

## Regular Article

# Second-by-second infant and mother emotion regulation and coregulation processes

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## Abstract

Context-appropriate infant physiological functioning may support emotion regulation and mother–infant emotion coregulation. Among a sample of 210 low-income Mexican-origin mothers and their 24-week-old infants, dynamic structural equation modeling (DSEM) was used to examine whether within-infant vagal functioning accounted for between-dyad differences in within-dyad second-by-second emotion regulation and coregulation during free play. Vagal functioning was captured by within-infant mean and variability (standard deviation) of respiratory sinus arrhythmia (RSA) during free play. Infant emotion regulation was quantified as emotional equilibria (within-person mean), volatility (within-person deviation from equilibrium), carryover (how quickly equilibrium is restored following a disturbance), and feedback loops (the extent to which prior affect dampens or amplifies subsequent affect) in positive and negative affect during free play; coregulation was quantified as the influence of one partner’s affect on the other’s subsequent affect. Among infants with lower RSA variability, positive affect fluctuated around a higher equilibrium, and negative affect fluctuated around a lower equilibrium; these infants exhibited feedback loops where their positive affect dampened their subsequent negative affect. As expected, infants with higher mean RSA exhibited more volatility in positive affect, feedback loops between their positive and negative affect, and stronger mother-driven emotion coregulation. The results highlight differences in simultaneously occurring biological and emotion regulation.

**Keywords:** emotion regulation, Mother × Infant interaction, vagal functioning

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Early developmental milestones include the effective regulation of one’s emotions and their expression in response to contextual demands (Cole, Michel, & Teti, 1994). Poverty and ethnic minority status in the United States may hinder children’s socioemotional development. By school entry, low-income Mexican American children exhibit poorer self-regulation and interpersonal skills relative to their White peers (e.g., Galindo & Fuller, 2010). Relative to their ethnic majority, socioeconomically advantaged counterparts, low-income, Mexican-origin and immigrant mothers in the United States are at elevated risk for poor mental health (e.g., Beck, Froman, & Bernal, 2005; Kuo et al., 2004), which in turn jeopardizes their children’s development of self-regulatory skills and emotional wellbeing (e.g., Goodman et al., 2011). Parenting stress associated with socioeconomic hardship (Mulsoow, Caldera, Pursley, Reifman, & Huston, 2002) and ethnic minority identity (Nomaguchi & House, 2013) has been shown to directly impede Mother × Infant interactions, with adverse consequences for both partners of the dyad (Winstone, Curci, & Crnic, 2021). However, nurturing, sensitive “serve and return”

interactions between mothers and their infants facilitate children’s regulatory development (e.g., Bernard, Meade, & Dozier, 2013) and may mitigate the risks associated with contextual adversities. Consistent with developmental psychopathology theory (Richters & Cicchetti, 1993), it is important to understand the factors that increase risk for poor emotion regulation and coregulation or confer resilience among high-risk populations in order to understand the processes underlying individual pathways to adaptive or maladaptive outcomes (Cicchetti & Toth, 2009; Sroufe, 2007).

## Infant Vagal Functioning and Emotion Regulation

According to mutual regulation (Tronick & Reck, 2009) and bio-behavioral synchrony (e.g., Feldman, 2003) theories, infants and mothers participate in an emotional communication system characterized by moment-to-moment coordination in mothers’ and infants’ affect, expressed not only facially, but also vocally and bodily (Weinberg, Tronick, Cohn, & Olson, 1999, 2008), which functions to regulate infants’ emotional states. Infants vary in emotion regulation and coregulation processes during mother–infant play (e.g., Cohn & Tronick, 1988), likely due in part to differences in simultaneously occurring, biologically-based regulatory processes. Children’s internal, biological rhythms may facilitate and promote overall engagement and contingent responsiveness in Mother × Infant interactions, which in turn give rise to fluency in these interactions (Calkins, Dedmon, Gill,

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Lomax, & Johnson, 2002; Feldman, 2015). Research on the contributions of autonomic nervous system functioning to emotion regulation has focused primarily on the role of the parasympathetic nervous system and, more specifically, on vagal activity. According to Porges' polyvagal theory, the myelinated vagus nerve acts like a "brake" – during resting conditions, this brake supports physiological homeostasis and calm behavioral states (e.g., Porges, 2001, 2007). In contrast, release of the vagal brake during acute environmental challenges supports adaptive and metabolically-efficient behavioral and emotional responses. However, excessive vagal withdrawal during neutral or low-arousal events may confer risk as it is associated with overly rapid mobilization of the stress response and, over time, may contribute to wear and tear on these systems (Porges, 2007). Context-appropriate vagal functioning, for example stable high levels of infant vagal functioning during pleasurable situations (Porges, Doussard-Roosevelt, Portales, & Greenspan, 1996), is thought to support infants' communication with their environment via facial expressions, vocalizations, and behavioral engagement (e.g., crying to signal negative states and smiling to signal positive states) (Porges, 2001).

Vagal functioning is frequently assessed by respiratory sinus arrhythmia (RSA), a measure of the degree of change in heart rate during a respiratory cycle mediated via the myelinated vagus. Consistent with polyvagal theory's central tenet that context-appropriate RSA functioning facilitates contingent and appropriate emotion expression, regulation, and social engagement (Porges, 2007; Porges & Furman, 2011), among infants from ethnic majority middle-class families, decreases in infant RSA during socially challenging situations and rapid subsequent recovery to baseline infant RSA following social stress have been related to behavioral regulation (e.g., Bazhenova, Plonskaia, & Porges, 2001). By contrast, lower baseline infant RSA and smaller decreases in infant RSA (i.e., change in average RSA from baseline to a stressor task) in response to stress have been associated with deficits in self-regulation, and social, emotional, and behavioral problems in childhood (Feldman, 2009; Field & Diego, 2008; Porges, 2001; Porges et al., 1996). Prior work from our group demonstrated that higher within-infant variability (standard deviation, SD) of RSA during free play, suggestive of difficulties maintaining homeostasis in vagal functioning in the absence of environmental challenges, predicted elevated behavior problems in toddlerhood (Somers, Curci, & Luecken, 2020). Context-appropriate infant RSA (indicated by higher within-infant mean and lower within-infant SD of RSA during free play) may enable infants to more effectively participate in social interactions, leading to smoother Parent × Child interactions and more sensitive caregiving (e.g., Perry, Mackler, Calkins, & Keane, 2014). In contrast, context-inappropriate infant RSA may not only impair infant emotion regulation but also limit infants from reaping the benefits of maternal regulatory support (e.g., Feldman, 2015; Feldman & Eidelman, 2007; Porter, 2003).

Despite theoretical and empirical support that brainstem-limbic processes (e.g., vagal functioning) support the development of self-regulation and social engagement (Feldman, 2015), existing research has largely overlooked dyads from socioeconomically disadvantaged, ethnic minority backgrounds (Propper, 2012). Thus, it is particularly important to examine whether infant RSA is associated with the processes by which infants self-regulate and mother–infant dyads coregulate each other's internal emotional states in vulnerable populations, which may shed light on how children adapt to their environments in ways that either promote adjustment or confer risk (Cicchetti & Toth, 2009; Sroufe, 2007). Among pre-locomotor infants, playful interactions are

distinguished by social engagement goals, supported by long periods of mutual gaze, vocalizations, imitations, and positive affective sharing (Feldman, Greenbaum, Mayes, & Erlich, 1997), making mother–infant play an important context for evaluating coregulation processes. A dyad's ability to modulate affect to meet this goal, including downregulating negative affect or flexibly switching into more positive affective states, may not only support smooth Parent × Child interactions but may also lay the foundation for children's emerging self-regulatory abilities and prevent the development of behavior problems (Feldman, Greenbaum, & Yirmiya, 1999; Granic, O'Hara, Pepler, & Lewis, 2007; Lunkenheimer, Olson, Hollenstein, Sameroff, & Winter, 2011).

### Moment-to-Moment Emotion Regulation Processes During Mother–Infant Play

Complementing influential work on executive processes that children use to dynamically modulate their behavior and achieve regulatory goals (e.g., Cole, Ram, & English, 2019), emotion regulation can also be thought of as "an ongoing process of the individual's emotion patterns in relation to moment-by-moment contextual demands" (Cole et al., 1994, p. 74). By extension, dyadic emotion coregulation is evident in infants' and their mother's ongoing coordination of emotional exchanges with each other (Cole et al., 1994; Feldman, 2003; Tronick & Reck, 2009). Examining coordinated, moment-to-moment changes in infants' and their mothers' emotions offers insight into processes that may support or hinder effective emotion regulation, reflect ongoing emotion regulation, or occur as a byproduct of regulatory efforts. Together, we refer to micro-level processes that characterize momentary fluctuations in mothers' and infants' affect under the broad umbrella of emotion regulation and coregulation processes (see Table 1 for key terms and their definitions).

