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Infant Physiological Regulation and Maternal Risks as Predictors of Dyadic Interaction Trajectories in Families With a Preterm Infant

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This longitudinal study examined predictors of rates of growth in dyadic interaction quality in children born preterm who did not experience significant neurological findings during neonatal intensive care unit (NICU) hospitalization. Multiple methods were used to collect data from 120 preterm infants (48% girls, 52% boys) and their mothers. Infant heart rate variability (HRV), gestational age, neonatal health, feeding route, and maternal socioeconomic (SES) risks were assessed at NICU discharge (mean of 36 weeks postconception). Mother–child interactions were observed at 4, 9, 16, and 24 months postterm and analyzed with hierarchical linear modeling. On average, children's quality of play, interest, and attention increased over time while their dysregulation and irritability decreased, whereas average maternal positive affect and involvement declined in quality (*p*s $< .05$), although there was individual variation in rates of change. Mothers of infants with higher postfeeding HRV (i.e., vagal regulation) exhibited less decrease in positive affect and involvement between 4 months and 24 months, compared with mothers of infants with lower HRV ($p < .05$). Although infants with higher postfeeding HRV showed less positive affect and communication at 4 months, they exhibited significantly greater increases in positive affect and social competence and decreases in dysregulation and irritability between 4 months and 24 months, compared with infants with lower HRV (*p*s $< .05$). Dyads experiencing more SES risks showed less optimal interactions at 4 months; this difference remained as children grew older (*p*s $< .05$). Results have implications for our understanding of social development in preterm infants.

Keywords: interaction quality, HRV, preterm, risk

The rate of preterm birth (<37 weeks gestation) increased by 15% during the past decade, resulting in more than 500,000 preterm births per year in the United States (March of Dimes, 2006). As they grow older, infants born preterm experience elevated risk for developmental and behavioral problems (Bhutta, Cleves, Casey, Cradock, & Anand, 2002), although research is only beginning to elucidate pathways leading to these difficulties, especially for infants who appear healthy at discharge from the neonatal intensive care unit (NICU). In addition to infant factors such as prematurity level, quality of parent–child interactions is an important predictor of developmental problems and competencies for infants born preterm (e.g., C. A. Clark, Woodward, Horwood, & Moor, 2008; Smith, Landry, & Swank, 2006). Identification of early predictors of interaction quality is important because they may direct intervention efforts to preterm children who are most vulnerable to developing subsequent social problems. In the present study, we examined infant and maternal predictors of rates of growth in interaction skills between 4 months and 24 months in a sample of infants born preterm who did not experience significant neurological complications during the NICU stay.

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Theoretical Framework

Ecological models (Bronfenbrenner & Ceci, 1994; Sameroff & Fiese, 2000) provide the theoretical basis for this work. Ecological theories stress the importance of bidirectional influences at multiple contextual levels of development, emphasizing the importance of child factors, parenting processes, and socioeconomic (SES) influences. Biological factors, such as infant physiological regulation, are seen as key contributors to proximal processes, or the day-to-day interactions with parents that facilitate infant development (Bronfenbrenner & Ceci, 1994). In addition to biological processes, parental behaviors play a significant role in shaping such interactions, such as helping infants maintain states of alertness and positive affect while facilitating turn taking and affective regulation through modeling and through responding as infants and toddlers exhibit more social initiatives. In the present study, we examined several proximal predictors of child and maternal interaction trajectories over time for families of preterm infants, including biological factors (gestational age, neonatal health risks, infant heart rate variability [HRV]) and maternal factors (feeding route, SES risks).

Social Interaction Quality in Preterm Infants

Parent–child interaction quality is a robust predictor of developmental problems and competencies for infants born preterm, including emerging self-regulation (C. A. Clark et al., 2008), cognitive skills (Smith et al., 2006), and behavior problems (Poehlmann et al., in press). Infants born preterm show a more limited range of interactional skills and lower quality play compared with low risk full-term infants (Barnard, Bee, & Hammond, 1984; Korja et al., 2007; Landry, 1995; Macy, Harmon, & Easterbrooks, 1987). During early infancy, many preterm infants provide unclear distress signals, and in general, they are less alert, active, and responsive and more easily stressed and overstimulated than are low risk, full-term infants (Als, 1982; Eckerman, Oehler, Hannan, & Molitor, 1995; Field, 1987), suggesting that preterm infants may experience some level of physiological or behavioral dysregulation during dyadic social interactions. Although the interactive behaviors of infants born preterm are likely to improve over time as they attain various developmental milestones (e.g., motor and language skills), it is unclear how early biological risks, including physiological regulation and neonatal health, relate to children's interaction trajectories.

