas.

Overall, Chapter 4 has elucidated that parenting stress experienced by the mother is associated with reduced inter-brain synchrony in the mother-child dyad. This chapter has also demonstrated that maternal anxious attachment is associated with diminished dyadic inter-brain synchrony. These observations are proposed to reflect dissimilarities in the mentalisation process of mother and child during the co-viewing task, and an increase in the mother's need to exercise cognitive control to attend to the videos, respectively.

CHAPTER 5

PRESCHOOLERS' AND PARENTS' BRAIN RESPONSES TO VIDEO STIMULI

Methods

Participant Recruitment

A total of 62 parent-child dyads participated in this study and they were recruited via online platforms like forums and Facebook groups. Of this number, 31 were mother-child dyads (13 girls, 18 boys) and 29 were father-child dyads (11 girls, 18 boys). The sociodemographic information of the mother-child and father-child participants are reported in **Table 19** and **Table 20**, respectively. To be eligible for the study, participants had to meet the following inclusion criteria: 1) parents must be at least 21 years old, 2) children should be between the ages of 36 and 48 months at the point of data collection, 3) children had to be the biological offspring of the parent, 4) parent and child participants must be residing together, and 5) participants should not have any known visual or hearing impairments, cognitive deficits and medical or psychological conditions that could prevent them from attending to the video stimuli task. All participants gave their informed consent prior to the empirical session which adhered to the regulations stipulated by the Helsinki declaration. At the end of the study, participants were remunerated with monetary compensation.

This study received approval from the Institutional Review Board of Nanyang Technological University (IRB-2018-06-016). Data collected from this study may be retrieved from this URL: <https://doi.org/10.21979/N9/CTR0YX> and <https://doi.org/10.21979/N9/PFHB88>.

Table 19.*Sociodemographic information of mother-child dyads.*

<i>Age (Mothers)</i>	Mean = 34.8 years, SD = 4.22 years	
<i>Age (Children)</i>	Mean = 42 months, SD = 6.09 months	
<i>Educational Level (Mothers)</i>	9 (27.3%) 17 (51.5%) 7 (21.2%)	Graduate/ Professional degrees Standard college (Bachelor's degree) / Partial college Pre-university
<i>Employment Status</i>	18 (54.5%) 2 (6.1%) 7 (21.2%) 6 (18.2%)	Full-time Part-time Self-employed Homemaker/ Unemployed
<i>Household Income</i>	5 (15.1%) 12 (36.4%) 11 (33.3%) 2 (6.1%) 1 (3.0%) 2 (6.1%)	\$1,000 - \$4,999 \$5,000 - \$8,999 \$9,000 - \$12,999 \$13,000 - \$19,999 > \$20,000 Undisclosed

Table 20.*Sociodemographic information of father-child dyads.*

<i>Age of Fathers</i>	Mean = 38.1 years, SD = 3.67 years	
<i>Age of Children</i>	Mean = 42.2 months, SD = 5.25 months	
<i>Educational Level (Fathers)</i>	8 (27.6%) 12 (41.4%) 2 (6.9%) 7 (24.1%)	Graduate/ Professional degrees Standard college (Bachelor's degree) Partial college Pre-university
<i>Employment Status</i>	26 (89.7%) 1 (3.4%) 2 (6.9%)	Full-time Part-time Self-employed
<i>Household Income</i>	9 (31.0%) 8 (27.6%) 5 (17.2%) 4 (13.8%)	\$1,000 - \$4,999 \$5,000 - \$8,999 \$9,000 - \$12,999 \$13,000 - \$19,999

	3 (10.3%) > \$20,000
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Study Design

The study consisted of an fNIRS empirical session during which mother-child and father-child dyads engaged in a co-viewing activity together, during which they watched 1-minute excerpts from *Brave*, *Peppa Pig* and *The Incredibles* animation movies (see Chapter 4 for details). Although fNIRS data was collected in hyperscanning mode, this chapter investigated data obtained from the child only, whereas hyperscanning data was previously examined in Chapters 4 and 5.

At the start of the study, research assistants briefed the empirical task to the parents before preparing the experimental set-up. Then, the child sat on the parent's lap and research assistants placed NIRS caps of a suitable size on both the parent and child (**Figure 8**). A short video clip from *Moana* was played to distract the child during the preparation process. After the cap was placed onto the dyads, the optodes were adjusted and signal quality was calibrated. fNIRS data was collected in hyperscanning mode, which allowed for brain responses of the parent and child to be recorded simultaneously.