Affect fluctuates over time and, at any given point during play, one's affect may be higher or lower than his or her emotional equilibrium (mean level of positive or negative affect). In a regulated state, affect will return to its emotional equilibrium, following a perturbation (Butler, 2011). During Mother × Infant interactions, momentary increases in infant negative affect, reflected in the volatility of their affect or the extent to which they deviate from their emotional equilibrium (see Figure 1 of the Supplementary Material), may be context-appropriate signals infants use to communicate sudden needs (e.g., hunger, too much/little stimulation) and capture their mother's attention (Perry, Dollar, Calkins, & Bell, 2018; Stifter & Fox, 1990). Emotion regulatory processes, characterized by the timing and degree of change in infant affective expression (Crockenberg & Leerkes, 2003), are also reflected in carryover, or how quickly an infant returns to his or her equilibrium, following a disturbance to the equilibrium (see Figure 2 of the Supplementary Material), and feedback loops, by which infant affect at one moment in time either dampens (negative feedback) or amplifies (positive feedback) subsequent affect as part of continuous regulation and maintenance of a stable emotional equilibrium (Butler, 2015; Hollenstein, 2015). More frequent and intense (e.g., higher equilibrium of negative affect) and prolonged expressions of negative affect (e.g., higher carryover of negative affect and less adaptive feedback with positive affect) may impede Mother × Infant interactions and reflect deficits in infant emotion regulation (Beebe & Steele, 2013; Calkins et al., 2002; Cole, 2016). In contrast, more frequent and intense (e.g., higher equilibrium of positive affect) and sustained expressions of positive affect (e.g., higher carryover of

**Table 1.** Regulatory processes: Key terms and their definitions

Key term	Definition	Operationalization
Equilibrium	Within-person mean in positive or negative affect, over the defined period of time	Within-person intercept of latent mean-centered positive or negative affect
Volatility	Extent to which a person deviates from their equilibrium in positive or negative affect, over the defined period of time	Within-person residual variance of positive or negative affect
Carryover in emotion	How quickly a person returns to their emotional equilibrium in positive or negative affect, following a disturbance	Autoregressive relation of affect at time $t$ on the same affect at $t - 1$
Feedback loops	Extent to which prior affect either dampens (negative feedback) or amplifies (positive feedback) subsequent affect	Cross-lagged predictive relation of positive affect at time $t$ on negative affect at $t - 1$ ; cross-lagged predictive relation of negative affect at time $t$ on positive affect at $t - 1$
Mother-driven coregulation	Extent to which maternal affect either dampens or amplifies subsequent infant affect	Cross-lagged predictive relations of infant's positive or negative affect at time $t$ on their mother's positive affect at $t - 1$
Infant-driven coregulation	Extent to which infant affect either dampens or amplifies subsequent maternal affect	Cross-lagged predictive relations of mother's positive affect at time $t$ on their infant's positive or negative affect at $t - 1$

positive affect), and the ability to activate positive affect and down-regulate negative affect (indexed by feedback loops between positive and negative affect) may reflect more sophisticated infant emotion self-regulation (Beebe & Steele, 2013).

*Coregulation* is often indexed by synchrony, or time-lagged influences of fluctuations in each partner's affect on the other's, which serve to maintain emotional equilibria (e.g., Beebe et al., 2010; Butler & Randall, 2013; Feldman, 2006). Caregivers' positive affect plays a unique role in promoting infant positive affect (e.g., Tronick, 1989). Infants require caregivers' assistance to express and maintain positive affect through corresponding, moment-by-moment synchrony in parent and infant positive affect (Feldman, 2003). Mothers' positive affect expression may not only be mirrored by their infants, but may also be "state transforming," such that mothers' positive affect facilitates change in their infants' arousal and affect state from more negative to neutral or positive states (Beebe et al., 2010). Yet, despite theoretical accounts of the bidirectional nature of mother–infant emotion coregulation, the limited research on dyadic synchrony often assumes that emotion coregulation is led by mothers (e.g., Feldman, 2012) without empirical disambiguation of the "drivers" of emotion coregulation.

### Dynamic RSA

Like emotion regulation, parasympathetic regulation has historically been assessed as a static process, obscuring the dynamic fluctuation of vagal functioning during social interaction. According to polyvagal theory, *rapid* modulation of the vagal brake supports context-appropriate emotional and social responding (Porges, 2007). However, the extant research has typically captured global changes in vagal functioning (e.g., RSA averaged across 30-s epochs) that reflect mean-level differences from one task to the next, leading researchers to argue for a paradigm shift toward focusing on the dynamic fluctuations in RSA throughout an interaction (e.g., Giuliano, Skowron, & Berkman, 2015). Recent innovations in the assessment of vagal functioning, such as the RSAseconds program (Gates, Gatzke-Kopp, Sandstein, & Blandon, 2015), allow researchers to derive time-varying estimates of infant RSA during ecologically meaningful tasks, which affords researchers the opportunity to examine vagal functioning *during* a

task, nearer to the time scale on which RSA-mediated influences on behavior are thought to occur. Within-infant mean RSA during a task reflects infants' overall vagal tone (i.e., overall level of vagal functioning) *within* an interaction, which supports infants' capacity to respond in a flexible and contingent manner to internal and external demands during social interactions (Porges, 2001). In contrast, within-infant variability (*SD*) in RSA during a task, reflecting deviations from one's mean, can be viewed as moment-to-moment vagal variability. Whereas vagal withdrawal in response to acute stressors is an efficient cardiometabolic strategy for facilitating rapid adjustment in social engagement and affective responding, excessive responsivity of the vagal brake during periods of relative quiescence may constitute a maladaptive physiological reaction (Porges, 2006). During a period of unstructured ("free") play with their mothers, which is characterized by social engagement goals and a relative lack of internal and external challenges, higher within-infant mean RSA and lower within-infant *SD* of RSA may be linked with context-appropriate patterns of emotion regulation and coregulation.

### The Current Study

Drawing on polyvagal theory (Porges, 2007) and dynamic biobehavioral models of infant emotion regulation and mother–infant emotion coregulation (Feldman, 2015; Tronick, 1989), we sought to evaluate whether infant vagal functioning was associated with concurrent emotion regulation and coregulation processes during mother–infant free play at child age 24 weeks. Because infants are generally not biologically able to sustain long periods of face-to-face play before 3 months of age (Beebe & Steele, 2013) and meaningful differences in face-to-face emotion coregulatory processes may not be evident when most (but not all) infants first show affect synchrony, we focused on differences in synchronous coregulatory processes at a child age of approximately 6 months. Guided by our integrated theoretical framework, we leveraged recent methodological innovations in the study of dynamic regulatory processes to examine whether within-infant mean RSA and *SD* of RSA during mother–infant free play accounted for between-dyad differences in concurrent second-by-second emotion regulation and coregulation processes among low-income families of Mexican origin.

The first aim of this study was to evaluate whether within-infant mean and *SD* of RSA during free play accounted for between-dyad differences in infants' emotion regulation processes. We expected that higher within-infant mean RSA and lower within-infant *SD* of RSA during free play would be related to potentially more adaptive emotion regulation processes, specifically to (a) higher equilibrium of infant positive affect and lower equilibrium of negative affect, (b) more volatility in positive and negative affect, (c) less carryover in negative affect (i.e., quicker restoration of equilibrium in negative affect following a perturbation) and more carryover in positive affect (i.e., slower restoration in equilibrium in positive affect following a perturbation), and (d) feedback loops, such that among infants with higher mean RSA and infants with lower *SD* of RSA during free play, increased positive affect will dampen subsequent negative affect whereas, when they experience increased negative affect, they will return more quickly to their equilibrium of positive affect.

The second aim of this study was to evaluate whether within-infant mean and *SD* of RSA during free play accounted for between-dyad differences in mother–infant coregulation processes during free play. Of note, we disentangled the drivers of synchronous interactions in order to evaluate whether infant vagal functioning is related to mother-driven coregulation (i.e., infants' contingent responses to their mothers), infant-driven coregulation (i.e., mothers' contingent responses to their infants), or both mother- and infant-driven coregulation processes. We expected that higher within-infant mean and lower within-infant *SD* of RSA would each be related to stronger mother-driven coregulation, such that infants would exhibit more contingent responses to prior maternal positive affect (e.g., increased maternal positive affect would amplify subsequent infant positive affect and dampen subsequent infant negative affect), and to stronger infant-driven coregulation, such that mothers would exhibit more contingent responses to prior infant positive and negative affect (e.g., increased infant positive affect would amplify subsequent maternal positive affect and decreased infant negative affect would dampen subsequent maternal positive affect).

