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Dynamics of frontal alpha asymmetry in mother-infant dyads: Insights from the Still Face Paradigm

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ABSTRACT

The parent-infant dynamic has a foundational role in emotion regulation development. Electroencephalography (EEG) hyperscanning from mother-infant dyads can provide an unprecedented window into inter-brain dynamics during the parent-infant exchange. This potential depends on the feasibility of hyperscanning with dyads in emotionally taxing contexts. We sought to demonstrate feasibility of hyperscanning from 10 mother-infant dyads during the Still Face Procedure (SFP). We measured frontal alpha asymmetry (FAA) to elucidate ongoing regulatory dynamics and considered maternal caregiving quality as a window into dyads' history. Results showed dyads exhibited a rightward shift in FAA over the course of SFP, indicating growing negative emotionality and desire to withdraw. Results also showed growing variability in FAA for infants over the course of SFP, indicating less active emotional control as stress ensued. Variability was especially low for mothers during periods when asked to be emotionally unavailable, suggesting active control to match the task demands. Dyads with a more responsive mother exhibited higher (more left) FAA relative to dyads with a less responsive mother, which might reflect a more positive emotional experience overall. We raise important methodological and theoretical questions that hyperscanning during SFP can address, such as the developmental origins of trait-like self-regulatory dispositions.

1. Introduction

Parent-infant interactions exert a lasting impact on almost every aspect of child development, including growth in self-regulation, social-emotional and cognitive functioning (Bernier, Calkins, & Bell, 2016; Blair, Cybele Raver, & Berry, 2014; Hane & Fox, 2006). These enduring influences are rooted in the real-time parent-infant exchange. This exchange has a “dance” quality during which mother and child temporally match their behavior, emotion, and biology (Feldman, 2007a; Tronick, 1989). Empirically, this dance is characterized as synchrony. Behavioral and physiological indicators of synchrony emerge early and become more prominent over the first year, with this accentuation of coordination thought to reflect ongoing co-regulatory processes (2007b, Feldman, 2007a). Research addressing cardiac physiological synchrony has a longstanding history (for review, see Davis, West, Bilms, Morelen, & Suveg, 2018) and has been used to better understand the real-time dynamics of co-regulatory processes in mother-infant dyads (Waters, West, & Mendes, 2014; Waters, West, Karnilowicz, & Mendes, 2017). The study of inter-brain synchrony in mother-infant dyads is relatively

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new, accomplished via simultaneous recording of brain activity from multiple participants, a methodology referred to as hyperscanning. The current study reports results from a feasibility study using electroencephalography (EEG) hyperscanning with 10 mother-infant dyads in the context of the Still Face Procedure (SFP), a hallmark emotion regulation task which introduces mild social stress for both mothers and their infants as dyads play and mothers' emotional availability comes and goes over time (Tronick, 1989).

SFP has been used to examine a variety of physiological correlates of emotion regulatory processes (Conradt & Ablow, 2010; Gartstein, 2019; Haley & Stansbury, 2003; Moore & Calkins, 2004; Moore et al., 2009; Weinberg & Tronick, 1996). SFP is, by design, a co-regulatory context that becomes increasingly stressful for mothers and their infants over time; thus, we expected to observe synchronized neurophysiological signatures of emotion regulation over the course of the procedure. In adult dyads, distinct patterns of synchronization have been demonstrated in couples relative to strangers (Kinreich, Djalovski, Kraus, Louzoun, & Feldman, 2017). As the mother-infant relationship is arguably equally emotionally rich and intense, we should expect to observe distinct synchronization related to the developmental history of the mother-infant dyad. As such, we report frontal alpha asymmetry (FAA), a neural correlate of emotion regulatory processes, as it unfolds over the course of the procedure, considering the contribution of maternal caregiving quality as a window into individual dyads' history.

The purpose of this special issue is to share methodological advances in characterizing the dynamics of caregiver-infant interactions. Hyperscanning has the potential to provide an unprecedented window into inter-brain dynamics during parent-child interactions and address unresolved theoretical issues, including those related to the origins of individual differences in emotion regulatory capacity. Though exciting, this potential critically depends on the feasibility of acquiring hyperscanning data from mother-infant dyads in emotion regulatory contexts, which is not trivial as these are often taxing and require recording brain activity for extended duration while emotion regulatory processes unfold. The overarching goal of the present investigation was to demonstrate feasibility of acquiring hyperscanning data during SFP. In the sections that follow, we set the stage for the current study with a brief overview of conceptual foundations of physiological synchrony, the infant hyperscanning literature, and the role of maternal caregiving quality in cortical development and emotion regulation during infancy.

