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Developmental foundations of physiological dynamics among mother–infant dyads: The role of newborn neurobehavior

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Abstract

This study tested whether newborn attention and arousal provide a foundation for the dynamics of respiratory sinus arrhythmia (RSA) in mother–infant dyads. Participants were 106 mothers (M_{age} = 29.54) and their 7-month-old infants (55 males and 58 White and non-Hispanic). Newborn attention and arousal were measured shortly after birth using the NICU Network Neurobehavioral Scale. Higher newborn arousal predicted a slower return of infant RSA to baseline. Additionally, greater newborn attention predicted mothers' slower return to baseline RSA following the still-face paradigm, and this effect only held for mothers whose infants had lower newborn arousal. These findings suggest that newborn neurobehavior, measured within days of birth, may contribute to later mother–infant physiological processes while recovering from stress.

Infants and parents exchange affective, behavioral, and physiological states through face-to-face interactions, especially when an infant is distressed (Feldman, 2007; Tronick & Beeghly, 2011). These early experiences of co-regulation, or the dynamic coordination within parent–infant dyads, may explain how young children develop emotion regulation competencies (Bell, 2020; Leerkes & Parade, 2015). These competencies are essential for children's socioemotional health and academic achievement (Calkins, 2007; Diamond

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& Aspinwall, 2003). Identifying developmental antecedents of effective parent–infant co-regulation processes are therefore important for our understanding of the etiology of adaptive and maladaptive emotion regulation (Sroufe, 1990).

Infants' characteristics play an important role in shaping their interactions with their parents. This foundational literature has a rich history in developmental science (Bell, 1968; Belsky, 1984; Brazelton et al., 1974; Tronick & Gianino, 1986). Historically, it was thought that the infant did not influence affective exchanges with the caregiver. By examining face-to-face interactions between caregivers and infants, pioneering research by Bell, Brazelton, Tronick, and their colleagues demonstrated that infants are active participants in organizing interactions with their mothers. However, dyadic physiological dynamics have received far less attention in the literature. Understanding how mothers' and infants' physiological responses change dynamically in response to a stressor may help reveal underlying mechanisms of dyadic co-regulation that cannot be assessed through behaviors alone. Because regulation and co-regulation between mothers and infants are temporal, moment-to-moment processes (Cole et al., 2019; Ekas et al., 2018), we sought to leverage concepts and analytic tools from dynamic system theory to understand these physiological processes. We examined whether newborn neurobehavior—assessed shortly after birth—predicted physiological dynamics of mothers and their 7-month-old infants while recovering from a relational stressor, the still-face paradigm (Tronick et al., 1978).

RSA: A physiological index of regulation

A commonly used research paradigm to elicit acute stress in mother–infant dyads is the still-face paradigm (Tronick et al., 1978). In this paradigm, infants and their mothers first interact as they typically do before mothers are asked to become unresponsive and maintain a neutral facial expression. The sudden absence of contingent responses from mothers can cause significant distress in infants. Respiratory sinus arrhythmia (RSA), a measure of parasympathetic nervous system functioning, has been measured in many studies of the still-face paradigm to examine infant physiological stress responses. Infants typically respond to the still-face episode with decreased RSA levels (Jones-Mason et al., 2018) and increased distress, self-soothing, and attention-seeking behaviors compared to a typical play interaction (Mesman et al., 2009). Individual differences in RSA responses to stress may serve as a physiological index of self-regulation (Beauchaine & Thayer, 2015; Berntson et al., 1993). Decreases in RSA in response to stress may reflect the shifting of attentional and regulatory resources to cope with environmental demands. Additionally, increases in RSA during recovery may facilitate restorative processes (Porges, 2007). As such, patterns of change and recovery in RSA levels can provide valuable information about individuals' regulatory abilities under stress. The expected overall trend of RSA changes aligns with existing findings that withdrawal of parasympathetic engagement in response to stress (i.e., reduced RSA) correlates with infants' behavioral responses to a stressful context (Moore & Calkins, 2004).

Following the still-face episode, mothers resume typical interactions with their infants (i.e., reunion episode), which could provide an opportunity to examine how dyads achieve calm, physiological regulation. Infants' RSA levels generally increase during the reunion episode of the still-face paradigm, although not always to prior levels. Infants may be supported in this recovery via coregulatory processes from their mothers (Jones-Mason et al., 2018). The absence of RSA recovery in infants has been associated with low levels of infant attention, engagement, and positive affect (Conradt & Ablow, 2010; Moore & Calkins, 2004; Suurland et al., 2018). Meanwhile, mothers tend to show an opposite but complementary pattern of RSA change to that of their infants. Maternal RSA decreases from the still-face to the reunion episode, which may index their active attempts to ameliorate infant distress (Busuito et al., 2019; Conradt & Ablow, 2010; Moore et al., 2009). Taken together, average RSA levels typically change in opposite directions for a mother and her infant during the reunion episode, a pattern that may indicate physiological co-regulation of the dyad.

Understanding rsa recovery with linear modeling versus dynamic system approach

Mother–infant everyday interactions often involve rapid, back-and-forth shifts from matched to mismatched states, rather than stationary matched or mismatched states (Tronick & Beeghly, 2011). The ability to return to baseline after fluctuations between matched and mismatched states may be an early indicator of dyadic relationship quality. However, these temporal patterns have received limited empirical attention, especially among mother–infant dyads (cf. Brazelton et al., 1974; Chow et al., 2010). Mean-level changes in individuals' affective, behavioral, and physiological states have largely been the focus of studies on mother–infant interactions rather than dynamics of these states over short intervals (e.g., Conradt & Ablow, 2010; Moore & Calkins, 2004).

Traditionally, RSA recovery is measured by subtracting the average RSA level after a stressor from that during a stressor. This linear approach emphasizes mean RSA differences between the stressful and non-stressful episodes but fails to measure specific RSA change processes over short intervals during the recovery episode for mother–infant dyads. Dynamic system-based concepts may be useful for measuring dyadic RSA change patterns. In the current study, we focused on two characteristics of dynamic systems: *return strength* and *coupling*.

Return strength is the tendency to revert to a baseline state after being perturbed. For example, caregivers' unresponsiveness perturbs infant parasympathetic nervous system activity during the still-face episode. During the reunion episode, the return strength of infant RSA may index self-regulation because it measures the degree to which the disturbed (and usually reduced) infant RSA moves back to the baseline state once infants and caregivers re-engage during typical interactions.

Coupling is defined as the association between a dyad member's current state and the subsequent change in the other member's state. Mother-to-infant coupling occurs when infants receive coregulatory support from their mother, which may manifest at the physiological level as the predictive association between maternal RSA and subsequent change in infant RSA. The inverse process, infant-to-mother coupling, captures the extent to which infant RSA predicts maternal RSA changes. Coupling effects may be mapped onto long-standing theories that caregivers and children evoke affective or behavioral responses from each other (Brazelton et al., 1974; Sameroff, 1983; Tronick & Gianino, 1986).