## Method

### Participants

The sample consisted of 210 women and their children who participated in a broader study of very low-income Mexican-origin children's development (*Las Madres Nuevas*). During pregnancy, women were recruited from hospital-based prenatal clinics that serve low-income women. Eligibility criteria included (a) self-identification as Mexican or Mexican American, (b) fluency in English or Spanish, (c) 18 years of age or older, (d) low-income status (defined as family income below US\$25,000 or eligibility for Medicaid or Federal Emergency Services coverage for child-birth), and (e) anticipated delivery of a singleton birth. To reduce participant burden, a "planned missing" design was employed as part of the broader (*Las Madres Nuevas*) study in which each participant was randomly assigned to miss one of the 12-, 18-, or 24-week postpartum visits. The expected number of participants at each time point was thus approximately two-thirds of the sample. Of the 322 women who met the inclusion criteria and consented to participate in the larger study, 210 (93% of the randomly assigned 226 women) completed the 24-week assessment. Sample characteristics are presented in Table 2.

**Table 2.** Sample demographics

Age: range; <i>M</i> ( <i>SD</i> )	18–42; 27.8 (6.5)
First-time mothers	20.4%
Number of children: range; <i>M</i> ( <i>SD</i> )	0–9; 1.6 (1.7)
Country of birth	
Mexico	86.6%
United States	13.4%
Years in the United States <sup>a</sup> : range; <i>M</i> ( <i>SD</i> )	0–32; 11.8 (5.9)
Maternal education	
0–8 years of school	26.9%
Some high school completed	33.3%
High school graduate	25.9%
Some college or vocational school	9.0%
College degree or above	5.0%
Work status	
Not employed	85.6%
Working part-time	9.5%
Working full-time	5.0%
Family income	
≤US\$10,000	32.7%
US\$10,001–15,000	26.6%
US\$15,001–25,000	25.2%
≥US\$25,001	15.5%
Relationship status at prenatal visit	
Living with a partner/spouse	79.6%
Not living with a partner/spouse	20.4%
Child sex	
Male	47.8%
Female	52.2%
Preterm birth (<37 weeks) – %	4.8%
Gestational age (weeks): range; <i>M</i> ( <i>SD</i> )	26–42; 39.3 (1.5)
Low birth weight (<88 oz or <2500 g)	1.0%
Child birth weight (oz): range; <i>M</i> ( <i>SD</i> )	42–174; 119.9 (18.4)

<sup>a</sup>Of women not born in the United States.

### Procedures

The Arizona State University Institutional Review Board and the Maricopa Integrated Health System IRB approved study procedures prior to study inception. A bilingual female interviewer from the research team obtained informed consent in the women's homes between 26 and 39 weeks gestation. Data for the analyses were from prenatal and 24-week postpartum home visits. For infants born at less than 37 weeks gestation ( $n = 10$ ), the 24-week home visit date was age-corrected to represent the age of the child from the expected date of delivery. Home visits lasted 2–3 hours and included the collection of physiological measurements, structured interviews, questionnaire presentations, and five interaction tasks with mothers and their infants. The female bilingual interviewers read survey questions aloud and recorded participant

responses on a laptop computer. The interaction tasks started with a 5-min free play in which study team members provided mothers with a basket of toys and asked them to play with their infants as they normally would. The mothers were asked to try to make sure their infant had eaten and slept prior to the home visit in order to minimize the possibility of infant hunger or sleepiness during the tasks. Women were compensated US \$75 and small gifts for the prenatal visit and US\$50 and small gifts (e.g., bibs) for the 24-week postpartum visit.

## Measures

### Infant RSA

Infants were seated upright in a study-provided seat and a research assistant placed electrodes on the infants' left shoulder and right and left waist in a standard lead configuration. Child heart rate data were recorded at 256 Hz with electrocardiography (ECG) equipment from Forest Medical, LLC (Trillium 5,000; East Syracuse, NY, USA). QRSTool software 1.2.2 (Allen, Chambers, & Towers, 2007) was used to process the data and automatically obtain R-spikes from the ECG data. Trained coders used QRSTool to manually correct misidentified or unidentified R-spikes, and obtain R-R interval data.

We estimated time-varying heart rate variability in the frequency band of RSA (0.3–1.3 Hz for infants) for the 5-min free play period using the MATLAB toolbox RSAseconds (Gates et al., 2015). Each of the cleaned infant interbeat interval (IBI) series was interpolated at 4 Hz using a cubic spline to create equal data intervals. The data were then tapered using peak matched multiple windows; this is an optimal way to identify changes in RSA over time as it yields RSA estimates with lower variance and less bias than the Porges method (Hansson-Sandsten & Jönsson, 2007). A short-time Fourier transform was applied to 32-s IBI windows to produce second-by-second RSA. Values from the short-time Fourier transform approach are always lower than the values from the Porges approach due to the scaling that is introduced via the peak matched multiple windows technique (K. Gates, personal communication, April 29, 2019). During one or more seconds of the free play task, 11 infants had negative estimates of RSA; data from these infants were removed prior to analysis.

From the time-varying RSA estimates, infants' within-person mean and SD of RSA during free play were calculated for use in primary analyses. The within-infant mean represents the infant's average level of RSA across the 300 s free play task; within-infant SD reflects the amount of variation during the task in the infant's RSA around his or her own mean. Infants with higher mean RSA during free play also exhibited more intra-individual variability in their RSA,  $r(130) = .26$ ,  $p = .003$ .

### Micro-coded affect

Consistent with the perspective that affect is expressed in multiple modalities (e.g., Beebe et al., 2010; Feldman, 2003, 2006; Moore & Calkins, 2004; Moore et al., 2009; Weinberg et al., 1999, 2008), affect was assessed by combining facial/vocal affect and engagement behaviors into affect categories. Mother and infant facial/vocal affect (maternal positive, negative, neutral affect, and unscorable affect; infant positive, negative-fussy, negative-crying, neutral, and unscorable affect) and engagement in social interaction (mother active engagement, comforting engagement, passive engagement, and disengagement; infant active engagement, infant passive engagement, and infant disengagement) were coded

independently from the videorecorded free play interaction task using an adapted version of the Infant and Maternal Regulatory Scoring Systems (Tronick & Weinberg, 1990). These systems are micro-coding systems used to capture mothers' and infants' behavior and facial expressions during dyadic interactions.

Trained undergraduate research assistants were instructed to begin rating behaviors as soon as each task began, which was indicated by a beep on the experimenter's stopwatch. Using Noldus 9.0 software, coders rated specific behaviors in real time using event-based coding, which was subsequently transformed into second-by-second affect and engagement time series using the time stamp (recorded to the millisecond). Each code in the series reflected whether the specified state was present or absent during that second. Coders achieved acceptable agreement ( $\kappa > .60$ ) with master coders during training; 20% of each coder's videos were checked against master coders to continually assess reliability and minimize drift over time (average  $\kappa = .62$  for infant behaviors and average  $\kappa = .66$  for mother behaviors).

The facial/vocal affect and engagement time series were combined into four multimodal affect time series (positive and negative affect, for infants and mothers) of approximately 300 observations (for the 5-min free play) for use in analyses. Positive affect was rated from 0 to 4 (0 = no positive affect; 2 = neutral affect, active (or comforting) social engagement; 4 = positive affect, active social engagement). Negative affect was also rated from 0 to 4, with 0 = no negative affect, 2 = negative affect, social disengagement (e.g., frowning or pouting, with gaze averted), and 4 = negative, active social engagement (e.g., furrowed eyebrows while whining or crying). The specific combinations of facial/vocal affect and engagement that matched each level of infant and maternal positive and negative affect are shown in the Supplementary Material (Table 2).

The infants showed the full range of both positive and negative affect during free play. Across the sample, the infants spent 75.2% of the free play task exhibiting any positive affect and 22.1% of the free play task exhibiting any negative affect. In contrast, the mothers showed positive affect 100% of the time during free play; because no mothers showed negative affect during free play, only maternal positive affect (ranging from 1 = positive, disengaged to 4 = positive, actively engaged) was included in the analyses.