1.1. Conceptualization of physiological synchronization

Parent-infant synchrony is often conceptualized within the bio-behavioral framework in which co-regulation, synchronization, and growth in synchrony is supported by physiological systems and their maturation (2007b, Feldman, 2007a; for an excellent review, see Bell, 2020). Parent-infant synchrony likely helps to establish internal processes that support regulation (e.g., modulation of emotional expression) in a variety of contexts at later points in development (e.g., Feldman, Greenbaum, & Yirmiya, 1999). Indeed, measures of cardiac physiological synchronization during infancy are predictive of children's self-regulatory abilities during early childhood (see Feldman, 2007b). As noted, hyperscanning provides a new toolkit to examine synchronization in neural systems in co-regulatory contexts, informing our understanding of dyadic synchrony as well as its role in developmental outcomes for children. The study of inter-brain synchronization relying on neuroimaging is embedded within the broader discipline of second-person neuroscience which ascribes to the view that a unique experience emerges between people during social interactions that does not exist within individuals alone, observable on the level of brain activity (Schilbach et al., 2013). Hyperscanning studies have shown inter-brain synchronization emerges during cooperation (e.g., Cheng, Li, & Hu, 2015; Jahng, Kralik, Hwang, & Jeong, 2017; Liu et al., 2016; Osaka et al., 2015; Xue, Lu, & Hao, 2018), communication (Ahn et al., 2018; Pérez, Dumas, Karadag, & Duñabeitia, 2019), and educational activities (Bevilacqua et al., 2019; Zheng et al., 2018).

1.2. Inter-brain synchronization in early development

The study of inter-brain synchronization during early development is beginning to blossom and has similarly shown synchronization between infants and adults emerges during social interactions (e.g., Piazza, Hasenfratz, Hasson, & Lew-Williams, 2020). For example, using EEG with infants and an adult experimenter, Leong et al. (2017) found an adult reciting nursery rhymes had directional influence on infants' cortical activity in theta and alpha rhythms during direct gaze. They also found longer infant vocalizations led to stronger synchronization for the adult member of the dyad. These results are consistent with studies with adults showing greater synchronization during face-to-face communication or joint attention (e.g., Jiang et al., 2012; Saito et al., 2010). Also using EEG, Wass et al. (2018) examined cortical activity for infants and mothers during solo and joint play with objects. During solo play, infants' theta activity increased prior to shifting gaze to an object, indicating theta activity precedes overt shifts in attention. During joint play, parents' theta activity increased following infants' gaze shifts to an object, indicating parental neural responsiveness, such that infants' behavior led maternal cortical activity.

The study of inter-brain synchronization can help us better understand emotion regulatory processes. For instance, Santamaria et al. (2020) used a social referencing procedure in which mothers expressed positive or negative affect toward objects while EEG was recorded. Using graph theory, they found inter-brain networks were more strongly interconnected in the infant alpha range (6–9 Hz) during maternal expression of positive relative to negative emotions. We can also garner insights into co-regulatory processes from hyperscanning. For example, Atzaba-Poria, Deater-Deckard, and Bell (2017) used EEG hyperscanning to probe relations between FAA and mother-child negativity during a puzzle task. FAA is a well-studied neural correlate of ongoing emotion regulatory and motivational processes measured as the difference in alpha band power at left and right sites over frontal cortex. More left frontal alpha activity (i.e., lower relative left alpha power, higher FAA) is associated with dominant positive emotional states and approach motivation, whereas more right frontal activity (i.e., relatively lower right alpha power, lower FAA) is associated with negative emotional states and avoidance or withdraw (e.g., Allen, Keune, Schönenberg, & Nusslock, 2018; Coan & Allen, 2004; Davidson,

Schwartz, Saron, Bennett, & Goleman, 1979). Atzaba-Poria et al. found higher levels of maternal negativity during a puzzle task was associated with more right frontal alpha activity in their 3-year-old children during the task and, similarly, higher levels of child negativity was associated with more right frontal alpha activity for mothers during the same task. We measured FAA over the course of SFP and expected dyads to exhibit a shared pattern of activity over the course of the procedure, sometimes referred to as trend synchrony (Helm, Miller, Kahle, Troxel, & Hastings, 2018). Specifically, we expected mothers and their infants to exhibit more right frontal alpha activity over the course of SFP as the task induces increasingly more stress, negative emotionality, and desire to withdraw for both members.