Infant characteristics influencing physiological regulation and co-regulation

Presently, it remains unclear whether physiological return strength and coupling between mothers and their infants predict adaptive or maladaptive child outcomes; nonetheless, researchers have begun to examine how these physiological dynamics vary across dyads (Depasquale, 2020; Ostlund et al., 2017). Relative to the role of mothers, less is known about how infant characteristics contribute to later mother–infant physiological dynamics. Individual differences in neonatal neurobehaviors, such as attention and arousal, may shape mother–infant dyadic interactions in daily life. Because assessments of neonatal behavior occur within the first few days of life, they are largely independent of postnatal caregiving influences. Therefore, focusing on neonatal behaviors shortly after birth is a valuable method to examine the role of newborn characteristics on later mother–infant physiological dynamics.

The role of newborn attention

In newborns, high attention is characterized by sustained alertness, persistent engagement with auditory or visual stimuli, and highly coordinated visual tracking (Liu et al., 2010; Ostlund et al., 2019), which may reflect individual differences in attentional networks that are foundational for self-regulation (Rothbart et al., 2011). Highly attentive neonates are faster at achieving an alert state and orienting to sensory events. Neonates with low attentional capacities, on the other hand, tend to have difficulties maintaining physiological stability (Boukydis et al., 2004). Therefore, one possibility is that newborns with high attention may show stronger RSA return strength after stress because of their quick ability to orient and attend to changes in caregivers' affect.

Infants with high attention may also contribute to synchronized mother–infant exchanges in gaze and affect (Tronick, 1989). Highly attentive newborns are more responsive to external stimuli, and therefore may be more responsive to mother's attempts to regulate (i.e., stronger mother-to-infant coupling). Backer et al. (2018) reported that high attention was a robust indicator of "well-regulated" 6-month-old infants whose distress can be effectively down-regulated by their mothers following immunization. Furthermore, mothers of highly attentive infants may be more attuned to their infants' bids for attention and needs for support (i.e., stronger infant-to-mother coupling). For instance, mothers whose newborns were attentive to them 24 h after birth were more responsive to their infants' cues on days 2 and 3 after birth compared to mothers whose newborns tended to avert their gaze (Noble, 1984).

If mothers are more engaged in concordant affective and physiological exchanges with their attentive infants, unresponsive interactions may be particularly salient to these mothers. Mothers of highly attentive infants may find the still-face episode particularly stressful and may be more likely to exhibit weaker RSA return strength during reunion than mothers of less attentive infants because they are accustomed to providing contingent responses to their infant. These mothers may be “programmed” by their attentive infants to be more responsive and may work harder to soothe the infant following stress. As a result, it may take mothers of highly attentive infants longer to achieve their baseline level of parasympathetic nervous system functioning. Moore et al. (2009) reported that more sensitive mothers exhibited lower RSA levels during reunion compared to mothers who were less sensitive. Slower RSA recovery during reunion may reflect a mother's greater effort to regulate their infant's distress.

The role of newborn arousal

Some newborns are calm and easy to soothe, whereas others are high in arousal and exhibit high motor agitation, irritability, and excitability (Lester et al., 2004; Rothbart & Bates, 2006). Variations in newborn arousal may underlie important temperamental traits, such as motor activity, emotional reactivity, and prolonged distress that are predictive of emotion regulation difficulties and behavioral problems (Kagan & Fox, 2006; Morales et al., 2021; Rothbart & Bates, 2006; Santucci et al., 2008; Thomas et al., 2017). As such, highly aroused neonates seem to be at higher risk for impaired self-regulatory capacities, which may be evidenced by a weaker return strength of RSA.

Highly aroused infants may be perceived as “fussy” by their caregivers because they are difficult to soothe when distressed (Lester et al., 2009). Infant negative emotionality is related to less affectionate, supportive, and responsive parenting, resulting in the parental withdrawal of supportive emotion regulation strategies (Bridgett et al., 2009; Kiff et al., 2011; Mills-Koonce et al., 2007). Mothers of infants with high neonatal arousal may show less physiological coupling when reestablishing face-to-face interactions. These mothers may also show less parasympathetic responses (i.e., weaker RSA return strength) because they may have become accustomed to infants’ negative emotionality and are less likely to be affected by their infants’ distress. It could be that repeated experiences of ineffective co-regulation attempts undermine mothers’ perceptions of their parenting efficacy, which leads to mothers’ further withdrawal of sensitivity and reduced parasympathetic responses (Stifter & Bono, 1998; Vik et al., 2009).

An opposite pattern, however, may also be true: irritable and agitated infants could engender more engaged mother–infant interactions because parents are invested in reducing infant distress and ameliorating difficult predispositions (Putnam et al., 2002). Parents may spend more time soothing infants with high negative affect and fussiness (Brown et al., 2011; Kotila et al., 2014). In this case, mother–infant coupling may be stronger for dyads of infants with higher newborn arousal, suggesting more effective coregulatory processes that may be attributed to mothers’ past experiences of soothing a distressed infant. Furthermore, mothers with highly aroused infants may exhibit stronger RSA return strength than those with less aroused infants, a physiological response pattern underlying caregiving responses to reduce infant distress (Moore et al., 2009; Putnam et al., 2002).

A highly aroused newborn can show either high or low attention. Infants who are highly active and excitable but have low attention may encounter difficulties when exploring the surrounding environment due to their highly labile states (Rothbart & Bates, 2006; Rothbart et al., 2011). Therefore, infants who display high negativity (arousal) and poor alertness (attention) may show high physiological dysregulation. In one study, Liu et al. (2010) identified a group of neonates characterized by high excitability and low self-regulation at the highest risk for problematic medical and behavioral outcomes in toddlerhood and early childhood. However, it remains to be tested how newborn attention and arousal interact to predict mother–infant physiological dynamics 7 months after birth.

Present study

The overarching aim of the present study was to investigate the extent to which observed newborn neurobehavior was related to physiological dynamics in 7-month-old infants and their mothers. Although low newborn attention and high newborn arousal have been associated with children's later behavioral and emotional outcomes (e.g., Liu et al., 2010), no studies to our knowledge have linked newborn neurobehavior to physiological indices of infant self-regulation, nor examined the role of newborn neurobehavior in shaping mother–infant physiological dynamics. We aim to expand our understanding of how mothers and infants recover physiologically in response to distress by examining two core questions focused on the predictive roles of newborn neurobehavior.

Our first core research question concerned whether and how newborn neurobehavior predicts mother and infant parasympathetic recovery following the stress of the still-face episode. Parasympathetic recovery was operationalized as the residualized change score from the still-face to the reunion episode. We hypothesized that

H1a Newborns with higher attention and/or lower arousal would show more increases in RSA from still-face to reunion than those with lower attention and/or higher arousal, suggesting a pattern of parasympathetic regulation following the stress of the still-face.