The video stimuli were presented to participants on a 15-inch Acer laptop, placed on a table in front of the dyads, with the brightness and volume set at 165nits and 44dB respectively. The laptop was placed at a distance of approximately 40cm away from the pair. fNIRS data recording was synchronised to the onset of the video stimuli.

The researchers left the room during the experiment and returned at the end of the stimuli presentation to conclude the fNIRS recording and remove the caps from the parent and child. Finally, the parent was debriefed and monetary reimbursement was provided.

Figure 8. Experimental set-up of the parent-child dyad. *Note: Data on brain activity from the child and parent was investigated separately.*

Video Stimuli

The same video stimuli that were used in Chapter 4 were screened to parent-child dyads in this chapter. Prior to experiment, the emotional valence, and audio and visual properties of the three clips from *Brave*, *Peppa Pig* and *The Incredibles* were evaluated and presented in **Table 11** (see Chapter 4). However, unlike Chapter 4 which was concerned with the generalisability of the

passive task of co-viewing shows together, this chapter aimed to uncover the effects of different emotional valences of the video stimuli on the child's brain responses.

Six sequences were generated from different arrangements of the three clips (e.g., Incredibles-Peppa-Brave, Brave-Incredibles-Peppa), and participants were randomly assigned to one of the six sequences to mitigate any order effects. Prior to the start of the study, all dyads were randomly assigned to one of six video sequences. The video stimuli commenced with a fixation cross “+” which lasted for 5 seconds against a black screen. Subsequently, an inter-stimulus interval of 10 seconds was incorporated between any two clips, during which the same fixation cross was screened to participants.

Functional Near-Infrared Spectroscopy (fNIRS)

fNIRS Experimental Set-Up and Data Acquisition

fNIRS data was only collected from the prefrontal cortex region using the NIRSport system (NIRSport, NIRx Medical Technologies LLC) in hyperscanning mode at a scan rate of 7.81Hz. LED emissions of 760nm and 850nm wavelengths were used in a standard 20-channel PFC montage, comprising 8 sources and 7 detectors (NIRStar v.14.2) (see **Figure 2** in Chapter 3). The optodes were arranged in a manner that maintains an optimal inter-optode distance of 3cm. Optical data collected from the detectors were converted to haemodynamic signals to monitor local blood oxygenation (oxyHB) and deoxygenation (deoxyHB), which served as a proxy of brain activation and deactivation.

fNIRS data collection and preprocessing were conducted in the same manner as in Chapter 4. However, instead of obtaining a metric of synchrony, Chapter 5 examined individual brain responses in children and parents. Quality control of the channels led to the omission of 746 channels from child participants who co-viewed the video stimuli with their father (out of 3114, 24.0%), and 1290 channels from child participants who co-viewed the video stimuli with their mother (out of 3564, 36.2%). This channel omission rate is similar to that found in other fNIRS studies involving child participants.

Cluster Grouping of Channels

Given the novelty of investigating factors that influence a child's brain responses during co-viewing of television with their parent, this preliminary study was conducted on prefrontal clusters rather than on individual channels so as to derive practical interpretations from the results.

The 20 channels were grouped based on proximity into 4 clusters: frontal left, frontal right, medial left and medial right clusters. **Figure 2** (see Chapter 3) depicted the locations of the channels, and their corresponding PFC cluster. The cluster signal for each subject was derived by calculating the average signals of channels that fall within that cluster. Python software (python v3.x) was used for the analyses in this chapter.

Analytic Plan

To obtain optimal signal-to-noise ratio, cluster signals were computed for the first 30-second time window of the video. Subsequently, a two-way Analysis of Variance (ANOVA) was performed to examine the effects of the following variables on children's PFC activity: type of

parent (mother or father), PFC region (frontal left, frontal right, medial left and medial right) type of stimulus (positive, neutral, negative) and gender of the child (female or male).

Likewise, a two-way Analysis of Variance (ANOVA) was conducted on parents' PFC activity with the following variables: type of parent (mother or father), PFC region (frontal left, frontal right, medial left and medial right) type of stimulus (positive, neutral, negative) and gender of the child (female or male). Since there was 48 degrees of freedom, p-value was Bonferroni corrected to $0.05/48 = 0.001$.

Prior to conducting cluster analyses, whole-PFC analyses (Fishburn et al., 2019; Moriarty et al., 2019) were conducted to determine if any factor was associated with activity within the PFC in general. ANOVA results which were found to be significant from the whole-PFC and cluster analyses were subsequently examined with post-hoc tests.