1.3. Maternal caregiving quality

A growing body of evidence has shown maternal caregiving quality is associated with several measures of cortical development and neural correlates of self-regulation. Many of these observations are based on baseline EEG recordings while infants sit quietly and watch a dynamic display (e.g., Baby Einstein's Baby Mozart). For example, Bernier et al. (2016) found maternal positive affect observed at 5 months of age was associated with higher frontal theta and alpha at 10 and 24 months of age during baseline. Hane and Fox (2006) found high quality maternal caregiving was associated with more relative left frontal alpha activity as well as less fearfulness, more joint attention, and less negative affect. Low quality caregiving was associated with the opposite pattern of results. Swingler, Perry, Calkins, and Bell (2017) found infants demonstrating more left frontal alpha activity with high quality caregiving exercised better self-regulation during a frustration task. However, infants who exhibited more relative right frontal alpha activity were more likely to display negative affect during the same task if their mothers exhibited higher quality caregiving. A recent study by Gartstein (2019) showed high quality caregiving ascertained through observing mother-infant play exchanges predicted less right frontal alpha activity in SFP for infants high in approach. We contend these connections between maternal caregiving quality and infants' brain development are built from real-time interactions structuring brain development (for discussion, see Perone & Gartstein, 2019a), which hyperscanning can elucidate in an unprecedented manner.

We focused on maternal responsiveness, a commonly examined dimension of maternal caregiving quality, for the purposes of this study. Highly responsive mothers appropriately interpret their infant's communication attempts and provide prompt, contingent, and supportive responses, and they engage their infant in a non-intrusive, interested, and emphatic fashion (Ainsworth, Bell, & Stayton, 1974; Bornstein & Manian, 2013). Maternal caregiving quality is an indicator of the unique history of mother-infant dyads which may be linked to distinct patterns of synchronization as we measure them over the time scale of the laboratory session. A more positive emotional experience and greater synchronization can be expected for dyads with a more responsive mother, reflecting the relatively richer, more attuned developmental history.

1.4. The current study

The overarching objective of the current study was to probe the feasibility of acquiring EEG from mother-infant dyads over the course of SFP. We used the repeated variant of SFP in which regulatory demands on mothers and infants are increased through repeated trials of interactivity and emotional unavailability (Gartstein, 2019; Haley & Stansbury, 2003). We expected mothers and their infants to exhibit a rightward shift in FAA over the course of SFP as an indicator of negative emotionality and desire to withdraw. We also measured variability in FAA during all segments of SFP. Although our understanding of variability in FAA is still developing, higher variability in FAA is thought to indicate more fluctuation between approach- and avoidance-related states (Minnix & Kline, 2004). The degree to which people exhibit more right frontal alpha activity has also been described as reflecting greater self-regulation over approach and avoidance motivational processes (Gable, Neal, & Threadgill, 2018). Within this framework, lower levels of FAA (i. e., greater right frontal activation) could reflect more regulatory efforts exerted over these motivation forces. We expected variability in FAA to be higher during stressful periods of the task, such as while the task unfolds or during still face segments. A secondary goal of the current study was to explore measures of synchronization as they relate to maternal caregiving quality. We expected to observe dyads with more responsive mothers to exhibit less right frontal alpha activity overall, as an indicator of a more positive emotional experience and greater co-regulation resulting from their dyadic history.