H1b Compared to newborns with lower attention, newborns with higher attention would have mothers whose RSA decreases from still-face to reunion, indicating that mothers of more attentive newborns may take longer to recover from the stress of the still-face compared to mothers of less attentive newborns. No specific hypothesis was established for the association between newborn arousal and maternal RSA, considering that both positive and negative associations were plausible based on existing literature.

The second core research question moved beyond models using average RSA recovery responses. Using dynamic system concepts and techniques, we examined whether and how newborn neurobehavior predicted mother and infant RSA return strength and coupling during the reunion episode.

H2a Newborns with higher attention and/or lower arousal would have stronger RSA return strength during reunion, indicating a quicker return to baseline levels.

H2b Higher newborn attention would be related to stronger mother-to-infant and infant-to-mother coupling effects because these infants may be more attuned to caregiving behaviors, and mothers may have had more experiences soothing and responding to their highly attentive infants.

H2c Higher newborn attention would be related to weaker maternal RSA return strength, given that mothers of highly attentive newborns may be more likely to wait until their infant has fully recovered from stress before they are able to recover themselves. We did not establish specific hypotheses linking newborn arousal to mother-to-infant or infant-to-mother coupling or maternal RSA return strength.

Given that we made specific and bidirectional hypotheses based on previous research, especially with respect to the role of newborn attention, our study is more confirmatory in nature. However, examining associations between newborn arousal and maternal physiological responses was exploratory because these associations have not been examined in the extant literature. Therefore, although we explored whether the interaction between newborn attention and arousal affected caregiver–infant RSA dynamics, no hypotheses were made prior to analyses.

METHOD

Participants

Mother–infant dyads came from a longitudinal study that spanned the third trimester of pregnancy to 36 months postpartum. Data were from two time points: at birth and 7 months postpartum. From January 2016 to October 2018, pregnant women were recruited from the local community via flyers, brochures, and social media posts, and during prenatal care appointments at OB/GYN clinics with the University of Utah. Women who showed interest in participation completed the Difficulties in Emotion Regulation Scale (DERS; Gratz & Roemer, 2004) and answered questions related to eligibility criteria (i.e., ages 18–40, 25 weeks or more into pregnancy, no pregnancy complications, no substance use during pregnancy, anticipated singleton delivery, and planned delivery at a participating hospital). In an attempt to achieve a uniform distribution of emotion dysregulation, women with high and low scores on the DERS were oversampled. A total of 162 pregnant women were recruited and participated in the prenatal visit. More detailed information on recruitment and the initial sample can be found in Lin et al., 2019.

Trained research assistants assessed newborn neurobehavior shortly after birth. One hundred and fifty-five newborn infants were examined (77 male infants, 47.5%). Among the seven newborns whose data were not available, three mothers declined the assessment at the hospital, one mother withdrew from the study, one mother experienced a fetal demise, one mother was incarcerated, and one mother was unable to be contacted. Most deliveries were vaginal (72.8%). The average gestational age at the time of delivery was 39 weeks (range: 34–41 weeks).

At 7 months postpartum, 135 mothers provided laboratory or questionnaire data. Twenty-one mothers only completed questionnaires online, resulting in a total of 114 mothers who participated in the laboratory visit at 7 months. There were no significant differences between mother–infant dyads who provided data at 7 months ($N = 135$) and those who dropped out with respect to infant age at the time of the laboratory visit, infants' biological sex, maternal education, maternal race and ethnicity, household income, and neonatal attention and arousal. Of the 114 mother–infant dyads who participated in the laboratory visit, eight dyads' physiological data were not available due to hardware problems or infants being too distressed to participate. As a result, the final sample size included 106 mother–infant dyads. Demographic information of the final sample is presented in Table 1.

Procedure

Women and their newborn infants were visited at the hospital post-delivery when possible. A trained examiner administered the NICU Network Neurobehavioral Scale (NNNS; Lester et al., 2004), which took approximately 20 min, and completed all scoring upon conclusion of the exam. Fourteen NNNS exams were completed in participants' homes.

At 7 months postpartum, mothers completed a series of questionnaires online about themselves and their infants before coming for the laboratory visit. At the laboratory visit, heart rate and respiration monitoring equipment were attached to both the mother and the infant to collect physiological data during behavioral tasks. A research assistant introduced the still-face paradigm (Tronick et al., 1978) after the infant was placed in a high chair. The still-face paradigm has been widely used as an interpersonal stressor to elicit infants' physiological and behavioral responses. It consists of three episodes: play, still-face, and reunion. First, mothers played with their infants as they typically would for 2 min (i.e., play). Then, mothers were asked to turn their face away for a moment and then turn back to face their infant with a neutral expression for 2 min (i.e., still-face). Last, mothers were instructed to look away again for a moment before resuming normal interactions with their infant for another 2 min (i.e., reunion) while remaining seated. Mothers were instructed not to touch the infant throughout the still-face paradigm, and pacifiers were not permitted. The procedure was terminated early if infants cried for more than 15 s uninterruptedly or at the request of mothers.

Participants provided written informed consent before each phase of the study and were compensated $30 for the hospital visit and up to $95 for 7-month participation. All study protocols were approved by the Institutional Review Board at the University of Utah.

Measures

Newborn neurobehavior—Newborn neurobehavior was assessed with the NNNS within the first week after birth when possible (M_{days} = 1.60, Mdn_{days} = 1.00, SD = 1.23). Due to scheduling difficulties, however, 11 neonates were administered the NNNS after the first week of life. The NNNS examination is valid in infants who are less than 2 months old (e.g., Liu et al., 2010), a period within which all of our participating neonates fell. Five trained experimenters administered the NNNS following a standard protocol to assess newborn neurological and behavioral functioning (Lester et al., 2004). The NNNS captured a variety of functional domains in newborns, including responses to stimuli (i.e., gaze, sustained alertness), irritability and fussiness, and soothability. The NNNS has good psychometric properties, such as internal consistency and test–retest reliability (Lester et al., 2004). A detailed description of the NNNS assessment in this sample can be found elsewhere Ostlund et al., 2019. In the current study, summary scores of the attention and arousal scales were used. The attention scale captures newborns' ability to attend and respond to auditory and visual stimulation. Newborns who receive high attention scores exhibit more appropriate headturning, gaze, and sustained alertness, indicating their ability to attend to auditory and visual stimuli (Cronbach's α = .80). The arousal scale indicates the newborn's overall levels of arousal and associated motor activity during the examination. High scores on this scale represent high activity, fussing, and crying during the examination (Cronbach's α = .62).