Results

Children's Brain Activity

ANOVA only revealed significant results for the whole-PFC analyses but not for the cluster analyses. From the whole-PFC analyses, a main effect of type of parent emerged ($F(1, 484) = 5.358, p = 0.021$), which suggests that children who co-viewed the video stimuli with their mothers ($M = 0.016, SD = 0.323$) showed less PFC activation compared to those who co-viewed the video stimuli with their fathers ($M = 0.077, SD = 0.309$).

Whole-PFC analyses also elicited an interaction between the stimulus and the gender of the child ($F(2, 484) = 6.086, p = 0.002$). Subsequently, post-hoc Mann-Whitney U-test was performed to determine the different responses between girls and boys towards each of the three

video stimuli. Significant child gender differences only surfaced when children were screened the positive *Brave* stimulus ($U = 2564$, $p = 0.0003$), where girls showed greater PFC activation than boys, but not the neutral *Peppa Pig* ($U = 4207$, $p = 0.204$) and negative *The Incredibles* ($U = 4036$, $p = 0.325$) stimuli (see **Figure 9**).

Figure 9. PFC activation of boys and girls for each of the three video stimuli: *Brave* (positive valence), *Peppa Pig* (neutral valence) and *The Incredibles* (negative valence). TOP: Significant gender difference was found for *Brave*, where girls showed greater PFC activation than boys.

Parent's Brain Activity

Similar to the analyses on child's PFC activity, only whole PFC analyses elicited a significant result. Whole-PFC analysis revealed a significant three-way interaction effect between sex of parent, type of video and sex of child ($F(2,484) = 12.96, p = 2.98 \times 10^{-6}$). Post-hoc Mann-Whitney U-test was later performed to differentiate the PFC activity between mothers and fathers towards each of the three video stimuli and when co-viewing with either a male or female child.

When co-viewing the conflict scene of *The Incredibles* with their sons, fathers showed greater PFC activity than mothers ($U = 3068, p = 0.0161$). However, when co-viewing the conflict scene of *The Incredibles* with their daughters, mothers showed greater PFC activation than fathers ($U = 629, p = 0.00114$, see **Figure 10**). No other significant difference in PFC activation of mothers and fathers was observed.

Figure 10. PFC activation of fathers and mothers for *The Incredibles* (negative valence) with their sons and daughters. LEFT: Fathers of sons showed significantly more PFC activation than mothers of sons when co-viewing *The Incredibles*. RIGHT: Mothers of daughters showed significantly more PFC activation than fathers of daughters when co-viewing *The Incredibles*.

Discussion

Chapter 5 of this thesis aimed to identify the factors that influence preschoolers' and parental prefrontal cortical (PFC) responses to video stimuli when they engage in a co-viewing task. We embarked on this study with four hypotheses to be tested. The first postulation, that greater PFC activation would be observed when children co-viewed with their father, compared to their mother, was supported. Next, the hypothesis that greater activation would be observed in girls, compared to boys, in response to only the positive but not the negative or neutral videos was also supported. Third, the prediction that specific PFC activity would be seen in children in response to each of the three emotional valences was not supported as no significant main effect of emotional valence emerged. Finally, the prediction that mothers and fathers would exhibit

different PFC activation when co-viewing with girls compared to boys was fulfilled, and only emerged in the negatively valenced condition. Fathers of sons showed greater PFC activation than mothers of sons when co-viewing the conflict scene from *The Incredibles*, whereas mothers of daughters showed greater PFC activation than fathers of daughters when viewing the conflict scene. The findings from this chapter have been accepted for publication in Durnford, Balagtas, Azhari et. al (2020).

A critical finding from this study is that children exhibit different PFC responses depending on whether they engaged in co-viewing with their mother or father. Notably, children showed greater PFC activity when co-viewing with their father, compared to their mother. This result suggests that the parental figure with whom a child co-views may influence the manner in which he/she processes video information. Previous studies have generally supported the notion that parental presence modulates a child's response to emotionally salient stimuli (Cassidy & Shaver, 2008). Across various studies, distinct physiological reactivity has been observed when a child engages in a task either alone, with his/her parent or with a stranger (Gee et al., 2014; Keene et al., 2019; Myruski et al., 2019). However, no study has made father vis-a-vis mother comparisons using a co-viewing paradigm. With little literature available to interpret our finding, we offer several possible conjectures that warrant further investigation.