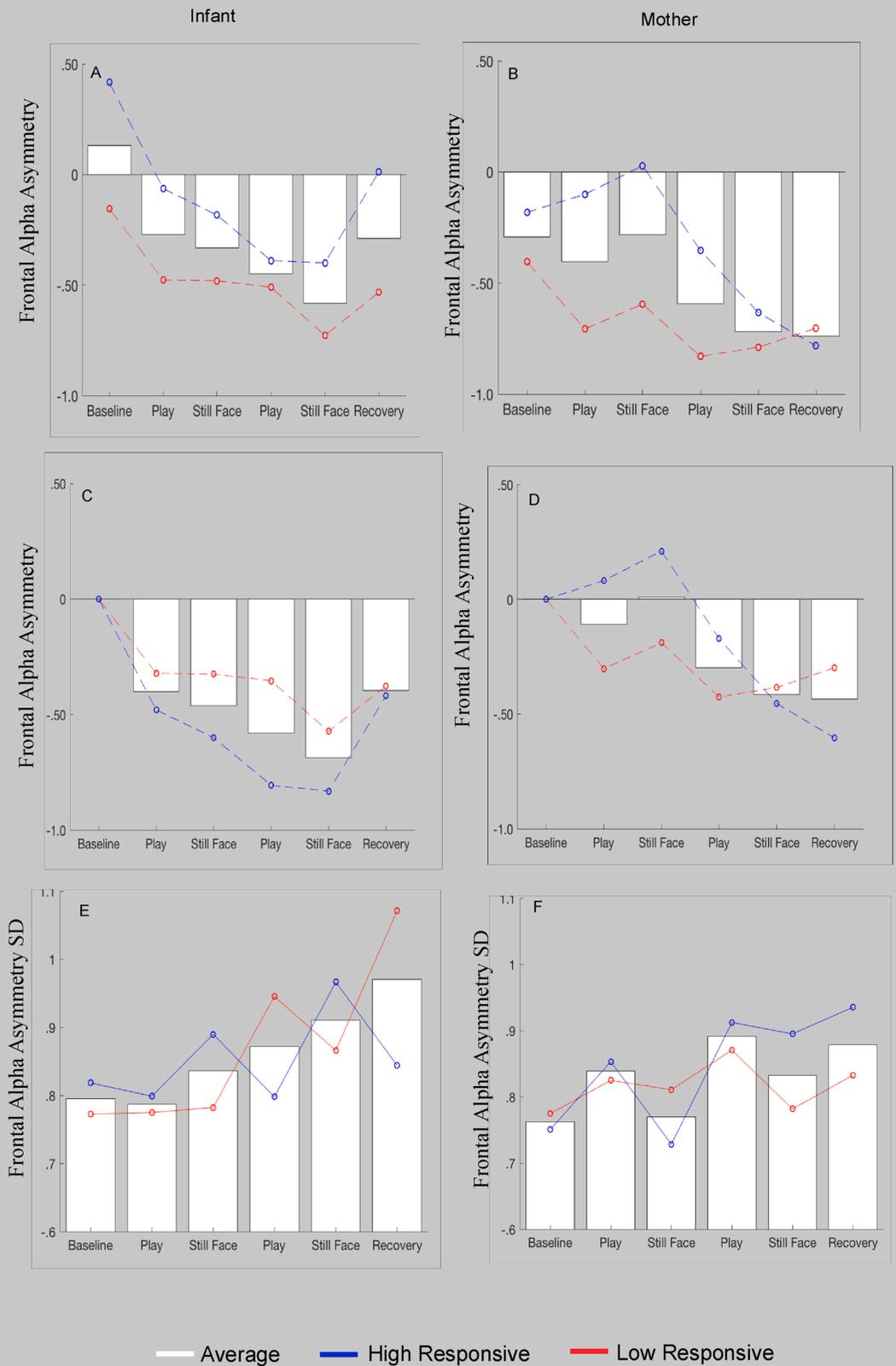
2. Method

2.1. Participants

Ten mother-infant dyads participated in this study. Infants were between 8 and 12 months old ($M = 10.72$ months, 7 males). One child did not complete the last two segments of SFP due to fussiness/distress and was excluded from analyses of those segments (see subsequent sections).

2.2. Design and procedure

Mothers and their infants were each fitted with a 128 channel hydrocel net manufactured by Electrical Geodesics, Inc (EGI). The EEG was synchronized by simultaneously placing an event marker in the EEG for infants and their mothers. Four facial channels designed to detect blinks were not placed on the infant to maximize comfort. We aimed to set impedance levels below 50 k Ω prior to beginning the procedure but accepted impedances up to 100 k Ω . The EEG was monitored to ensure a high-quality signal prior to



(caption on next page)

Fig. 1. Shows frontal alpha asymmetry (FAA) measures for infants (left) and mothers (right). The white bars show average scores. The blue and red lines show scores for dyads with more and less responsive mothers, respectively, based on a median split. 1A-B show FAA beginning with baseline on the left through recovery of the Still Face Procedure (SFP) on the right. 1C-D shows baseline corrected FAA over the course of the session, and 1E-F shows variability in FAA over the course of the session. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

recording and electrodes were adjusted as needed. Mothers were fitted with the net first while infants sat on their laps. Once all electrodes were set on mothers, the net was placed and electrodes were set on the infant. Infants were then situated in a high-chair next to their mothers who sat in a chair for baseline and SFP. A curtain hung between dyads and the experimenter during the procedure. For baseline, dyads watched a 60 s segment of Baby Einstein, Baby Mozart (Gartstein, 2019; Perone & Gartstein, 2019b; 2019b). Immediately following baseline, mothers were provided instructions on how to participate in SFP which consisted of play with stacking cups, during which mothers were instructed to play naturally with their infant, and still face, during which mothers were instructed to be maintain a neutral face and be emotionally unavailable (i.e., not to communicate with the infant in any way, verbally or non-verbally). SFP was 10 min in duration and consisted of two-minute segments in the following sequence: play, still face, play, still face, and recovery/play (DiCorcia, Snidman, Sravish, & Tronick, 2016; Haley & Stansbury, 2003). A video camera that was synchronized to the EEG was used to record and code behavior. The EEG was recorded at 1000 Hz and referenced to Cz online.