## Data analysis plan

### Preliminary analyses

Stationarity (or the assumption of no mean level changes, no time-related trends, as well as constant variance, constant autocovariance, and constant lagged covariance) is a requirement of many time series analytical methods, including dynamic structural equation modeling (DSEM). Prior to analysis, the three affect series of the outcome variables (mothers' positive affect; infants' positive and negative affect) for each dyad were evaluated to determine if each met mean-level and trend-level stationarity using the augmented Dickey–Fuller test (Dickey & Fuller, 1979) for stationarity.

### Primary analyses

DSEM (Asparouhov, Hamaker, & Muthén, 2018) was conducted in Mplus v.8.4 (Muthén & Muthén; 1998–2017) to account for within-person and within-dyad variability in multiple affect time series while also modeling between-dyad differences in dynamic emotion regulatory and coregulation processes. DSEM enabled estimation of the effect of each dyad member's affect at

one second in time on their own and their partner's affect in the subsequent second, which was allowed to vary for each mother–infant dyad, and this variation was accounted for by inclusion of between-dyad covariates (infant mean and *SD* of RSA during free play) in the model.

In the analytic model, random effects were added to the intercepts for mothers' and infants' affect, residual variances of mothers' and infants' affect, and all of the possible paths between mothers' and infants' affect. In order to yield pure within effects, lagged variables (lag – 1) of mothers' and infants' affect were latent centered to yield pure within effects (Hamaker & Grasman, 2015). All autoregressive (i.e., carryover) and cross-lagged paths (i.e., feedback loops within an infant and coregulatory paths between infants and their mothers) were estimated. In other words, in the within-dyad level of the model, all possible paths (slopes) between maternal and infant affect from one second to the next were estimated. Whereas multilevel models have generally assumed homogeneity of Level 1 variance across people (e.g., assuming that how predictable each person is is homogenous), DSEM allows the residual variance to be different for every person in order to reflect differential predictability across people in the sample. As such, each person's time series can be differentially volatile. The analytic model included random residual variances (hereafter referred to as volatility), allowing each individual to have a different course of the time series (Hamaker, Asparouhov, Brose, Schmiedek, & Muthén, 2018). Because residual variance has to be positive, the coefficients for volatility are on the log-linear scale, which has implications for interpreting coefficients, similar to other log-linear models (e.g., Poisson or negative binomial for count data).

The proposed model yielded estimates of average within-dyad relations between mothers' and infants' affect (i.e., fixed effects). Including random effects means that the intercepts, residual variances, and aforementioned paths (slopes) become latent variables at the between-level, and between-dyad differences in these latent variables can be accounted for. Within-infant mean and *SD* of RSA during free play were grand-mean centered and included as covariates of all random effects, allowing for examination of whether vagal functioning accounted for between-dyad differences in the within-dyad means, volatilities, carryover, feedback loops, and coregulatory effects in infants' and mothers' affect.

The proposed model is shown in Figure 1. Following Curran and Bauer's (2007) recommended notation for multilevel path diagrams, measured variables are indicated by boxes, intercepts are indicated by a triangle with a label of 1, regression parameters (slopes) are indicated by a straight single-headed arrow, and random coefficients are indicated by circles and a subscript *i*, which denotes that the path is allowed to vary across dyads in the sample. Random intercepts were allowed to covary, but no other possible covariances between random effects were included given the large sample size requirements for reliably estimating random effects covariances (McNeish, 2019; Rast & Hofer, 2014). If the 95% credible intervals (CIs) of the posterior distribution summaries (the Bayesian analog of frequentist point estimates) did not contain zero, the effects were determined to be non-null (i.e., significant).

## Results

### Preliminary analyses

Two augmented Dickey–Fuller unit root tests for stationarity were conducted per time series (maternal positive affect and infant

positive and negative affect) per dyad – one was to determine whether the series was nonzero-mean stationary (single mean) and the other to determine whether the series was linear time-trend stationary (trend). In both the single mean and trend models, a lag of one was specified. During free play, there were 13 (6.19%) infants whose positive affect series may be nonstationary, 18 (8.57%) infants whose negative affect series may be nonstationary, and six (2.86%) mothers whose positive affect series may be nonstationary, based on nonzero-mean stationarity and/or linear time-trend stationarity. Although the overall pattern of primary results was similar, there were meaningful differences in the pattern of statistical significance (i.e., whether CIs contained zero) when possibly nonstationary time series were included or excluded from the analyses. Therefore, we set the possibly nonstationary affect time series to missing in the data for the analyses presented here.

Stationarity on infant positive affect and maternal positive affect did not differ depending on the infant mean or *SD* of RSA, maternal sociodemographic characteristics, or birth outcomes. However, stationarity on infant negative affect differed by maternal country of origin ( $\chi^2(2) = 6.444$ ,  $p = .040$ ). Infants whose mothers were born in the United States were more likely to have possibly nonstationary negative affect series than those whose mothers were born in Mexico, meaning infants whose mothers were born in the United States were more likely to have missing data on infant negative affect. In addition, infants whose mothers were born in the United States had higher within-infant *SD* of RSA ( $M = 0.56$ ,  $SD = 0.22$ ) than those whose mothers were born in Mexico ( $M = 0.44$ ,  $SD = 0.15$ ),  $t(127) = 2.55$ ,  $p = .012$ . Therefore, maternal country of origin was included as a covariate of infant negative affect.

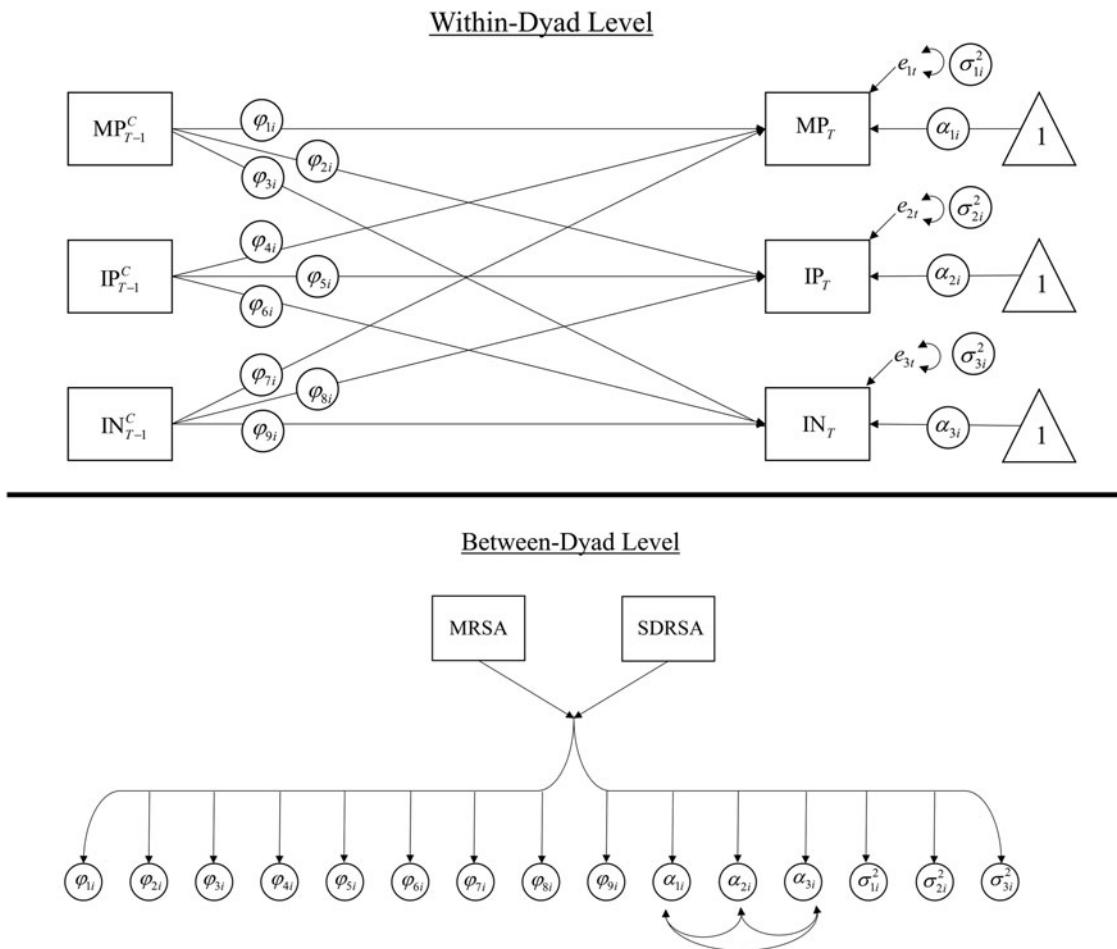
The model equations are shown in Table 1 of the Supplementary Material. The primary results are shown in Tables 3 and 4, showing unstandardized posterior distribution summaries and Bayesian 95% CIs for the posterior distributions.