First, mothers and fathers could have differed in how they engaged with their child during the experiment. Since the child sat on the parent's lap throughout the duration of the study, different PFC activities across father-child and mother-child groups could indicate differences in how mothers and fathers communicated with their child through interactive mechanisms such as gestures, physical touch, facial expressions and vocalisations. Previous studies have likewise found that mothers and fathers interact with their children in different ways (Aznar & Tenenbaum,

2016; Lewis & Lamb, 2003). Since the PFC is the seat of top-down regulation, another possible explanation is that lower PFC activity reflects a reduced need for self-regulatory processes (Ochsner & Gross, 2005). One speculation is that mothers lend a greater source of external regulation to their children (Cassidy & Shaver, 2008; Gee et al., 2017), bearing more of the regulatory load, which in turn reduces the need for children to self-regulate themselves in the physical presence of their mother. Conversely, another postulation is that greater PFC activity in children might indicate the recruitment of more mentalisation processes in order to mentalise with the characters in the videos (Richardson & Saxe, 2020). In that case, co-viewing with a father could have enhanced mentalisation during the video screening. Since the difference in PFC activity between mother-child and father-child groups did not pivot on any particular area of the PFC, yet another interpretation is that different PFC activity levels are simply a manifestation of different extents of cognitive effort expended by children when co-viewing videos with their parents (Herff et al., 2013). More research is required to discriminate between these various interpretations.

This chapter has also revealed an interaction between preschoolers' gender and the emotional valence of the video in which girls exhibited greater PFC responses than boys towards the positive movie clip. A recent review on children's emotional development by Kauschke et al. (2019) showed that preschoolers harbour a positivity bias due to being generally sheltered and exposed to predominantly positive life experiences. This leads to positive information being processed more efficiently compared to negative or neutral emotional information. Therefore, with positive experiences to draw from, and a greater emotional knowledge base (Barrett et al., 2000; Wright et al., 2018), girls might be able to process positive video information more efficiently than boys even at a tender age. An alternative interpretation is that the gender difference could be due to different mirroring processes that girls and boys employ towards the movie clip (Christov-

Moore et al., 2014). The video excerpt from *Brave* featured female main characters which could be more relatable to girls than boys. Likewise, similarities in the PFC activity of boys and girls could either reflect a paucity of prior negative life experiences or comparable mirroring processes. Future research would be required to accurately ascertain the mechanisms underpinning this gender difference towards positively valenced videos.

This study has also revealed that parents of children with the same gender as them (i.e., mother-daughter, father-son dyads) exhibited greater PFC activity compared to parents in mixed gender dyads (i.e., mother-son, father-daughter dyads) when co-viewing the negative conflict scene from *The Incredibles*. For instance, mothers of daughters showed greater activity than fathers of daughters, whereas fathers of sons showed greater activity than mothers of sons. The conflict scene depicted two characters, that of a mother and father, arguing with and shouting at each other. A possible explanation underlying this observation of heightened brain activity in parents belonging to same-gender dyads is that the presentation of only two characters of opposite genders could have made gender a salient information. Thus, co-viewing the conflict scene that is gender-salient with a child of the same gender could have enhanced brain activity of the parent, and essentially reveals that parental brain response is significantly influenced by salient gender-specific information from both the stimulus and the social environment.

There are several limitations that ought to be highlighted pertaining to this study. First, this study did not have a control group where the child views the videos on his/her own. Future studies can incorporate a control into their empirical paradigm to account for baseline PFC activity in the absence of a parent. Second, behavioural measures such as eye gaze patterns and facial expressions were not examined in this study which could have provided more in-depth information regarding parent-child co-viewing. Third, the mother-child and father-child dyads recruited in this study did

not belong to the same family. Recruiting dyads from the same family in future studies would allow for within-subject mother vs father comparisons that control for the family setting. Fourth,. mediating variables such as the amount of time each parent spent with the child was not obtained and hence not included in the analyses. Future studies should incorporate these potential third variables to better elucidate the mechanisms that contribute to differential brain responses in children and parents. Finally, the sample size of this study was relatively small which could have diminished the statistical power required for between-groups comparisons.

In conclusion, Chapter 5 presents a novel investigation into the effects of co-viewing on the PFC activity of preschool-aged children and their parents. Findings show that greater PFC activity is observed when children watch videos with fathers compared to mothers. Additionally, girls exhibited greater PFC activity towards positive video stimulus compared to boys. Parents from same-gendered dyads displayed greater PFC activity than parents of opposite-gendered dyads when co-viewing a scene in which gender was salient. Subsequent research is undoubtedly required to understand the nuances of preschoolers' and parental PFC mechanisms during co-viewing, which is a dyadic activity that has gained immense momentum in today's digital world.