Respiratory sinus arrhythmia—Electrocardiogram data were collected from both mother and infant using a two-lead configuration with spot electrodes placed on the right clavicle and left ribcage. MindWare mobile devices (MindWare Technologies Ltd.; Biolab software version 3.1) were used. RSA was scored in 30-s epochs by trained research assistants using Mindware's software, resulting in 12 epochs for each person across the 6-min-long still-face paradigm (i.e., 24 epochs per dyad). RSA was defined as the natural logarithm of the high-frequency band of the power spectrum waveform, which was 0.12–0.42 Hz and 0.24–1.04 Hz for mothers and infants, respectively (Fracasso et al., 1994). In scoring RSA, Mindware software flagged R peaks within each QRS complex and identified whether the surrounding inter-beat intervals were within an expected range for the series. Flagged R peaks were examined by trained research assistants and were corrected when necessary (i.e., misidentified R peak). When there were missing or unusable data, or when RSA values fell outside the expected range of 1–10, the entire 30-s epoch was marked as missing. Once data were initially cleaned, they were double-checked by a senior investigator who had extensive experience cleaning physiological data.

Analytic plan

Hierarchical regression models were used to examine our first research question: the contribution of newborn attention and arousal to changes in infant RSA from the still-face to the reunion episode of the still-face paradigm. Infant gestational age, age when the still-face procedure was administered, sex, and infant RSA during the still-face episode were entered as controls on the first step of a hierarchical regression model. Newborn attention and arousal scores were added to the model on the second step, with infant RSA during reunion as the outcome variable. In the final step, an interaction term computed with centered newborn attention and arousal scores was added to examine interactions on infant RSA change during reunion. A hierarchical regression model with maternal RSA during reunion as the outcome variable and maternal RSA during still-face as the predictor was also tested.

Coupled nonlinear dynamic system models (Hamaker et al., 2015; Taylor-Swanson et al., 2018) were used to examine the role of newborn attention and arousal on shaping mother–infant physiological dynamics. The models were built using change scores of maternal and infant RSA as simultaneous outcomes in multilevel models. By doing so, we were able to accommodate the nested nature of the data (30-s epochs nested within individuals who were members of dyads). Change scores of each person's RSA were computed by subtracting the value of the previous epoch from the current epoch. Positive change scores indicated an increase from the previous epoch, whereas negative scores indicated a decrease. All analyses were conducted in SPSS 26.0.

First, a null model was built (Model 2.0) to establish the mother–infant RSA dynamics during reunion. For dyad (*i*) at a given time point (*t*), the two simultaneous equations were as follows:

Model 2.0:

$$
\begin{aligned}
\left(\mathrm{RSA}_{\mathrm{mom}\,t} - \mathrm{RSA}_{\mathrm{mom}\,t-1}\right)_i &= m_{00} + m_{10}\mathrm{RSA}_{\mathrm{mom}(t-1)i} \\
&\quad + m_{20}\mathrm{RSA}_{\mathrm{baby}(t-1)i} + e_{(t-1)i}, \\
\left(\mathrm{RSA}_{\mathrm{baby}_t} - \mathrm{RSA}_{\mathrm{baby}_{t-1}}\right)_i &= b_{00} + b_{10}\mathrm{RSA}_{\mathrm{baby}(t-1)i} \\
&\quad + b_{20}\mathrm{RSA}_{\mathrm{mom}(t-1)i} + e_{(t-1)i},
\end{aligned}
$$

with $\mathrm{RSA}_{\mathrm{mom}\,ti}$ and $\mathrm{RSA}_{\mathrm{baby}_{ti}}$ indicating person-mean centered RSA for mother and infant, respectively. RSA scores were centered around each person's RSA during the play episode of the still-face paradigm, which was conceptualized as that person's homeostatic point of RSA level. Thus, a positive value of one's RSA would indicate an RSA level above this person's homeostatic point, whereas a negative value would mean a below-homeostatic-point RSA value. The error terms (*e*) encompassed separate error variances for each mother's and infant's RSA, with a covariance between them to account for dependencies in the dataset.

The return strength of maternal and infant RSA was captured by coefficients and b_{10}, respectively. Negative coefficients meant that when a person's RSA level at time $t - 1$ was above the homeostatic point, their RSA level was predicted to decrease at time t, which indicated the return of RSA to a homeostatic point after perturbation. Lower negative values of m_{10} and b_{10} represented stronger return strength (i.e., returning to the homeostatic point more quickly after a perturbing stressor).

In addition, m_{20} and b_{20} captured the coupling effects between maternal and infant RSA. Both the sign and magnitude of m_{20} and b_{20} were important when interpreting their meanings. Positive values indicate that when one member's RSA was above homeostasis at time $t - 1$, their partner's RSA would increase at time t, which indicated the partner's RSA was leaving homeostasis. Negative values, on the other hand, indicate that one member's RSA at time t was related to the other member's RSA's return to homeostasis. An infant's RSA might induce changes in the mother's RSA (m_{20}) which could, in turn, carry over to affect the infant's own RSA (b_{20}).

After establishing the dynamics of mother–infant RSA, we added NNNS attention and arousal scores as level-2 predictors. Newborns' attention and arousal scores were grand-mean centered. To save space, combined equations (i.e., level-1 and level-2 compressed) are presented below (Model 2.1). Newborn attention may affect the return strength (m_{11} and b_{11}) as well as the coupling effects (m_{21} and b_{21}) of mother–infant physiology. Similarly, newborn arousal may also be associated with return strength (m_{12} and b_{12}) as well as the coupling effects (m_{22} and b_{22}) of the mother–infant physiology.

Model 2.1:

$$\begin{aligned}(\mathrm{RSA}_{\mathrm{mom}\,t} - \mathrm{RSA}_{\mathrm{mom}\,t-1})_i = {} & m_{00} + m_{10}\mathrm{RSA}_{\mathrm{mom}(t-1)i} \\ & + m_{20}\mathrm{RSA}_{\mathrm{baby}_{(t-1)i}} + m_{01}\mathrm{Attention}_i + m_{11}\mathrm{RSA}_{\mathrm{mom}(t-1)i} \\ & \times \mathrm{Attention}_i + m_{21}\mathrm{RSA}_{\mathrm{baby}_{(t-1)i}} \times \mathrm{Attention}_i + m_{02}\mathrm{Arousal}_i \\ & + m_{12}\mathrm{RSA}_{\mathrm{mom}(t-1)i} \times \mathrm{Arousal}_i + m_{22}\mathrm{RSA}_{\mathrm{baby}_{(t-1)i}} \times \mathrm{Arousal}_i + e_{(t-1)i}, \\ (\mathrm{RSA}_{\mathrm{baby}_t} - \mathrm{RSA}_{\mathrm{baby}_{t-1}})_i = {} & b_{00} + b_{10}\mathrm{RSA}_{\mathrm{baby}_{(t-1)i}} \\ & + b_{20}\mathrm{RSA}_{\mathrm{mom}(t-1)i} + b_{01}\mathrm{Attention}_i + b_{11}\mathrm{RSA}_{\mathrm{baby}_{(t-1)i}} \\ & \times \mathrm{Attention}_i + b_{21}\mathrm{RSA}_{\mathrm{mom}(t-1)i} \times \mathrm{Attention}_i \\ & + b_{02}\mathrm{Arousal}_i + b_{12}\mathrm{RSA}_{\mathrm{mom}(t-1)i} \times \mathrm{Arousal}_i \\ & + b_{22}\mathrm{RSA}_{\mathrm{baby}_{(t-1)i}} \times \mathrm{Arousal}_i + e_{(t-1)i}\,.\end{aligned}$$