### Aim 1: Dynamic processes of infant emotion regulation

**Aim 1a: Infants' equilibrium of positive and negative affect.** Across the sample, within-infant equilibrium (i.e., average level) of positive affect,  $\gamma_{10}$ , was 1.410, 95% CI [1.318, 1.503]; after adjusting for maternal country of origin, within-infant equilibrium of negative affect,  $\gamma_{20}$ , was 0.262, 95% CI [0.206, 0.313]. Contrary to expectations, mean infant RSA during free play did not predict infants' equilibrium of positive affect,  $\gamma_{11} = 0.118$ , 95% CI [−0.010, 0.260], or negative affect,  $\gamma_{21} = 0.019$ , 95% CI [−0.065, 0.097].

Consistent with expectations, within-infant *SD* of RSA during free play predicted infants' positive affect equilibrium,  $\gamma_{12} = -0.787$ , 95% CI [−1.360, −0.146]. Relative to their counterparts with higher *SD* of RSA, infants with lower *SD* of RSA during free play displayed a higher equilibrium of concurrent positive affect. Similarly, within-infant *SD* of RSA predicted negative affect equilibrium,  $\gamma_{22} = 0.639$ , 95% CI [0.242, 1.004], such that infants with lower *SD* of RSA during free play displayed a lower equilibrium of concurrent negative affect.

**Aim 1b: Volatility in positive and negative affect.** Infants' volatility in positive affect,  $\exp(\omega_{10})$ , was 0.167,  $\omega_{10} = -1.787$ , 95% CI [−1.951, −1.641]; infants' volatility in negative affect,  $\exp(\omega_{20})$ , was 0.051,  $\omega_{10} = -2.979$ , 95% CI [−3.286, −2.699]. Mean infant RSA during free play predicted the volatility in infants' positive affect,  $\gamma_{13,1} = 0.327$ , 95% CI [0.097, 0.563], such that for a one-unit increase in mean infant RSA, the volatility in infants' positive



**Figure 1.** Proposed dynamic structural equation model.

affect changed multiplicatively by 1.39. Mean infant RSA did not predict the volatility in infants' negative affect,  $\gamma_{14,1} = 0.143$ , 95% CI [-0.243, 0.498]. Within-infant SD of RSA during free play did not predict the volatility in infants' positive affect,  $\gamma_{13,2} = -0.841$ , 95% CI [-1.936, 0.374], or negative affect,  $\gamma_{14,2} = 1.529$ , 95% CI [-0.473, 3.376].

**Aim 1c: Carryover in infant positive and negative affect.** Infants showed non-null positive carryover in positive affect,  $\gamma_{70} = 0.815$ , 95% CI [0.799, 0.829], and negative affect,  $\gamma_{11,0} = 0.759$ , 95% CI [0.732, 0.784]. Mean infant RSA during free play did not predict carryover in infant positive affect,  $\gamma_{71} = -0.019$ , 95% CI [-0.004, 0.040], but did predict carryover in infant negative affect,  $\gamma_{11,1} = -0.084$ , 95% CI [-0.115, -0.044]. Post-hoc probing using a multi-level moderation web utility (<http://quantpsy.org/interact/hlm2.htm>; Preacher, Curran, & Bauer, 2006) indicated that carryover in infant negative affect was positive and statistically significant at all levels of mean infant RSA observed in the sample (i.e., infants whose mean RSA during free play was less than or equal to 8.21). Within-infant SD of RSA did not predict carryover in infant positive affect,  $\gamma_{72} = -0.049$ , 95% CI [-0.179, 0.100], or negative affect,  $\gamma_{11,2} = 0.187$ , 95% CI [-0.019, 0.381].

**Aim 1d: Feedback loops between infant positive and negative affect.** Infants' positive affect at one time point did not predict their subsequent negative affect,  $\gamma_{80} = -0.006$ , 95% CI [-0.012,

0.001], and infants' negative affect at one time point did not predict their subsequent positive affect,  $\gamma_{10,0} = .006$ , 95% CI [-0.013, 0.026]. Mean infant RSA during free play predicted the relation between infants' positive affect and their subsequent negative affect,  $\gamma_{81} = -0.013$ , 95% CI [-0.020, -0.005], and the relation between infants' negative affect and their subsequent positive affect,  $\gamma_{10,1} = 0.050$ , 95% CI [0.023, 0.076]. Results of post-hoc probing indicated that, for infants with below average RSA (at least 1.28 SD below the mean on within-infant mean RSA during free play; 6.9% of the sample), changes in positive affect were *positively* related to changes in subsequent negative affect (e.g., an increase in positive affect augmented subsequent infant negative affect), estimate = 0.01,  $p = .05$ . For infants with below average RSA during free play (at least 0.88 SD below the mean; 24.6% of the sample), changes in negative affect were *negatively* related to subsequent positive affect (e.g., an increase in negative affect damped subsequent infant positive affect), estimate = -0.03,  $p = .05$ .

In contrast, for infants with average or above RSA (above the mean; 44.6% of the sample), changes in positive affect were *negatively* related to changes in subsequent negative affect (e.g., sustained decline in negative affect following an increase in positive affect), estimate = -0.01,  $p = .05$ . For infants with above average RSA (at least 0.42 SD above the mean; 32.3% of the sample), changes in negative affect were *positively* related to subsequent positive affect (e.g., sustained elevation in positive affect following an increase in negative affect), estimate = 0.02,  $p = .05$ .

**Table 3.** Primary model results

Intercepts				
Effect	Notation		Posterior median	95% CI
Intercept (MP)	$\gamma_{00}$		<b>2.800</b>	[ <b>2.715, 2.890</b> ]
Intercept (IP)	$\gamma_{10}$		<b>1.410</b>	[ <b>1.318, 1.503</b> ]
Intercept (IN)	$\gamma_{20}$		<b>0.262</b>	[ <b>0.206, 0.313</b> ]
ln[Variance (MP)]	$\omega_{00}$		<b>-1.738</b>	[-1.879, -1.596]
ln[Variance (IP)]	$\omega_{10}$		<b>-1.787</b>	[-1.951, -1.641]
ln[Variance (IN)]	$\omega_{20}$		<b>-2.979</b>	[-3.286, -2.699]
Regression path intercepts				
Predictor at time $t - 1$	Outcome at time $t$	Notation	Posterior median	95% CI
Mom PA	Mom PA	$\gamma_{30}$	<b>0.818</b>	[ <b>0.806, 0.829</b> ]
Mom PA	Infant PA	$\gamma_{40}$	<b>0.021</b>	[ <b>0.014, 0.028</b> ]
Mom PA	Infant NA	$\gamma_{50}$	<b>-0.007</b>	[-0.013, -0.002]
Infant PA	Mom PA	$\gamma_{60}$	<b>0.022</b>	[ <b>0.015, 0.029</b> ]
Infant PA	Infant PA	$\gamma_{70}$	<b>0.815</b>	[ <b>0.799, 0.829</b> ]
Infant PA	Infant NA	$\gamma_{80}$	-0.006	[-0.012, 0.001]
Infant NA	Mom PA	$\gamma_{90}$	-0.003	[-0.013, 0.007]
Infant NA	Infant PA	$\gamma_{10,0}$	0.006	[-0.013, 0.026]
Infant NA	Infant NA	$\gamma_{11,0}$	<b>0.759</b>	[ <b>0.732, 0.784</b> ]
Between-dyad residual variances				
Effect	Notation		Posterior median	
Variance ( $u_{0i}$ )	$\tau_{00}$		<b>0.312</b>	
Variance ( $u_{1i}$ )	$\tau_{11}$		<b>0.322</b>	
Variance ( $u_{2i}$ )	$\tau_{22}$		<b>0.079</b>	
Covariance ( $u_{0i}, u_{1i}$ )	$\tau_{10}$		<b>0.078</b>	
Covariance ( $u_{0i}, u_{2i}$ )	$\tau_{20}$		0.000	
Covariance ( $u_{1i}, u_{2i}$ )	$\tau_{21}$		<b>-0.125</b>	
Variance ( $u_{3i}$ )	$\tau_{33}$		<b>0.005</b>	
Variance ( $u_{4i}$ )	$\tau_{44}$		<b>0.001</b>	
Variance ( $u_{5i}$ )	$\tau_{55}$		<b>0.001</b>	
Variance ( $u_{6i}$ )	$\tau_{66}$		<b>0.001</b>	
Variance ( $u_{7i}$ )	$\tau_{77}$		<b>0.009</b>	
Variance ( $u_{8i}$ )	$\tau_{88}$		<b>0.001</b>	
Variance ( $u_{9i}$ )	$\tau_{99}$		<b>0.001</b>	
Variance ( $u_{10i}$ )	$\tau_{10,10}$		<b>0.006</b>	
Variance ( $u_{11i}$ )	$\tau_{11,11}$		<b>0.023</b>	
Variance ( $u_{12i}$ )	$\tau_{12,12}$		<b>0.834</b>	
Variance ( $u_{13i}$ )	$\tau_{13,13}$		<b>1.190</b>	
Variance ( $u_{14i}$ )	$\tau_{14,14}$		<b>3.493</b>	

Note: MP = maternal positive affect; IP = infant positive affect; IN = infant negative affect; PA = positive affect; NA = negative affect. Unstandardized estimates are shown. Bold entries designate effects that are non-null based on zero not being within the 95% credible interval (CI). Residual variances (volatilities) are not exponentiated and will not include zero in the CI due to the prior used.