CHAPTER 6

OVERVIEW OF FINDINGS

This thesis has demonstrated that inter-brain synchrony occurs across parent-parent and parent-child attachment pairs during joint engagement in passive tasks. Even in the near absence of social communication, inter-brain synchrony nonetheless emerged which suggests that shared intersubjective experiences during passive activities could be reflected in similarly matched brain activation patterns in the prefrontal cortex (PFC). The findings from these chapters have made significant theoretical contributions to the parenting literature which, as of present, has yet to investigate inter-brain synchrony in co-parenting couples, and have predominantly examined parent-child inter-brain synchrony only in interactive contexts (e.g., cooperation tasks like solving a puzzle).

The former research gap was addressed in Study 1 (Chapter 3), which, to the best of our knowledge, serves as the first study in the parenting literature to demonstrate that co-parents display unique inter-brain synchrony that is significantly greater than the synchronisation displayed by arbitrary male-female adults. Chapter 3 also showed that the physical presence of a spouse modulates synchrony, with more synchronous brain responses in the attentional network elicited when co-parenting couples were exposed to salient auditory stimuli together than when apart. The enhanced inter-brain synchrony associated with the physical presence of a co-parenting partner could be an underlying mechanism that supports the couple's coordination when responding to everyday demands, including the concerted effort of rearing their infant. Chapter 3 also sheds light on the ongoing debate of whether synchrony is necessarily a positive construct.

Although enhanced synchrony was observed when couples were together compared to when they were apart, these increments were in response to vocalisations which were positive and neutral, but not those which were negatively valenced. Reduced inter-brain synchrony towards negative vocalisations (i.e., cries) could be adaptive to co-parenting couples as it could reflect less inclination for couples to be adversely influenced by each other during stressful situations. Conversely, selective entrainment of brain responses towards stimuli which are neutral and positive when couples are together could bolster dyadic bonding and facilitate co-parenting tasks.

The latter research gap on the paucity of inter-brain synchronisation studies in parent-child dyads during passive joint activities was addressed in Study 2 (Chapter 4). Given that passive tasks like co-viewing of television is a common everyday activity that parent-child dyads engage in this digital age, synchronous brain mechanisms that support shared intersubjective experiences which is associated with an enhanced quality of dyadic bonding could potentially be evaluated from an inter-brain perspective. Indeed, this thesis showed that dyads of mothers with greater parenting stress and mothers with more anxious-related attachment exhibited less inter-brain synchronisation in brain areas responsible for mentalisation of narrative scenes. Differences in mentalisation processes during viewing of narrative animation scenes together could reflect differences in the inter-subjective experiences of mothers who are more stressed and anxiously-attached and that of their children. Although the implications of these observations transcend beyond the scope of this thesis, a possible conjecture is that parents who experience greater parenting stress and those who are less securely attached might find it more difficult to fully engage in co-viewing an animation show together with their child, potentially undermining the quality of such bonding activities.

Taken together, this thesis has demonstrated that inter-brain synchrony can be observed in attachment pairs within the parenting context (i.e., co-parenting spousal dyads and parent-child

dyads). The findings from these studies lend neurophysiological evidence to earlier postulations made by Feldman (2012b), who proposed that human attachments are supported by synchrony in underlying brain and physiological mechanisms. The finding that inter-brain synchrony is enhanced when partners are together, and when mothers experience less parenting stress and are more securely attached, further attest to the role of inter-brain synchrony mechanisms in fostering attachment in the context of favourable social situations.

Due to developmental differences in mentalisation capacities between children and adults (Richardson et al., 2018), Study 3 (Chapter 5) adopted a developmental perspective to uncover social and stimuli factors that influence preschool-aged children's prefrontal processing of animation scenes while co-viewing with either their mother or father. From Chapter 5, it was found that girls showed greater PFC activity than boys in response to the positive movie excerpt which points to the role of child's gender and emotional valence in modulating differential PFC responses. Moreover, children exhibited enhanced PFC activation when they viewed narrative scenes with their fathers than with their mothers which indicate that parental gender potentially exerts differential effects on how children process narrative scenes. The factors that have been identified in Chapter 5, namely emotional valence and gender, were controlled for in our investigations on inter-brain synchrony, and should continue to be accounted for in future synchrony studies involving adult-child pairs in co-viewing paradigms. To supplement this developmental perspective, this chapter has also investigated differences in parental brain responses when co-viewing animation scenes with their children. An intriguing finding at the intersection of gender and emotional valence emerged, where parents in same gender dyads (i.e., mother-daughter, father-son) dyads displayed greater prefrontal activation than parents in oppositely-gendered dyads (i.e., mother-son, father-daughter dyads) when co-viewing a conflict