Positive values of b_{11} would mean that infants who scored higher on NNNS-attention returned to their homeostatic point slower when being disturbed. Interpretations were the same for the effect of newborn attention on mothers' RSA return strength (i.e., m_{11}). The extent to which infant's RSA was affected by (b_{21}) or affected (m_{21}) their mother's RSA as a function of newborn attention was also tested. The same interpretations hold for coefficients related to NNNS-arousal (b_{12}, m_{12}, b_{21}, m_{21}).

Subsequently, we built Model 2.2 by adding interaction terms (i.e., ×) in Model 2.1 to examine whether newborn attention and arousal interact to predict mother–infant physiological dynamics. Newborn attention and arousal scores were both centered before creating the interaction term. Finally, simple slope analyses were used to probe statistically significant interaction effects (e.g., arousal on infant RSA return strength, or b_{11}) following Preacher et al.'s (2006) procedure. Simple slopes were estimated at 1 *SD* above and below mean levels of the corresponding newborn neurobehavior.

Because infant distress may affect RSA return strength and coupling of infants and their mothers, we also tested models including infant negative affect. Results remained the same when infant negative affect was added to the model (see Supporting Information for how infant negative affect was measured and results of these models). Below we only report results from the parsimonious model without infant negative affect.

Missing data—Comparing our final sample (N = 106) and the excluded sample due to unavailable physiological data (N = 8), we found no significant differences for any of the following variables (ps > .05): infant age at the time of the 7-month visits, infant sex, maternal education, maternal race and ethnicity identification (i.e., Hispanic/Latina and women of color), household income, and maternal emotion dysregulation at the prenatal and 7-month visits.

When scoring RSA, epochs were marked as missing if there were <30 s of contiguous data present or if RSA values fell outside the expected range 1–10. As a result, 5.9% of maternal RSA epochs and 7.0% of infant RSA epochs were marked as missing during the entire still-face paradigm. Missing data were estimated using full information maximum likelihood methods.

RESULTS

Infant and maternal RSA changed in expected ways across the three episodes of the still-face paradigm. Results from a series of paired *t*-tests indicated that infant RSA decreased significantly from the play to still-face episode, $t(102) = 2.70$, $p = .008$, suggesting infants' parasympathetic withdrawal during the still-face episode. However, there was no significant difference in infant RSA between the still-face and reunion episodes, which suggests that, on average, infant parasympathetic nervous systems did not recover after typical interactions resumed. For mothers, there was no significant change in mean RSA between the play and still-face episodes. However, maternal RSA significantly decreased from the still-face to the reunion episode, $t(102) = 2.71$, $p = .008$. This decrease may suggest maternal parasympathetic regulation in response to a distressed infant.

Means, standard deviations, and bivariate correlations between newborn neurobehavior and mother and infant average RSA during each episode of the still-face paradigm are presented in Table 2. Higher newborn attention was related to lower infant RSA during reunion ($r = -.24$, $p = .02$). No other significant associations emerged between newborn neurobehavior and maternal or infant RSA during any portion of the still-face paradigm.

Newborn neurobehavior predicting maternal and infant average RSA responses

Two hierarchical regression models were conducted to examine whether newborn neurobehavior was related to linear changes in infant RSA, as well as maternal RSA, from the still-face to the reunion episode. Infant RSA decreased during reunion with higher levels of newborn attention, which is inconsistent with hypothesis H1a, $b = -.21$, $t = -3.11$, $p = .003$ (Table 3, Model 1.1). Newborn neurobehavior did not significantly predict maternal RSA. Models that included the interaction between newborn attention and arousal were also tested but were not statistically significant (Table 3, Model 1.2).

Newborn neurobehavior predicting RSA return strength and coupling within mother–infant dyads

The correlation between newborn attention, arousal, and infant and maternal RSA during the play episode was not significant, as shown in Table 2. Given that homeostatic points were defined based on average levels during the play episode, these results showed that newborn attention and arousal did not predict infants' (or mothers') homeostatic points (i.e., mean levels). We first tested Model 1.0 (null model) to examine mother–infant RSA dynamics during reunion. Both mothers' and infants' physiology functioned as a dynamic system with attractive features. Specifically, mothers' ($m_{10} = -0.77$, $t = -12.71$, $p < .001$) and infants' RSA ($b_{10} = -0.60$, $t = -10.17$, $p < .001$) exhibited significant return strength, indicating that maternal and infant RSA had the tendency to return to homeostasis when perturbed. However, we did not observe significant mother-to-infant or infant-to-mother RSA coupling effects. Next, we examined whether newborn neurobehavior predicted these dynamics and present results from Model 2.1 and Model 2.2 (the interaction model) in Table 4. Note that although results related to infant and maternal RSA dynamics were summarized in separate sections below for clearer presentations, they were estimated simultaneously in the same model.

Infant RSA dynamics—Newborn arousal, but not attention, predicted infant RSA return strength ($b_{12} = 0.21$, $t = 2.11$, $p = .04$), as shown in Table 4 (Model 2.1). Newborns with higher arousal had weaker RSA return strength at 7 months. In other words, and consistent with hypothesis H2a, infants who had higher arousal scores at birth were slower in returning to their RSA homeostatic point after a stressor than newborns who had exhibited lower arousal at birth (Figure 1a). Simple slope analyses showed that infant RSA return strength was significant for both infants with lower arousal (1 *SD* below mean, simple effect = −0.86, $t = -7.49$, $p < .001$) and higher arousal (1 *SD* above mean, simple effect = −0.37, $t = -2.46$, $p = .015$), though infants with lower arousal showed stronger attraction to their homeostatic points.

The interaction effect between newborn arousal and newborn attention on infant return strength was not significant (Table 4, Model 2.2). Newborn arousal or attention did not significantly predict either mother-to-infant RSA coupling during reunion.

Maternal RSA dynamics—Newborn attention ($m_{11} = 0.18$, $t = 3.47$, $p = .001$) and newborn arousal ($m_{12} = -0.22$, $t = -2.22$, $p = .027$) both significantly predicted maternal RSA return strength. However, we chose not to interpret these main effects because the interaction effect of newborn attention and arousal was also significant ($m_{13} = -0.17$, $t = -2.02$, $p = .045$; Table 4, Model 2.2). We probed this significant interaction and present maternal RSA return strength at different levels of newborn neurobehavior in Figure 1b.