2.3. Coding

Maternal responsiveness was coded by a reliable coder, demonstrating agreement with the standard ratings assigned to test cases ($N = 20$; ICC $> .70$). Responsiveness was coded during each of the play segments following established protocols on a 1–7 Likert scale (1-low responsiveness/7-high responsiveness). Responsive interactions were operationalized in terms of mothers providing prompt, contingent, warm, and supportive responses, appearing to be genuinely interested and emphatic, accurately interpreting communication attempts. Low responsiveness scores were assigned to interactions lacking these attributes (e.g., parent does not initiate/motivate child activity or draw the child into joint action; does not use versatile motivational strategies; or uses intrusive techniques). Moderate responsiveness was characterized by mid-level empathy and interest in the infant, periodic initiation of play, reinforcement, drawing infant into joint activity, encouragement of infant independent play, and effective extension of infant activity (Gartstein, Crawford, & Robertson, 2008; Gartstein, Hancock, & Iverson, 2018; Perone & Gartstein, 2019a). Responsiveness scores were collapsed across play segments. Not surprisingly, responsiveness was high ($M = 5.43$, $SD = .86$, range 3.67–6.33) in our low-risk community sample. Nevertheless, prior studies have showed variation in maternal caregiving in samples of similar composition is meaningfully related to neural activity and emotion regulation development in infants (Hane & Fox, 2006).

2.4. EEG preprocessing

The EEG was processed in Matlab using custom scripts relying on functions from EEGLab (Makeig & Delorme, 2004), ERPLab (Lopez-Calderon & Luck, 2014), FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011), and CSD Toolbox (Kayser & Tenke, 2006). The continuous EEG for mothers and infants was high-pass filtered at 1 Hz, a 60 Hz notch filter was applied, and excessively noisy electrodes were removed and interpolated following artifact correction. Ocular artifacts were identified and corrected for mothers using Independent Components Analysis (ICA). Ocular artifacts could not be reliably detected and corrected for infants. When blinks appeared in the infant EEG, the waveform at sites analyzed in the present report appeared unaffected. Prior to time-frequency decomposition, the EEG was Laplacian transformed to increase the topographical localization and obtain the current source density using the CSD toolbox with default parameters ($m = 4$, head radius = 10, $\lambda = .00001$).

The EEG for baseline and each SFP segment were divided into 1 s epochs with 75 % overlap. Epochs were rejected if more than 10 % of electrodes (e.g., Righi, Tierney, Tager-Flusberg, & Nelson, 2014) had voltage greater than 100 microvolts for 50 ms, eliminating epochs with widespread noise. Time-frequency decomposition on the remaining epochs was performed on Laplacian transformed EEG using Fast Fourier Transformation (FFT). The average proportion of epochs available for analysis for infants during baseline, first play, first still face, second play, second still face, and recovery was 90.25 % ($SD = 9.30$ %), 84.04 % ($SD = 21.05$ %), 76.16 % ($SD = 19.77$ %), 83.69 % ($SD = 17.50$ %), 82.65 % ($SD = 14.34$ %), and 84.18 % ($SD = 12.76$ %). The average proportion of epochs available for analysis for mothers during baseline, first play, first still face, second play, second still face, and recovery was 98.06 % ($SD = 2.18$ %), 87.74 % ($SD = 15.05$ %), 97.59 % ($SD = 2.59$ %), 82.27 % ($SD = 18.15$ %), 95.73 % ($SD = 5.36$ %), and 84.75 % ($SD = 15.69$ %).