scene where gender was made salient. This finding makes great strides in our understanding of the parental brain in real-world scenarios, where fathers' and mothers' brain responses are influenced by both the emotional valence of the stimulus and the gender of their child.

An overview of the results from this thesis on inter-brain synchrony in co-parenting couples and mother-child dyads, and children's and parental brain responses during co-viewing of screen stimuli, are summarised in **Figure 10**.

	Inter-brain Synchrony		Child's Processing	Parent's Processing
	Mother-father Dyads	Mother-child Dyads	Mother-child & Father-child Dyads	
Research Gaps	<ol style="list-style-type: none"> 1. No study on real-time inter-brain synchrony in mother-father pairs 2. No study investigated the effects of physical presence of spouse on inter-brain synchrony of the couples 3. No study conducted on synchrony when couple is presented with salient positive and negative infant and vocalisations 	<ol style="list-style-type: none"> 1. No study on inter-brain synchrony has been conducted during passive shared activities like co-viewing of shows 2. Prior to the publication of Chapter 3, no study has investigated the effects of parental factors like parenting stress and maternal attachment style on synchrony 	<ol style="list-style-type: none"> 1. No developmental real-world study on child's brain processing during co-viewing of screen media with their parent 2. No study has accounted for the different stimuli and social components involved in co-viewing (i.e., emotional valence, gender of child, gender of parent) 	<ol style="list-style-type: none"> 1. No parental real-world study on mothers' and fathers' brain processing during co-viewing of screen media with their child 2. No study has accounted for the different stimuli and social components involved in co-viewing (i.e., emotional valence, gender of child, gender of parent)
Findings	<ol style="list-style-type: none"> 1. Inter-brain synchrony is enhanced when spousal partners are in each other's physical presence 2. Synchrony was only heightened in response to positive or neutral auditory stimuli, but not to negative cry vocalisations 3. Synchrony emerged in attentional regions of the prefrontal cortex 	<ol style="list-style-type: none"> 1. Inter-brain synchrony is higher in dyads where the mother experiences less parenting stress 2. Inter-brain synchrony is higher in dyads where the mother is more securely attached 	<ol style="list-style-type: none"> 1. Children show more prefrontal activation when co-viewing with their fathers than with their mothers 2. Girls show greater prefrontal activation than boys towards positive animation stimuli 	<ol style="list-style-type: none"> 1. Mother-daughter dyads showed greater prefrontal activation than father-daughter dyads when watching a gender-salient conflict scene 2. Father-son dyads showed greater prefrontal activation than mother-son dyads when watching a gender-salient conflict scene
Interpretations	<ol style="list-style-type: none"> 1. Physical presence of spouse supports inter-brain synchrony in co-parenting couples 2. Synchrony might be adaptive only under favourable circumstances, and synchrony during stressful situations like towards cry vocalisations might be maladaptive 	<ol style="list-style-type: none"> 1. Inter-brain synchrony can be observed during passive shared activities 2. Parental factors might influence the extent of inter-brain synchrony 3. Reduced synchrony in dyads with more stressed and less securely attached mothers might reflect differences in intersubjective experiences between mother and child during bonding activities 	<ol style="list-style-type: none"> 1. Co-viewing with mothers might differ from co-viewing with fathers 2. Girls might process positive stimuli more efficiently than boys 	<ol style="list-style-type: none"> 1. Gender composition of dyads is an important social information that affects parental brain processing 2. Differences in parental brain responses based on gender composition of dyads emerge when watching gender-salient scenes
Implications	<ol style="list-style-type: none"> 1. Within the parenting context, inter-brain synchrony can be observed across co-parenting partners and parent-child attachment pairs 2. Findings support the initial notion that human social bonds are facilitated by underlying synchrony mechanisms (Feldman 2012) 3. Enhanced inter-brain synchrony when spouses are together, and in dyads with less stressed and more securely attached mothers, show that inter-brain synchrony is adaptive in cultivating attachment when the situation is favourable (i.e. not stressful, negative or conflictual) 4. Parental gender, child's gender and emotional valence of screen stimuli influences child's and parental brain processing of narrative scenes 			

Figure 10. Overview of findings on children's, mothers' and fathers' processing of narrative scenes, inter-brain synchrony in co-parenting couples, and inter-brain synchrony in mother-child dyads.