Mothers with infants who had relatively high attention and relatively low arousal at birth showed the weakest RSA return strength during the reunion episode, supporting hypothesis H2c. Simple slope analyses revealed that for dyads with a less aroused but more attentive newborn, maternal RSA returned to homeostasis slower than those whose newborns had lower levels of both arousal and attention ($t = 3.36$, $p = .001$). However, maternal RSA return strength did not vary as a function of newborn attention when arousal was high ($t = 0.05$, $p = .958$). Similarly, higher newborn arousal was related to stronger maternal RSA return strength at high levels of newborn attention ($t = -2.81$, $p = .006$), but not at low levels of attention ($t = -0.78$, $p = .436$). Taken together, newborn neurobehavior was related to the extent to which mothers' RSA dynamics were disrupted while resuming interactions with their distressed infant. Maternal RSA had the slowest return to baseline when the infant showed relatively high attention but low arousal at birth. There was no significant effect of newborn arousal, or attention, on infant-to-mother RSA coupling during the reunion episode.

DISCUSSION

The goal of this study was to explore early infant contributions to mother–infant physiological dynamics. We found that newborn attention and arousal were related to patterns of maternal and infant RSA changes when the dyad was recovering from the stress of the still-face paradigm. This study adds to the literature on infants' contributions to the caregiving environment and reveals new insights regarding how newborn characteristics predict later physiological dynamics among mother–infant dyads (Belsky, 1984; Brazelton et al., 1974; Tronick & Gianino, 1986).

The importance of newborn neurobehavior: Attention and arousal

We first adopted a linear approach to investigate how newborn neurobehavior predicted infant and maternal RSA responses to the reunion episode of the still-face paradigm. Hierarchical regression models showed that higher levels of neonatal attention (i.e., ability to attend and respond to environmental stimuli) predicted a continued withdrawal of RSA during reunion, suggesting that these infants might take longer to recover from the stress of the still-face episode. This result is surprising because we had hypothesized the opposite pattern based on the extant literature on the role of high attention in facilitating the development of regulatory abilities (Rothbart et al., 2011; Stępień-Nycz et al., 2015; Wu et al., 2021). One explanation is that the stressor used in the present study is an attachment-relevant stressor (i.e., the psychological separation from a caregiver that is the source of infants' stress). Other studies have used a physical stressor or a frustrating task (e.g., restricting the infant's arms, removing a favorite toy). Infant attention to the environment may elicit more engaged interactions from the caregiver, leading to highly synchronized, responsive dyadic interaction (Backer et al., 2018; Brazelton et al., 1974). As a result, mothers' unresponsiveness during the still face paradigm may be exceptionally unusual for dyads with a more attentive infant, resulting in prolonged physiological distress in the infants as indicated by lower RSA levels during the reunion episode.

We then analyzed the data with a dynamic system approach. Higher arousal was related to weaker infant RSA return strength during reunion, indicating that these infants may exhibit heightened parasympathetic nervous system stress reactivity to the still-face episode. This finding is consistent with broader literature documenting the association between arousal-related temperamental traits (e.g., surgency, negative affectivity) and regulatory difficulties (Dollar & Stifter, 2012; Thomas et al., 2017). Newborns with highly aroused neurobehavioral states may continue to exhibit amplified behavioral and physiological responses in the face of distressing situations, which presents challenges for a quick return to homeostasis. Biological mechanisms, such as epigenetic processes, may also be at play. Newborns with higher levels of arousal may exhibit repeated or "hypervigilant" activation of the autonomic nervous system, which may subsequently induce physiological changes by altering their gene expression (Lester et al., 2012). Future studies are necessary to test these two potential pathways.

A comprehensive understanding of the role of newborn attention requires simultaneous consideration of newborn arousal, as we found these two newborn characteristics interacted to predict maternal RSA return strength when dyads were recovering from the stress of the still-face. The effect of newborn attention on maternal RSA return strength was only significant at lower levels of newborn arousal. That is, mothers of newborns with higher attention exhibited weaker RSA return strength when newborn arousal was low, indicating that these mothers took longer to recover from the stress of the still-face. This finding was unexpected and is difficult to interpret without additional information on mothers' perception of their experience with the still-face paradigm or caregiver attempts at infant regulation during the reunion. These data are not available for the current study, thereby limiting the extent to which we can interpret this finding. Nevertheless, one possible interpretation is that newborns with higher attention but lower arousal may have a more well-regulated temperament that may potentially evoke sensitive parenting responses (Mills-Koonce et al., 2007; Rothbart & Bates, 2006). In this case, it may be more challenging for mothers of these infants to hold a “poker face” in the face of their infant's distress. This challenge may further activate mothers’ parasympathetic nervous system and result in a slower RSA return strength during reunion as mothers provide responsive coregulatory support to soothe their infants (Ham & Tronick, 2006; Moore et al., 2009). Future work aimed at disentangling the processes that may be at play during this interaction is warranted.

Neither mother-to-infant nor infant-to-mother RSA coupling effects were statistically significant in our study. These null findings are consistent with the mixed empirical evidence in the literature. As summarized by Depasquale (2020), only eight published studies have examined mother–infant parasympathetic synchrony and results have been inconsistent. Discrepant findings are thought to be partly attributable to the varying sample sizes, statistical models, and situational demands. Here, we highlight two factors that may be particularly relevant to the null findings in the current study. First, coupling was operationalized in this study as the effect of mother's RSA at time $t - 1$ on *changes* of infant RSA from time $t - 1$ to t (and vice versa) in multilevel models. This approach is different from the focus of most studies reporting caregiver–infant parasympathetic synchrony during infancy, which examine the correlation between caregiver RSA and infant RSA concurrently (Depasquale, 2020). Although our operationalization of coupling allowed us to examine potential lead-lag associations during active mother–infant interactions, these types of coupling effects may be difficult to detect and may only be observed in moments when infants are highly distressed (Wass et al., 2019). Second, the time-lag (30 s) of RSA sampling in our study may be too slow to capture the caregiver–infant coupling within the fast-acting autonomic system. Recent methodological advancements have made it possible to model RSA dynamics at the second-by-second level (Abney et al., 2021; Ravindran et al., 2021; Somers et al., 2021) and may be considered by future studies to capture fluctuations in parasympathetic activity on a shorter time interval. Nevertheless, the appropriate timescale (if any) has yet to be determined (Davis et al., 2018; Depasquale, 2020).