Average FAA was computed across epochs during baseline and each SFP segment for infants and mothers. Alpha peak frequency is slower during infancy than childhood and adulthood. During the second half of the first year – the age group studied herein – the alpha peak frequency is about 7–8 Hz (Marshall, Bar-Haim, & Fox, 2002) and alpha is routinely defined as 6–9 Hz during infancy, referred to as “baby alpha” (e.g., Bell & Fox, 1992; Cuevas & Bell, 2011; Gartstein, Bell, & Calkins, 2014). FAA was computed in the 6–9 Hz and 8–13 Hz ranges for infants and mothers, respectively, by subtracting natural log transformed alpha at left site F3 from right site F4 (e.g., Atzaba-Poria, Deater-Deckard, & Bell, 2017; Hane & Fox, 2006; Swingler, Perry, Calkins, & Bell, 2017). Lower levels of alpha power are understood to reflect greater neural activation, as alpha is inhibitory with respect to cortical network activity (Allen, Coan, & Nazarian, 2004). Thus, lower FAA reflects relatively more right frontal activity and higher FAA reflects relatively more left frontal activity. We also computed variability in FAA during baseline and each segment as the SD in FAA over the course of a baseline task

(Minnix & Kline, 2004; see also Schmidt, 2008). We computed the SD in FAA in bins of 4 overlapping (75 %) epochs during each segment for mothers and their infant. The same qualitative pattern of results was observed at bin sizes of 8, 12, 16 and 20 epochs.

3. Results

Our results are descriptive due to the feasibility focus of the current study and small sample size. Fig. 1A shows FAA for infants during baseline through recovery of SFP. The white bars show average FAA, and the blue and red lines show FAA for infants with relatively more and less responsive mothers based on a median split, respectively. 1B shows the same results for mothers. On average, infants and mothers exhibited a rightward shift in FAA over the course of SFP. Infants with a more responsive mother exhibited higher FAA than infants with a less responsive mother over the course of SFP, as did more responsive mothers relative to less responsive mothers. This pattern of results indicates that dyads with a more responsive mother exhibited relatively greater left frontal activity over the course of SFP than dyads with a less responsive mother.

Fig. 1C–D shows the same results normalized to baseline which helps control for the influence of individual differences in overall levels of FAA when computing averages as well as the degree to which FAA might shift from baseline to SFP. Normalizing FAA to baseline yielded a different pattern of results, particularly for infants. Infants with more responsive mothers exhibited more right frontal alpha activity during SFP than infants with less responsive mothers. This is due to the larger rightward shift from baseline to SFP for infants with more responsive mothers relative to infants with less responsive mothers. Raw and normalized FAA together provide a more complete picture of infants' and mothers' state during SFP.

Fig. 1E–F shows variability in FAA over the course of SFP which provides a window into dynamics of active regulatory processes during the emotional experience and, thus, distinct information from the directionality of FAA. For infants, variability in FAA increased, especially ramping up during the first still face segment (white bars, 1E). These observations could reflect more fluctuation between approach and avoidant states over the course of SFP as the task becomes increasingly stressful. A distinct pattern emerged for infants with more responsive (blue lines) than less responsive (red lines) mothers. In particular, infants with more responsive mothers exhibited more variability during the still face segments whereas infants with less responsive mothers showed more variability during the play segments. For mothers, variability in FAA generally increased over the course of SFP but also systematically fluctuated, higher during play than SFP (1 F, white bars). This pattern was exaggerated for higher responsive mothers. These observations are consistent with the notion still face segments require active control to maintain emotional unavailability. The especially high levels of variability for responsive mothers toward the end of SFP suggest the task may be more stressful for them.

3.1. General discussion

The parent-infant interaction is an important context through which co-regulation is built and has a foundational role in infants' developing emotion regulatory abilities. Hyperscanning represents a useful tool to uncover the neural dynamics involved in co-regulation, likely to provide novel insights into development of emotion regulation studied in standard lab tasks, such as SFP. Our primary findings focused on the co-evolution of a neural correlate of ongoing emotion regulatory processes, FAA, over the course of SFP. Infants and mothers exhibited a rightward shift in FAA over the course of SFP, which suggests growing negative emotionality and desire to withdraw as the experience became increasingly stressful. Although preliminary, this pattern of results is exactly what should be expected based on the approach-avoidance model of motivational and emotion regulatory processes (e.g., Allen et al., 2018; Coan & Allen, 2004; Davidson, 2002) as well on as the empirical FAA literature (e.g., Jackson et al., 2003; Perone, Weybright, & Anderson, 2019). We also examined variability in FAA across SFP segments, which is reported less frequently, yet may prove to be an informative indicator of active emotion regulatory processes. Variability in FAA may reflect the dynamics within the complex cortical-subcortical neural circuitry involved in approach- and avoidance-related motivational processes and regulation over them (see Davidson, 2000, 2002, 2004; Davidson & Irwin, 1999; see also Allen et al., 2018; Gable et al., 2018; Zotev et al., 2016). Higher levels of variability in FAA is thought to reflect more fluctuations between approach- and avoidance-related processes or relatively more positive and negative emotionality (Minnix & Kline, 2004). Our observations are consistent with this possibility. In particular, infants exhibited more variability in FAA over the course of SFP. We interpret this as the influence of increasing stress dominating the emotional experience and taxing emotional control processes. Variability in FAA for mothers also generally increased over the course of SFP and was a bit lower during the still face segments than the play segments. These segment differences could reflect the task demand to maintain emotional unavailability.