Within-infant SD of RSA during free play also predicted the relation between infants' positive affect and their subsequent negative affect,  $\gamma_{82} = 0.054$ , 95% CI [0.009, 0.093], such that, among

infants with relatively lower intra-individual variability in RSA (at least 0.01 SD below the mean on within-infant SD of RSA; 54.6% of the sample), changes in infant positive affect were

**Table 4.** Between-dyad covariate effects

Predictor	Within-infant mean of RSA during free play			Within-infant SD of RSA during free play		
	Effect	Notation	Posterior median	95% CI	Notation	Posterior median
$\alpha_{1i}$ on RSA	$\gamma_{01}$	0.010	[−0.113, 0.145]	$\gamma_{02}$	0.109	[−0.575, 0.734]
$\alpha_{2i}$ on RSA	$\gamma_{11}$	0.118	[−0.010, 0.260]	$\gamma_{12}$	<b>−0.787</b>	<b>[−1.360, −0.146]</b>
$\alpha_{3i}$ on RSA	$\gamma_{21}$	0.019	[−0.065, 0.097]	$\gamma_{22}$	<b>0.639</b>	<b>[0.242, 1.004]</b>
$\varphi_{1i}$ on RSA	$\gamma_{31}$	−0.015	[−0.032, 0.002]	$\gamma_{32}$	−0.003	[−0.040, 0.035]
$\varphi_{2i}$ on RSA	$\gamma_{41}$	<b>0.012</b>	<b>[0.004, 0.021]</b>	$\gamma_{42}$	−0.016	[−0.063, 0.027]
$\varphi_{3i}$ on RSA	$\gamma_{51}$	<b>−0.013</b>	<b>[−0.026, −0.003]</b>	$\gamma_{52}$	−0.037	[−0.087, 0.022]
$\varphi_{4i}$ on RSA	$\gamma_{61}$	0.004	[−0.008, 0.014]	$\gamma_{62}$	−0.006	[−0.059, 0.054]
$\varphi_{5i}$ on RSA	$\gamma_{71}$	0.019	[−0.004, 0.040]	$\gamma_{72}$	−0.049	[−0.179, 0.100]
$\varphi_{6i}$ on RSA	$\gamma_{81}$	<b>−0.013</b>	<b>[−0.020, −0.005]</b>	$\gamma_{82}$	<b>0.054</b>	<b>[0.009, 0.093]</b>
$\varphi_{7i}$ on RSA	$\gamma_{91}$	0.003	[−0.010, 0.016]	$\gamma_{92}$	−0.040	[−0.099, 0.029]
$\varphi_{8i}$ on RSA	$\gamma_{10,1}$	<b>0.050</b>	<b>[0.023, 0.076]</b>	$\gamma_{10,2}$	−0.063	[−0.215, 0.076]
$\varphi_{9i}$ on RSA	$\gamma_{11,1}$	<b>−0.084</b>	<b>[−0.115, −0.044]</b>	$\gamma_{11,2}$	0.187	[−0.019, 0.381]
$\ln(\sigma_{1i}^2)$ on RSA	$\gamma_{12,1}$	0.224	[−0.002, 0.421]	$\gamma_{12,2}$	0.738	[−0.541, 1.954]
$\ln(\sigma_{2i}^2)$ on RSA	$\gamma_{13,1}$	<b>0.327</b>	<b>[0.097, 0.563]</b>	$\gamma_{13,2}$	−0.841	[−1.936, 0.374]
$\ln(\sigma_{3i}^2)$ on RSA	$\gamma_{14,1}$	0.143	[−0.243, 0.498]	$\gamma_{14,2}$	1.529	[−0.473, 3.376]

Note: RSA = respiratory sinus arrhythmia (of infant). Unstandardized estimates are shown. Covariate effects of maternal country of origin not shown. Covariates of the residual variances (volatilities) are not exponentiated. Bold entries designate effects that are non-null based on zero not being within the 95% credible interval (CI).

Null effects of maternal country of origin on average negative affect ( $\gamma_{23}$ ), volatility in infants' negative affect ( $\gamma_{14,3}$ ), carryover in infant negative affect ( $\gamma_{11,3}$ ), the association between infants' positive affect and their subsequent negative affect ( $\gamma_{83}$ ), the association between infants' negative affect and their subsequent positive affect ( $\gamma_{10,3}$ ), the association between mothers' positive affect and their infants' subsequent negative affect ( $\gamma_{53}$ ), and the association between infants' negative affect and their mothers' subsequent positive affect ( $\gamma_{93}$ ), are not shown.

*negatively related to subsequent negative affect (e.g., an increase in positive affect damped subsequent negative affect), estimate = −0.01, p = .05.* Within-infant SD of RSA did not predict the association between infants' negative affect and their subsequent positive affect,  $\gamma_{10,2} = −0.063$ , 95% CI [−0.215, 0.076].

#### Aim 2: Dynamic processes of mother–infant coregulation

*Mother-driven coregulation.* Mothers' positive affect at one time point was a non-null positive predictor of their infants' subsequent positive affect,  $\gamma_{40} = 0.021$ , 95% CI [0.014, 0.028], and a non-null negative predictor of their infants' subsequent negative affect,  $\gamma_{50} = −0.007$ , 95% CI [−0.013, −0.002]. As expected, mean infant RSA during free play predicted the association between mothers' positive affect and their infants' subsequent positive affect,  $\gamma_{41} = 0.012$ , 95% CI [0.004, 0.021], and the association between mothers' positive affect and their infants' subsequent negative affect,  $\gamma_{51} = −0.013$ , 95% CI [−0.026, −0.003]. Results of post-hoc probing indicated that, at below average levels of infant RSA during free play (at least 1.18 SD below the mean on within-infant mean RSA during free play; 11.5% of the sample), maternal positive affect did not predict subsequent infant positive affect,  $p > .05$ . Similarly, for infants with below average mean levels of RSA during free play (at least 0.10 SD below the mean; 50.8% of the sample), maternal positive affect did not predict subsequent infant negative affect,  $p > .05$ .

In contrast, for infants with low–average and higher mean levels of RSA during free play (at least 1.18 SD above the mean; 88.5% of the sample), changes in maternal positive affect were positively related to subsequent infant positive affect (e.g., an increase in maternal positive affect augmented subsequent infant positive affect), estimate = 0.01,  $p = .05$ . Similarly, for infants with

average and above mean levels of RSA during free play (at least 0.10 SD above the mean; 49.2% of the sample), changes in maternal positive affect were negatively related to subsequent infant negative affect (e.g., an increase in maternal positive affect damped subsequent infant negative affect), estimate = −0.01,  $p = .05$ . Within-infant SD of RSA during free play did not predict the relation between mothers' positive affect and their infants' subsequent positive affect,  $\gamma_{42} = −0.016$ , 95% CI [−0.063, 0.027], or the relation between mothers' positive affect and their infants' subsequent negative affect,  $\gamma_{52} = −0.037$ , 95% CI [−0.087, 0.022].