Understanding mother–infant dynamics with both linear and dynamic system approaches

A more comprehensive understanding of the role newborn neurobehavior plays in mother and infant physiological dynamics requires us to examine these dynamics on different timescales. Higher newborn attention predicted lower infant RSA levels during reunion, as shown in the results obtained by the linear approach. However, the effect of newborn attention with respect to infant RSA return strength in the dynamic system approach was not significant. This pattern suggests that newborns with higher (compared to lower) attention were more distressed during reunion on average, but the extent to which they engaged in parasympathetic regulatory processes was not significantly different from those with lower attention. Maternal RSA return strength was found to vary as a function of newborn attention: higher newborn attention predicted weaker maternal parasympathetic regulation, possibly reflecting their active attempts to soothe distressed infants. Together, results from both approaches may reveal a physiological “conversation” between infants with higher neonatal attention and their mother. More attentive newborns, on average, may take longer to recover from stress, a pattern that may be intuitively understood by their mothers after months of intimate interactions. As a result, these mothers may have learned to wait until the infant has recovered before they themselves can fully recover. This was evident in the weaker RSA return strength of mothers with more attentive babies. It is also supported by the literature showing that caregivers who are more sensitive to their infant cues take longer to recover from the still-face physiologically (Moore et al., 2009; Oppenheimer et al., 2013).

Additionally, newborn arousal was not predictive of mean changes in infant RSA from the still-face to the reunion episode but did predict slower RSA return to homeostasis. This finding seems to suggest that higher newborn arousal may hinder the process of effective physiological regulation, although it may not have an impact on the average level of physiological distress. Taken together, both linear and dynamic system approaches shed unique light on the predictive power of newborn attention and arousal. It may be important in the future to integrate both approaches to achieve a more comprehensive understanding of the developmental foundations of caregiver–infant physiological dynamics.

Strengths, limitations, and future directions

There are important limitations to consider when interpreting our findings. First, without behavioral and affective ratings of maternal and infant states during the still face paradigm, we could not determine whether interactive behavioral processes “drive” physiological processes (Feldman et al., 2011) or if physiological dynamics provide a biological platform for behavioral interactions (McFarland et al., 2020). It would be informative for future work to include both behavioral and physiological measures to track the dynamics between the behavioral and physiological systems. Second, we did not examine shared genetic effects or prenatal programming influences, which may have important implications for the momentary linkage of caregiver and infant physiology (Feldman, 2017; Lotzin et al., 2016).

Third, RSA homeostasis was operationalized as the mean level of RSA during the play episode, given that it aligns with our study goal to understand how caregivers’ and infants’ physiology return to typical dyadic interactions. However, alternative ways of operationalization may impact results and associated interpretations. Future studies should explore whether operationalizations of homeostasis, such as during sleep, could impact the observed caregiver–infant physiological dynamic.

Some missing data were caused by infant distress. For infants with only partial physiological data (i.e., only at baseline), their physiological dynamics under stress and how these dynamics are affected by newborn neurobehavior may differ from those with complete data. Although post hoc tests indicated that these two groups did not differ in baseline RSA or newborn attention and arousal, caution should be exercised when applying the current findings to highly distressed dyads or other caregiver–infant interaction contexts. Lastly, without data on other indices of child outcomes (e.g., emotion regulation assessed in early childhood), we could not discern whether the physiological change patterns observed in this study are “desirable” or “disruptive” to children's long-term development. Future studies that extend this study to toddlerhood and childhood are needed to obtain a developmental picture of the role of the innate infant characteristics.

This study is one of the first to provide evidence that newborn neurobehavior, such as attention and arousal, predicts mother–infant physiological dynamics when the dyad recovers from a face-to-face stressor. Infants' characteristics observed at birth may become biologically embedded through repeated caregiving interactions and manifested in different patterns of mother–infant physiological dynamics. Furthermore, by applying both linear, grand-mean approach and nonlinear dynamic system technique, our study offered new insights into the possible mechanisms through which mothers adjust their own physiology to provide the needed support for infants' regulation. Newborn neurobehavior, as assessed by a noninvasive examination— the NNNS— has the potential to aid early identification of developmental dysregulation when applied in clinical settings, such as pediatric care and community-based early intervention services.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Abbreviations:

DERS	Difficulties in Emotion Regulation Scale
NNNS	NICU Network Neurobehavioral Scale
RSA	respiratory sinus arrhythmia

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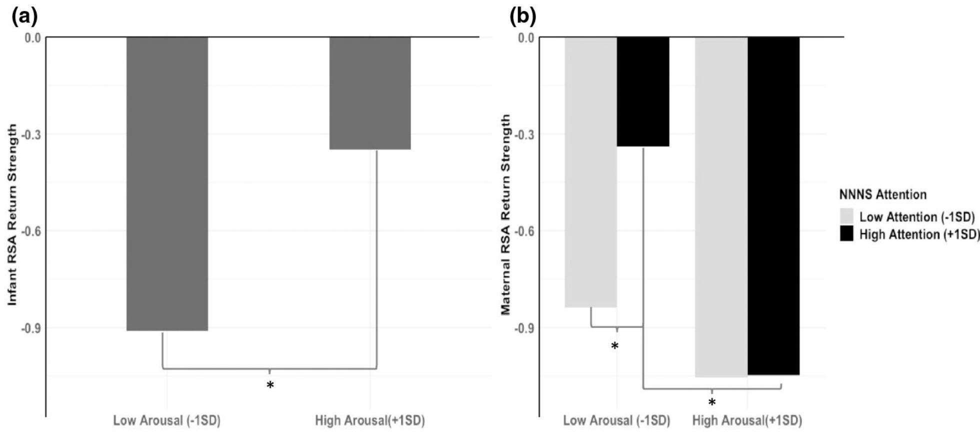

FIGURE 1.

Return strength of infant RSA (a) and maternal RSA (b) during reunion episode as a function of newborn neurobehavior. *Note*: Asterisks denote significantly different return strength between the two corresponding conditions. Values of the *Y* axis represent $b10$ (infant RSA, a) and $m10$ (maternal RSA, b) in Model 0. Values that are closer to 0 represent weaker return strength. (a) Infants with low arousal at birth showed stronger RSA return strength during reunion episode of the still-face paradigm than those with high arousal. (b) Infants with both low arousal and high attention at birth have mothers who exhibited the weakest RSA return strength during reunion episode of the still-face paradigm. Although it is commonplace to depict an interaction between continuous variables using a line graph rather than bar plots, the latter were used to facilitate understanding of the *return strength*—a key construct in our study. In the supplemental material, readers can find line graphs as an alternative way to represent these findings