All results related to maternal caregiving should be considered suggestive because our sample is small, data descriptive, and caregiving quality high in this community sample. With this caveat in mind, the results are in line with our expectations and worthy of further discussion. We found dyads with a more responsive mother exhibited more left frontal alpha activity relative to dyads with a less responsive mother overall. The observed pattern of results might reflect a more positive emotional experience and a sense of security that arises from a relatively richer, supportive relationship. This interpretation is consistent with numerous studies linking higher levels of maternal responsiveness and secure attachment, and extends our understanding of potential neurophysiological underpinnings (e.g., Ainsworth, Blehar, Waters, & Wall, 1978; Higley & Dozier, 2009).

Our findings with respect to maternal caregiving and FAA should be considered in the context of baseline corrected FAA. When FAA was baseline corrected, it was revealed infants with a more responsive mother exhibited a relatively larger rightward shift than infants with a less responsive mother. This observation might indicate these infants experienced a greater violation of expectation with regard to their typical experience than infants with a relatively less responsive mother, and may be viewed as an adaptive withdraw response in a stressful situation, such as SFP. The violations of expectations interpretation is consistent with Tronick et al's (1978) original

formulation of SFP, and the social stress that results from the mother failing to respond to the infant in an anticipated manner, becoming “unavailable” and challenging emerging self-regulation skills. Tronick (2005) later proposed the Dyadic States of Consciousness Model (DSCM), according to which infants rely on adult partners (intersubjectivity with these partners in particular) to create meaning, required in order to maintain a coherent state of consciousness, and by extension an optimal physiological state. Infants may also become uncertain regarding the caregivers’ intentions (Tronick, Als, Adamson, Wise, & Brazelton, 1978; Tronick, Als, & Brazelton, 1980), especially when these mothers are typically responsive. This effect is likely accentuated with the repeated version of SFP, compromising infants’ trust in return to typical interactions with the introduction of the second trial, and amplifying the challenge to child regulation and neurophysiological responses.

An important goal of this special issue is to advance the study of the dynamics of the parent-infant exchange. The current study adds to our methodological repertoire for studying the dynamics of parent-infant interactions in two ways. First, our study suggests obtaining hyperscanning EEG data during SFP is feasible. All infants, with the exception of one, were able to tolerate the entire procedure. This is notable because we used the repeated trial variant of SFP which is 10 min in duration and is emotionally taxing for infants and mothers. One exciting implication is that because SFP is a natural context with substantial ecological validity, our study suggests future research with larger samples sizes can rely on this procedure while pursuing measurement of neural synchronization during spontaneous behaviors, such as mutual gaze, joint attention, and signatures of distress (e.g., gaze aversion; for examples, see Piazza et al., 2020). Second, we reported on the dynamics of FAA as it evolved over the course of SFP. This is informative with respect to the evolution of the emotional experience dyads share through time. We also reported variability in FAA which provides a window into the rapid time scale of emotion regulatory processes as these are unfolding. The study of FAA as reflecting dynamic processes can help us understand the momentary processes through which emotion regulation development advances in infancy.

Relatedly, our study also points to a contribution hyperscanning can make to our theoretical understanding of the emotion regulatory processes FAA reflects. FAA has long been studied as an indicator of trait level dispositions across the lifespan (Allen et al., 2018; Fox, Henderson, Rubins, Calkin & Schmidt, 2001; Hane & Fox, 2006). Several studies have shown FAA reflects ongoing regulatory processes within a given context (Jackson et al., 2003; Perone et al., 2019). Thus, FAA most likely has trait and state contributions, as articulated in the context of the capability model (Coan, Allen, & McKnight, 2006). For example, the degree to which a person is able to match their response appropriately to the demands of a given task may be a function of a trait-like capacity, whereas the response in the moment reflects the active regulatory process (see Coan et al., 2006). Emerging research is providing support for the capability model operationalization of FAA (Gartstein, 2019; Lusby, Goodman, Bell, & Newport, 2014; Papousek, Freudenthaler, & Schuler, 2011), demonstrating the importance of context dependent FAA along with trait-level predisposition across the lifespan.