*Infant-driven coregulation.* Infants' positive affect at one time point was a positive predictor of their mothers' subsequent positive affect,  $\gamma_{60} = 0.022$ , 95% CI [0.015, 0.029]. However, infants' negative affect at one time point did not predict their mothers' subsequent positive affect,  $\gamma_{90} = −0.003$ , 95% CI [−0.013, 0.007]. Contrary to expectations, mean infant RSA during free play did not predict the relation between infants' positive affect and their mothers' subsequent positive affect,  $\gamma_{61} = 0.004$ , 95% CI [−0.008, 0.014], or the relation between infants' negative affect and their mothers' subsequent positive affect,  $\gamma_{91} = 0.003$ , 95% CI [−0.010, 0.016]. Within-infant SD of RSA also did not predict the relation between infants' positive affect and their mothers' subsequent positive affect,  $\gamma_{62} = −0.006$ , 95% CI [−0.059, 0.054], or the relation between infants' negative affect and their mothers' subsequent positive affect,  $\gamma_{92} = −0.040$ , 95% CI [−0.099, 0.029].

#### Discussion

Capitalizing on recent methodological innovations, the current study evaluated RSA-based differences in concurrently unfolding,

dynamic emotion regulation and coregulation processes among low-income, Mexican-origin families. Guided by Porges' polyvagal theory (Porges, 2007) and biobehavioral theories of dynamic mother–infant emotion regulation processes (e.g., Feldman, 2015; Tronick, 1989), we expected infants with higher mean RSA and lower SD of RSA during free play to show unique, potentially adaptive concurrent processes of emotion regulation and emotion coregulation during mother–infant free play. As hypothesized, infants with higher mean RSA during free play showed (a) more volatility in positive affect, (b) specific affect feedback loops (such that they were more able to dampen negative affect after showing increased positive affect during the prior second and activate positive affect after showing increased negative affect during the prior second), and (c) stronger mother-driven emotion coregulation. In addition, as expected, infants with lower SD of RSA during free play showed (a) higher equilibrium of positive affect and lower equilibrium of negative affect and (b) stronger feedback between negative and positive affect, such that they were better able to dampen negative affect after showing increased positive affect. However, other hypotheses, including those about RSA-based differences in infant-driven emotion coregulation, were not supported.

### *Infant vagal functioning and emotion regulation processes*

#### *Aims 1a and 1b: Equilibria and volatility of infants' emotions*

According to polyvagal theory (Porges, 2001; Porges, Doussard-Roosevelt, & Maiti, 1994), higher infant vagal tone supports appropriate physiological and socioemotional responsiveness to changing contextual demands. However, contrary to theory-derived expectations, only variability in vagal functioning (indexed by within-infant SD of infant RSA) predicted infants' positive and negative affect equilibrium. In contrast, infant vagal tone during free play (indexed by within-infant mean RSA) predicted volatility in infants' positive affect; neither infant vagal tone nor variability during free play predicted volatility in infants' negative affect. Relative to vagal tone, appropriate vagal variability during a task may be more germane to infants' ability to maintain optimal overall wellbeing. The findings of this study build on prior research that examined associations between infant affect and behavior and change in global vagal functioning from a baseline to a challenging task. Capturing variability in infant vagal functioning closer to the temporal resolution on which vagal functioning is thought to operate advances understanding of how variability in vagal functioning during play influences concurrent affect expression.

Lack of support for hypotheses regarding volatility in infant negative affect is surprising given that prior work relying on global measures of affect frequency and intensity suggests that infants with higher vagal tone may be more likely to activate negative affect when frustrated (Calkins et al., 2002; Fox, 1989; Stifter & Fox, 1990; Stifter, Fox, & Porges, 1989). However, global measures capture between-infant differences in qualitative aspects of behavior, whereas the present study focused on volatility, or *intra-individual* variation, of infant's affect throughout the task and its association with concurrent vagal functioning. In addition, the present study focused on infant vagal functioning and affect during mother–infant free play, as these interactions offer insight into naturalistic patterns that may support infants' developing emotion regulation capabilities; however, we found low average levels of infant negative affect during free play and there may be larger fluctuations around negative affect during a stressful situation.

Nevertheless, volatility in infant positive affect bears important implications for infant and dyadic functioning. Following the broaden-and-build model of positive affect (Fredrickson, 2001), infants with higher vagal tone during free play (who show more flexible expressions of positive affect) and infants with lower vagal variability during free play (whose positive affect fluctuates around a higher equilibrium) may capitalize on positive affect to broaden their actions in the moment, contributing to more fluent social interactions and, in turn, greater opportunities for heightened positive affect (Ramsey & Gentzler, 2015).

#### *Aim 1c: Carryover in infants' emotions*

Based on the goals of shared positive affect and social engagement during free play, we expected infants with more context-appropriate vagal functioning would be able to (a) sustain deviations in positive affect for longer (e.g., exhibit slower return to emotional equilibrium, including maintaining periods of increased positive affect for longer) but (b) restore equilibrium in negative affect more quickly following a perturbation (e.g., exhibit more stable and predictable negative affect, based on prior negative affect). However, these hypotheses were not supported. One possible explanation for these null findings is that carryover in infants' affect during free play may not directly reflect emotion self-regulatory processes. Whereas results from prior research (e.g., Beebe et al., 2018) lend support to the interpretation of positive carryover in vocal affect as a valid index of infants' self-regulatory processes, research with adolescent and adult populations suggests carryover may represent a form of "emotional inertia" that confers risk for psychopathology (Kuppens, Allen, & Sheeber, 2010). Of note, our results are specific to second-by-second carryover in infant affect during free play. The meaning of carryover may differ depending on the time lag between assessments of affect, developmental stage, or the context in which affect is expressed. Drawing on dynamic systems theories, examination of emotional and physiological self-regulation may be extended by not only considering the temporal dynamics over which regulation unfolds, but also the balance between flexible responsiveness to changing environmental inputs and unpredictability, suggesting a moderate level of carryover may be most optimal, supporting well-organized yet also flexible responding during Mother × Infant interactions (Beebe et al., 2010).

#### *Aim 1d: Predictive relations between infants' emotions (feedback loops)*

Similar to processes of emotional carryover, feedback loops speak to the timing and degrees of reduction in infant affective expression; feedback processes also speak to potential causal emotion regulatory mechanisms *between* affect valence systems (Krone, Albers, Kuppens, & Timmerman, 2018). Guided by polyvagal theory, we expected infants with more context-appropriate vagal functioning (characterized by higher mean RSA and less variability in RSA during a play task) to show more context-appropriate emotion regulatory processes, as reflected in second-by-second feedback loops that include the ability to augment positive affect and blunt negative affect (Krone et al., 2018). As expected, among the infants with above average levels of mean RSA during free play, positive affect dampened subsequent negative affect (negative feedback) and negative affect activated subsequent positive affect (positive feedback). In other words, infants' physiological regulatory capacity during free play, as suggested by higher mean RSA, was associated with context-appropriate concurrent

emotional functioning that served to blunt negative affect and augment positive affect. In contrast, the infants who exhibited lower overall physiological regulatory capacity during free play (as indicated by relatively lower mean RSA) demonstrated the opposite pattern of feedback processes, such that their positive affect augmented negative affect and their negative affect dampened subsequent positive affect. Similarly, as expected, among infants with context-appropriate vagal variability during free play (relatively lower SD of RSA during free play), positive affect served to dampened subsequent negative affect, whereas, among infants with heightened vagal variability during free play (relatively higher SD of RSA during free play), positive affect actually augmented subsequent negative affect.

Although feedback loops reflect the *process* and not the content of infant behavior, our results raise questions about RSA-based differences in infant behavioral emotion regulatory strategies that give rise to the observed feedback processes. According to Cole et al.'s (2019) unifying model of self-regulation, children's executive processes, such as attention, memory, language, and reasoning, modify the ongoing ebb and flow of their emotion action tendencies (Cole et al., 2019). Future work is needed to evaluate whether infant regulatory strategy use (e.g., gaze aversion, thumb sucking) accounts for RSA-based differences in temporally-based emotion regulatory processes. Infants with relatively lower vagal tone (i.e., mean RSA) during free play, for whom positive affect exerts a counterproductive effect on negative affect, may rely on different, less sophisticated strategies (e.g., thumb sucking vs. social support seeking) to regulate their arousal and emotions. Alternatively, infants with lower vagal tone may be more susceptible to regulatory interference (Cole, Bendezú, Ram, & Chow, 2016), such that positive affect may be overwhelming and thus undermine the interplay between strategy use and emotion action responses.