TABLE 1

Demographic information

	n (%)	*M* (*SD*)
Infant characteristics		
Average age at 7-month visit		6.5 months (0.8)
Sex (male)	55 (51.9)	
Race and ethnicity		
White, Hispanic/Latino	23 (21.7)	
White, non-Hispanic/Latino	58 (54.7)	
Asian	5 (4.7)	
Black	1 (0.9)	
Hawaiian or Pacific Islander	1 (0.9)	
Multiracial	18 (17.0)	
Maternal characteristics (at prenatal visit)		
Age (years)		29.5 years (4.6)
Income		
Less than $19,999	14 (13.3)	
$20,000–$29,999	12 (11.3)	
$30,000–$39,999	10 (9.4)	
$40,000–$49,999	11 (10.4)	
$50,000–$79,999	28 (26.4)	
$80,000–$99,999	14 (13.2)	
$100,000 and greater	12 (11.3)	
Education		
Less than 12th grade	2 (1.9)	
High school graduate or equivalent	15 (14.2)	
Junior college graduate, or some college, or technical school	32 (30.2)	
College graduate	32 (30.2)	
Any post graduate school	23 (21.7)	
Race and ethnicity		
White, Hispanic/Latina	26 (24.5)	
White, non-Hispanic/Latina	52 (49.1)	
Asian	11 (10.4)	
American Indian or Alaskan Native	2 (1.8)	
Hawaiian or Pacific Islander	1 (0.9)	
Multiracial	11 (10.3)	
No race indicated, Hispanic/Latina	3 (2.8)	

Note: Due to missing data, the numbers of sample size in the second column do not consistently add to 106 (the full sample).

TABLE 2

Descriptive statistics and bivariate correlations among newborn neurobehavior and average respiratory sinus arrhythmia (RSA) during each episode of the still-face paradigm

	1	2	3	4	5	6	7	8	*M*	*SD*
1. Newborn attention	—								4.74	1.23
2. Newborn arousal	−.09	—							4.17	.64
Maternal RSA during…										
3. Play	−.05	.06	—						6.05	0.98
4. still-face	−.01	.17	.65***	—					6.17	1.08
5. Reunion	.00	.15	.86***	.62***	—				5.94	1.09
Infant RSA during…										
6. Play	−.15	−.06	.17	.04	.07	—			3.60	1.02
7. Still-face	−.03	−.11	.23*	.22*	.20*	.56***	—		3.31	1.11
8. Reunion	−.24*	−.06	.16	.11	.08	.70***	.69***	—	3.33	1.26

Note: *M* and *SD* indicate sample-level mean and standard deviation.

* $p < .05$

*** $p < .001$.

TABLE 3

Newborn neurobehavior predicting change in infant and maternal respiratory sinus arrhythmia (RSA) from still-face to reunion episode of the still-face paradigm

	Predicting infant RSA during reunion									
	No interaction					**Interaction added**				
Model 1.1	***B***	**(*SE*)**	***β***	***t***	***p***	***B***	**(*SE*)**	***β***	***t***	***p***
Infant sex	−.28	.17	−.12	−1.65	.10	−.29	.17	−.12	−1.65	.10
Infant gestational age	−.02	.01	−.12	−1.66	.10	−.02	.01	−.12	−1.65	.10
Infant age at SFP	−.01	.00	−.12	−1.69	.09	−.02	.01	−.12	−1.61	.11
Infant RSA during SF	.73	.08	.70	9.74	.00	.73	.08	.70	9.60	.00
Newborn attention	−.21	.07	−.22	−3.11	.003	−.21	.07	−.22	−3.10	.003
Newborn arousal	−.12	.14	−.07	−.89	.37	−.12	.14	−.06	−.88	.38
Newborn attention × arousal						.02	.11	.02	.21	.83
Model 1.2	**Predicting maternal RSA during reunion**									
	B	**(*SE*)**	***β***	***t***	***p***	***B***	**(*SE*)**	***β***	***t***	***p***
Infant sex	−.14	.18	−.06	−.77	.45	−.17	.18	−.08	−.94	.35
Infant gestational age	.03	.01	.25	2.99	.004	.03	.01	.25	3.04	.003
Infant age at SFP	.00	.00	.07	.87	.39	.00	.00	.07	.87	.40
Maternal RSA during SF	.58	.09	.57	6.85	.00	.60	.09	.58	6.90	.00
Newborn attention	−.01	.07	−.01	−.10	.92	−.03	.08	−.03	−.35	.73
Newborn arousal	.12	.15	.07	.82	.42	.13	.15	.08	.91	.37
Newborn attention × arousal						.11	.12	.08	.92	.36

Abbreviations: SF, still-face; SFP, still-face paradigm.

TABLE 4

The role of newborn neurobehavior in predicting mother–infant respiratory sinus arrhythmia dynamics during the reunion episode of the still-face paradigm at 7 months postpartum

	Model 2.1			Model 2.2		
	b	***SE***	***t***	***b***	***SE***	***t***
Infant						
Intercept (b_{00})	.01	.09	0.11	.03	.09	0.34
× Attention (b_{01})	−.06	.06	−1.01	−.07	.06	−1.26
× Arousal (b_{02})	−.17	.11	−1.61	−.17	.11	−1.58
× Att × Aro (b_{03})				.15	.09	1.61
Return strength (b_{10})	−.63	.06	−10.10	−.64	.06	−10.22
× Attention (b_{11})	−.08	.05	−1.66	−.08	.05	−1.70
× Arousal (b_{12})	**.21**	**.10**	**2.11** *	**.24**	**.10**	**2.37** *
× Att × Aro (b_{13})				−.02	.08	−0.19
Coupling effects (mother → infant b_{20})	−.04	.08	−0.54	−.03	.08	−0.39
× Attention (b_{21})	−.09	.07	−1.29	−.07	.07	−0.99
× Arousal (b_{22})	−.05	.13	−0.36	−.03	.13	−0.21
× Att × Aro (b_{23})				−.15	.10	−1.48
Mother						
Intercept (m_{00})	.01	.07	0.09	.00	.07	0.02
× Attention (m_{01})	.01	.04	0.25	.02	.04	0.44
× Arousal (m_{02})	.06	.08	0.68	.05	.08	0.64
× Att × Aro (m_{03})				−.03	.07	−0.45
Return strength (m_{10})	−.82	.06	−13.29	−.81	.06	−13.22
× Attention (m_{11})	**.18**	**.05**	**3.47** ***	**.21**	**.05**	**3.85** ***
× Arousal (m_{12})	**−.22**	**.10**	**−2.22** *	**−.20**	**.10**	**−1.96** †
× Att × Aro (m_{13})				**−.17**	**.08**	**−2.02** *
Coupling effects (infant → mother m_{20})	.00	.05	0.06	.00	.05	0.03

	Model 2.1			**Model 2.2**		
	b	***SE***	***t***	***b***	***SE***	***t***
× Attention (m_{21})	.00	.04	0.09	.00	.04	0.08
× Arousal (m_{22})	−.07	.08	−0.94	−.06	.08	−0.81
× Att × Aro (m_{23})				−.03	.07	−0.45

Note: Results related to study hypotheses are bolded. All models controlled for infant gestational age, sex, and age when the still-face paradigm was administered. Abbreviations: Aro, NNNS arousal; Att, NNNS attention.

† $p = .051$.

* $p < .05$

*** $p < .001$.