CHAPTER 7

CONCLUSION

Each successive chapter in this thesis has provided novel insights into the brain mechanisms of parenting from a dyadic perspective, first investigating inter-brain synchrony that occurs in co-parenting spouses (i.e., mother-father), before uncovering synchrony within the context of mother-child dyads and children's prefrontal processes when co-viewing narrative scenes with their parents. Inter-brain synchrony is a mechanism postulated to emerge alongside the formation of human bonding and attachment (Feldman, 2012). Supporting this theory, this thesis demonstrated that synchrony was indeed observed in both mother-father and mother-child pairs during joint passive engagement, during which the former listened to salient human vocalisations together whereas the latter co-viewed narrative animation scenes. Taking this theory further, this thesis examined specific variables that could potentially influence inter-brain synchrony.

Variations in the extent to which synchrony was observed across both mother-father and mother-child dyads could be traced to social, psychological and stimuli factors. In mother-father couples, synchrony was significantly higher when partners were together compared to when they were apart. Couples did not display similar degrees of synchrony to all vocalisations either, displaying reduced synchrony towards negative vocalisations instead. These observations suggest that the social presence of a partner and the emotional valence of the stimuli are critical variables that moderate inter-brain synchrony. The subsequent chapters steered towards investigating brain

mechanisms in parent-child dyads, first examining inter-brain synchrony of mother-child dyads before making inquiry into the child's brain processes during co-viewing of narrative scenes. Maternal parenting stress and anxious attachment styles were both found to be associated with reduced inter-brain synchrony during co-viewing, even upon controlling for the factors which were found to influence child's processing of screen stimuli, namely gender and emotional valence of stimuli. These findings attest to the possibility of psychological variables affecting inter-brain synchrony during everyday joint passive activities like co-viewing of the television together. Subsequently, children's and their parents' PFC activity during co-viewing once again points to the role of emotional valence of stimuli and social characteristics, such as parental gender and child's gender, in influencing brain mechanisms.

Essentially, inter-brain synchrony reflects similarities in the temporal changes of brain signals between two people, capturing automatic and unbiased intersubjective experiences shared between dyadic partners. Along the same vein, it can be interpreted that co-parenting couples in this study share greater intersubjective experiences when together, but not in response to stressful negative vocalisations. In positive situations, sharing similar intersubjective experiences could be beneficial in enhancing dyadic bonding. Moreover, maladaptive psychological traits like parenting stress and maternal anxious attachment undermine dyadic inter-brain synchrony, and, by extension, the shared intersubjective experiences between a mother and child when watching television. Taken together, these interpretations suggest that inter-brain synchrony is nuanced in that it could be adaptive in favourable contexts such as listening to the sounds of laughter and watching animations shows together. However, adverse psychological traits can further refine the extent to which synchrony is observed in these situations.

Despite the novel inroads made in the understanding of dyadic brain mechanisms in the parenting context, the implications of inter-brain synchrony on the quality of bonding and parenting remain obscure. Although an inquiry into the behavioural correlates of inter-brain synchrony goes beyond the scope of the present thesis, a discussion on the potential link between brain and behavioural processes is warranted to facilitate future research. In the chapter on co-parenting spouses, constant exposure to the social presence of a co-parent through cohabitation might enhance the similarity in how couples process stimuli in general. Processing stimuli in a similar way might facilitate a couple's ability to coordinate their behavioural responses, and this coordination could potentially extend to caregiving activities as well. For example, a typical parenting scenario that requires cooperation from a co-parenting couple is changing their infant's diapers. Co-parents who rear their infant together would be familiar with the infant's signals of discomfort and would potentially be able to coordinate their caregiving actions to reassure the infant, clean the infant and prepare his/her new diaper. Moreover, couples who do not synchronise their brain response to the sound of their crying infant would probably experience less distress and would be able to complete caregiving tasks more efficiently. To derive ecologically-relevant interpretations of inter-brain synchrony in co-parenting couples, future research should endeavour to explore the link between inter-brain synchrony and coordinated caregiving behaviours in couples.