### *Infant vagal functioning and mother-infant emotion coregulation*

#### *Aim 2: Biologically-based differences in dynamics of mother-infant coregulation*

Although emotion coregulation, or the synchronous coordination of caregivers' and infants' affect states, is thought to be foundational to children's development (Feldman, 2003), children may not be equally equipped to participate in coregulatory processes. As expected, in this study, only infants with greater physiological regulatory capacity reaped the benefits of mother-driven emotion coregulation. Among infants with higher vagal tone (i.e., mean RSA) during free play, maternal positive affect was positively related to subsequent infant positive affect and negatively related to subsequent infant negative affect, such that increases in their mother's positive affect augmented their subsequent positive affect and dampened their subsequent negative affect. The present results build on prior work suggesting that neonatal vagal tone is related to stronger mother-infant synchrony at child age 3 months (Feldman, 2006; Feldman & Eidelman, 2007) by demonstrating that infants' vagal tone during free play is associated with *simultaneously assessed* coregulatory processes. Further, our results elucidate that infants with higher mean RSA during free play are more likely to reap the benefits of increased maternal positive affect, rather than the alternative – that these infants elicit more maternal positive affect.

Surprisingly, although responsivity of the vagal brake during social interactions is thought to be a direct mechanism through

which vagal functioning supports social engagement and disengagement (Porges et al., 2019), variability in infant vagal functioning during free play was not associated with mother-driven emotion coregulation. Instead of infant vagal variability to contextual demands, it may be the interpersonal coherence of infants' and their mothers' physiology that acts as a proximal mechanism to promote emotion coregulation (e.g., Feldman, 2003, 2012). Similar to the concept of hidden regulators (Hofer, 1995), infants may detect changes in their mothers' physiological state, which in turn may influence the infants' physiological and emotional state (e.g., Feldman, Magori-Cohen, Galili, Singer, & Louzoun, 2011). Supporting Feldman's biobehavioral synchrony model (e.g., Feldman, 2003, 2012), mother-infant affective synchrony has been related to physiological synchrony (Feldman et al., 2011), although the limited extant work is correlational in nature. In order to uncover mechanisms that undergird emotion coregulation, work is needed to build on and extend empirical investigations of associations between mother-infant emotional and physiological synchrony, including examination of how fluctuations in mothers' and their infants' emotions and physiology are linked in real time.

Contrary to expectations, we found no evidence of RSA-based differences in infant-driven coregulation. Modeling mother- and infant-driven coregulation separately is consistent with theoretical accounts of emotional coregulation, which highlight the bidirectional coordination between mothers and their infants, although this approach may have resulted in reduced variability to detect between-dyad differences in infant-driven synchrony. Overall, when children are 6 months old, there may be more variability in how infants respond to their mothers than in how mothers respond to their infants. Alternatively, infant biological characteristics may be stronger predictors of their emotional responding than of their mothers'. In contrast, maternal psychosocial characteristics, including mental health, stress, parenting experience, and expectations about the child's behavior, may shape how mothers respond to their infants during real-time interactions. Given evidence of infant-driven emotion coregulation and the substantial between-dyad differences therein, it is imperative to identify which dyads are most likely to effectively manage infant affect and arousal levels, which has implications for the long-term health and wellbeing of both members of the dyad.

### *Strengths and limitations*

By focusing on second-by-second fluctuations in mothers' and infants' affect and infant vagal functioning, we were able to test novel theory-driven hypotheses about whether infant vagal tone and variability during free play account for between-dyad differences in the dynamic processes of emotion regulation and coregulation that unfold during these interactions. Our results challenge preexisting conceptions regarding mother-driven coregulation by demonstrating there is mutual bidirectional coordination of mother and infant positive affect. Our analysis of multivariate time series in DSEM also enabled us to elucidate between-dyad differences in several within-dyad regulatory processes. Consistent with Tronick's (1989) multimodal perspective that affect is expressed not only facially, but also vocally and bodily, and polyvagal theory's description of the social engagement system as an interconnected network of neural circuits that controls looking, listening, vocalizing, and facial gesturing (Porges, 2003), we employed a multidomain assessment of affect. Cultural norms and emotion socialization may also influence mothers' and

infants' emotion-related behaviors and expressions (e.g., Cole, Bruschi, & Tamang, 2002; Eisenberg, Spinrad, & Cumberland, 1998) and self-regulatory and coregulatory processes (e.g., Cole, 2016; Silk, 2019), supporting our multidomain assessment of affect rather than focusing on specific affective behaviors. In this work, assessment of mothers' and infants' affect occurred in an ecologically valid setting (the families' homes), in contrast to the majority of studies that evaluate relations between infant vagal tone and Mother  $\times$  Infant interactions in laboratory settings (Thayer, Hansen, & Johnsen, 2008).

However, several limitations are noteworthy in considering our findings. Consistent with prior work, in this study, the mothers exhibited little negative facial/vocal affect or disengagement during free play. Examining mothers' and infants' affective responding to tasks that are designed to elicit fear (e.g., simulations of interparental conflict) may offer a better opportunity to examine infants' response to maternal negative affect. The results from the present investigation may not generalize to negative interaction contexts, different developmental stages, children from different ethnic or socioeconomic backgrounds, or other child-caregiver relationships. Although the majority of empirical work, including the present investigation, has evaluated associations between vagal functioning and mother-infant emotion coregulation, vagal functioning may also be related with regulation in the context of other important relationships with other caregivers.

Heeding the call for examination of regulatory processes that operate in stable emotional systems (Butler & Randall, 2013), the present study assessed emotion regulation and coregulation processes that occur around stable equilibria in mothers' and infants' affect. However, the dynamic processes that undergird effective emotion regulation may differ from processes that give rise to emotional dysregulation in mother-infant dyads. Dysregulation may be best captured by processes that contribute to unstable emotional equilibria (i.e., morphogenic processes; Butler, 2011), such as negative coercive cycles that lead to increased negative affect. Whereas the results of our tests of stationarity suggested that almost all of the dyads in the study demonstrated stable emotional equilibria, infants with unstable negative affect equilibrium were more likely to have mothers who were born in the United States. These findings point to the need for future work on factors (e.g., acculturative stress) that may contribute to infant emotion dysregulation. Nonlinear dynamic models that do not assume stationarity could offer a complementary approach to evaluating infant emotion regulatory processes. It is also important to note that our results are specific to the time interval (1-s lag) employed in our analyses and may change if a different time interval is considered (Asparouhov et al., 2018). Rather than examining children's emotional responding across discrete time intervals, treating time as continuous, as in differential equations, may offer a complementary approach to examining dynamic, continuously unfolding regulatory processes, although these methods are not as well developed as discrete-time models (Cole et al., 2016; Hamaker, Cuelmans, Grasman, & Tuerlinckx, 2015). Similarly, our examination of context-appropriate vagal functioning was well suited for free play, a task with limited demands for infants to increase arousal. However, during stressful contexts in which infant vagal withdrawal may offer a less metabolically-costly mechanism to support adaptive responding, other dynamic measures of RSA variability (e.g., cardiac complexity, fractality; Berry, Palmer, Distefano, & Masten, 2019) may be more appropriate.

## Conclusions

Relative to their White peers, low-income Mexican-origin children are at elevated risk for future regulatory and interpersonal skills deficits and emotional and behavioral problems (e.g., Avila & Bramlett, 2013; Bird et al., 2001; Galindo & Fuller, 2010). In addition, poverty and poverty-related stressors may not only hinder children's developing emotion self-regulation, but may also compromise mothers' ability to be emotionally aware and skillful in responding to children's emotional cues (Cole, 2016). By examining dynamic fluctuations in infants' and mothers' affect during social interactions, this study illuminated temporally-based emotion regulation and coregulation processes, as well as differences in emotion regulatory and coregulatory processes, based on *concurrently assessed* dynamic infant vagal functioning among a sociodemographically at-risk sample. Consistent with dynamic biobehavioral theories of emotion coregulation (e.g., Feldman, 2003; Tronick, 1989), during free play, infants exhibited contingent responsiveness to changes in their mothers' positive affect and mothers similarly exhibited contingent responsiveness to changes in their infants' positive affect, providing novel evidence for bidirectional, second-by-second, emotion coregulation. Further, as anticipated by polyvagal theory (Porges, 2003), infants' biological regulatory capacity and rhythms appear to support aspects of infant emotion regulation and mother-driven coregulatory processes, including stronger mother-driven emotion coregulation among infants with higher mean vagal tone during free play. Micro-level emotion regulatory processes that unfold during Mother  $\times$  Infant interactions may serve as a proximal mechanism through which children's RSA-based differential responsiveness to maternal sensitive care affects developmental trajectories (Somers & Luecken, 2020). Studying processes of emotion regulation and coregulation in vulnerable populations may lead to new insights about *for whom* and *how* interaction patterns shape mothers' and their infants' emotional wellbeing.

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**Conflicts of Interest.** None.

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