One question of great theoretical importance is where does this trait-like capacity come from? We contend the parent-infant exchange plays an important role (Fox, Henderson, Rubin, Calkins, & Schmidt, 2001; Hane & Fox, 2006). Our preliminary data suggest the degree to which mothers interact with their infant in a responsive fashion is related to both trait-like FAA, as measured via baseline (i.e., more left for infants with a more responsive mother), and active emotion regulation, as measured in an emotion regulatory task (i.e., greater rightward shift for infants with a more responsive mother). This type of connection between maternal caregiving quality and infants’ developing emotion regulatory capacity may reflect bi-directional interactions as well, such that infants’ given regulatory capacity influences maternal caregiving style (for related reading, see Blair, Raver, Berry, & Family Life Project Investigators, 2014; Kirchoff, Desmarais, Putnam, & Gartstein, 2019).

While our study suggests acquiring hyperscanning data during SFP is feasible, it also points to at least four important considerations when building on this work. First, age-related differences should be examined, ideally via longitudinal investigations with frequent assessments throughout infancy. Our study involved infants from 8 to 12 months of age which is a period during which changes in temperament, and attention-based regulation in particular, have been documented (e.g., Gartstein & Hancock, 2019) and could impact frontal asymmetry dynamics in SFP. With respect to the latter, a critical milestone involves a shift from a primary reliance on the alerting attention network, supported by areas of the parietal lobe and governed by the norepinephrine system, to a more flexible executive attention network, including the anterior cingulate, basal ganglia, and areas of the prefrontal cortex under dopamine modulation (Posner, Rothbart, Sheese, & Voelker, 2012). Second, sex differences should be considered in the future. Sex differences in temperament as it relates to frontal asymmetry have been noted (Gartstein et al., 2014; Gartstein, Hancock, Potapova, Calkins, & Bell, 2020). Few studies have observed sex differences in SFP but related research questions have not been sufficiently explored (for a review, see Mesman, van IJzendoorn, & Bakermans-Kranenburg, 2009). Third, an important direction for future research is to address the role of the specific partner as it relates to synchronization during infancy. We know from many studies synchronization emerges between strangers in shared contexts, including contexts as diverse as long-distance communication (e.g., Ahn et al., 2018), educational instruction (e.g., Bevilacqua et al., 2019), cheering with a group (e.g., Koide & Shimada, 2018), and gaze sharing (Leong et al., 2017; Piazza et al., 2020). In the current study, we observed a rightward shift in FAA over the course of SFP in mother-infant dyads. It is possible we would observe this pattern of results in stranger-infant dyads under the same SFP conditions. The degree to which the stranger is responsive to the infant may even influence the degree to which the infant shifts rightward during still face segments. Fourth, future research should also examine synchronization in father-infant dyads. Fathers are thought to play a unique role in the development of children’s self-regulation abilities (Cabrera, Karberg, Malin, & Aldoney, 2017) and, as such, father-infant dyads may exhibit distinct patterns of synchronization. Addressing these questions is essential to understand co-regulation in the context of the parent-infant exchange, as well as the contribution of synchronization within this exchange to emotion regulation development.

In closing, an important contribution of the current study is it demonstrated hyperscanning mother-infant dyads during SFP is feasible. Hyperscanning is intensive and demanding in every respect, requiring substantial human, monetary, and computational resources. Our study indicates such resources would be a good investment. This is especially true in light of the potential methodological and theoretical contributions hyperscanning during SFP can make to our understanding of the parent-infant exchange and

emotion regulation development. Moreover, such efforts will inform our theoretical understanding of FAA which is one of the most widely studied neural correlates of motivational and emotion regulatory processes across the lifespan. We can learn, for instance, what role the real-time parent-infant exchange has in emotion regulation in the moment and also over development at the level of the brain. Further, SFP provides an opportunity to observe these processes in a naturalistic context and opens the door to study synchronization during spontaneously occurring behaviors, such as shared gaze and joint attention. The current study also points to important future research, including investigation of the role of a specific interaction partner to better understand the unique contribution of familiar caregivers to co-regulatory processes.

CRedit authorship contribution statement

Sammy Perone: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Project administration, Writing - original draft. **Maria A. Gartstein:** Conceptualization, Methodology, Investigation, Resources, Project administration, Writing - original draft. **Alana J. Anderson:** Methodology, Software, Investigation, Project administration, Writing - review & editing.

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