Thereafter, the subsequent chapters of this thesis on parent and child co-viewing narrative scenes together have revealed that adverse maternal psychological traits diminished the degree to which inter-brain synchrony manifested. Although the association between maladaptive maternal traits and inter-brain synchrony, and, by extension, intersubjective experiences, has been elucidated, the link between reduced intersubjective experiences and the quality of dyadic bonding

has yet to be demonstrated. In fact, most studies on inter-brain synchrony have primarily measured cooperativity and efficiency in completing a task (e.g., Fishburn et al., 2018; Nguyen et al., 2020b), with limited attention to how inter-brain synchrony could be interpreted in terms of quality of dyadic bonding. Future research should investigate the behavioural correlates of reduced inter-brain synchrony that ensues following joint engagement in co-viewing activities. For example, given that parental mental state talk during conversations with preschool-aged children during shared picture book-reading is an indication of quality parenting and enhances preschoolers' executive functioning, further investigation could examine the quality of affect and the conversations about the animation shows that occur between a mother and child following the co-viewing activity (Baptista et al., 2017). One possibility is that mother-child dyads who exhibited greater inter-brain synchrony during co-viewing would have found the activity equally enjoyable, hence demonstrating positive affect and involved back-and-forth conversations shortly after the co-viewing task. Such potential extensions of this study would allow a clear relationship between inter-brain synchrony and quality of dyadic bonding to be drawn.

Finally, the results across all three studies from this thesis may be applied to therapeutic and clinical settings. The finding that co-parenting partners in healthy dyadic relationships synchronize towards positive and neutral, but not to negative emotional conditions may inform future therapy interventions for co-parenting partners who face difficulties in rearing their child together. For instance, synchrony approaches could identify co-parenting partners who tend to entrain to each other's distress, which entrenches them in a negative emotional state that inadvertently hinders optimal parenting responses and undermines the quality of their relationship. By understanding the mechanisms of emotional synchronisation that co-parenting partners undergo, tailored approaches to relationship therapy could be provided to help co-parenting

couples cope with social distress, the primary of which is constant exposure to child and infant cries, on a daily basis.

This thesis has also demonstrated that social characteristics of a dyad can be reflected in a brain-to-brain paradigm, where dyads with mothers reporting greater parenting stress and attachment anxiety displayed less brain-to-brain synchrony during passive co-viewing activities. These findings pave novel inroads for the applied uses of brain-to-brain synchrony approaches in clinical therapies that address psychopathological conditions. For example, children with conditions such as autism spectrum disorders (ASD) experience difficulties in understanding the perspectives and emotions of others. Future studies can be conducted to determine if dyads with children who are diagnosed with autism display significantly less PFC activity compared to dyads with neurotypical children in which case brain-to-brain approaches can be used as a potential screening tool by identifying dyads with substantial mismatches in temporal brain responses. Alternatively, brain-to-brain synchrony may potentially be used as a training tool to assist parents in attuning their own emotions to that of their child so as to improve the quality of parent-child relationships. For instance, brain-to-brain synchrony may assist parents who are entrenched in dysfunctional parent-child relationships to exercise greater awareness of their child's emotional state which would facilitate greater dyadic emotional attunement. In addition to engaging in existing therapies such as parent-child interaction therapy (PCIT), which focuses exclusively on improving the quality of interactional exchanges between a mother and child, brain-to-brain synchrony could be employed as a tool to provide neural feedback on how attuned the mother is to her child during less demanding joint occurrences such as passive co-viewing activities.

This thesis has scratched but the surface of inter-brain synchronisation and showed that the physical presence of a co-parenting partner, the emotional valence of stimuli and maternal

psychological variables affect inter-brain synchronisation of dyads during passive joint activities. In an ideal research progression, inter-brain synchrony could potentially become a marker that signals co-parenting efficiency and the quality of parent-child dyadic bonding. However, prior to such applications, extensive research on inter-brain synchronisation needs to be conducted to disentangle the factors that contribute to synchrony in specific situations. In particular, adaptive synchrony in which temporal alignment indicates attunement and supports synchronous behaviours (Feldman, 2012b) should be differentiated from maladaptive instances of synchrony where physiological entrainment in stressful conflictual contexts denotes that dyadic partners are mutually influenced by each other's adverse emotional states (Saxbe & Repetti, 2010). A nuanced understanding of inter-brain synchronisation could eventually render it as an indicator of real-time connectivity and attunement between dyadic partners. Finally, identifying factors that hinder adaptive synchronisation could assist dyadic partners to overcome these drawbacks and improve their co-parenting and parent-child relationships.

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