Infant Factors

Several infant factors are important to consider when examining interaction quality in preterm infants, including gestational age, birth weight, and physiological regulation. Several studies have shown that preterm infants born at lower birth weights, earlier gestational ages, or with elevated neonatal health complications typically exhibit more early interactional difficulties than do preterm infants with higher birth weights who are born closer to term or with fewer medical problems (Buka, Lipsitt, & Tsuang, 1992; Fiese, Poehlmann, Irwin, Gordon, & Curry-Bleggi, 2001; Landry, 1995; Poehlmann & Fiese, 2001). However, other studies of preterm infants have shown no association between neonatal medical risk and children's later social competence (e.g., Doussard-Roosevelt, Porges, Scanlon, Alemi, & Scanlon, 1997).

In preterm and full-term infants, previous research highlights infant physiological regulation as a key biological factor in early social and emotional development (Feldman, 2006; Feldman, 2009; Fox & Gelles, 1984; Stifter, Fox, & Porges, 1989). Infants born preterm are at risk for physiological dysregulation, often indexed as lower HRV, when compared with full-term infants (e.g., Longin, Gerstner, Schaible, Lenzm, & Konig, 2006). Although very low birth weight (VLBW; <1500 grams) preterm infants show an increase in HRV with increasing gestational age (Doussard-Roosevelt, Porges, & McClenny, 1996), no association between HRV and gestational age has been found in healthy preterms between 30 weeks and 36 weeks gestation (Cabal, Siassi, Zanini, Hodgman, & Hon, 1980).

HRV measures quantify fluctuations in the intervals between consecutive heartbeats and consecutive instantaneous heart rates (Task Force of the European Society of Cardiology & the North American Society of Pacing and Electrophysiology, 1996). During rest, the parasympathetic nervous system (PSNS) influences, or vagal tone, prevail as fluctuations in heart rate intervals depend largely on modulation by PSNS fibers in the vagus nerve. Although vagal pathways may originate in several areas of the brain stem, respiratory sinus arrhythmia (RSA) appears to be the product of vagal pathways stemming from the nucleus ambiguous (Porges, 1997). RSA is included within the high frequency (HF) band of HRV. Vagal cardiac neurons are inhibited during inspiration and appear to be mildly activated during the expiratory phase of respiration (Richter & Spyer, 1990; Saul, 1990; Saul & Cohen, 1994), and these changes can be quantified by HF HRV measures. Several HRV measures have been used with infants as indicators of physiological regulation and nervous system control of autonomic functioning, and recently, HRV has been conceptualized as an early physiological component of regulatory functioning in preterm infants (Feldman, 2009). In the present study, we assessed preterm infant vagal tone (the HF band of HRV during rest) and vagal regulation (the HF band of HRV following feeding). The HF HRV band includes RSA and reflects variation of heart periods that occur in a phasic relationship with inspiration and expiration.

Compared with lower vagal tone, higher vagal tone has been associated with appropriate developmental skills and emotional reactivity in infants (e.g., Fox & Gelles, 1984; Hofheimer, Wood, Porges, Pearson, & Lawson, 1995; Stifter & Fox, 1990). For example, 5-month old infants with higher vagal tone showed more frequent expressions of joy and interest and more frequent looking away during interactions with a stranger, compared with infants with lower vagal tone, although these associations were not present for 10-month old infants (Stifter et al., 1989). In addition, infants with lower vagal tone exhibit less negativity during negative tasks than did infants with higher vagal tone (Huffman et al., 1998), reflecting less emotionally appropriate engagement with the environment. HRV in full-term infants also has been associated with symmetry in mother–child interactions, with lower infant vagal tone associated with disruptive patterns of mother-child coregulation (Porter, 2003).

Researchers have documented associations between HRV and dyadic interactions in preterm infants as well. For instance, Feldman (2006) found that vagal tone during the neonatal period predicted mother–infant synchrony at 3 months in preterm infants. In addition, Feldman and Eidelman (2007) found that preterm infants with low vagal tone were less alert and received the least amount of maternal positive affect and gaze in the postpartum period and the least maternal touch at 3 months, compared with preterm infants with higher vagal tone. Vagal tone has also been associated with later developmental outcomes in preterm infants. Higher vagal tone in VLBW infants has been associated with more social competence at school age (Doussard-Roosevelt, McClenny, & Porges, 2001) and fewer behavior problems at age 5 years (Feldman, 2009). However, no studies with preterm infants have documented how early HRV (i.e., vagal tone or vagal regulation) relates to rates of growth in child social interactive skills over time.

In the present study, we assessed HRV in preterm infants during a prefeeding resting condition to examine vagal tone and also during a postfeeding condition to examine vagal regulation following a challenging but normative experience (feeding). For a preterm infant who is still hospitalized in the NICU, nipple feeding via breast or bottle can be a significant challenge (e.g., Comrie & Helm, 1997). Latching on to a nipple and coordinating suck–swallow–breathe reflexes may be challenging for preterm infants, as reflected in HRV measures (e.g., Brown, 2007). Several studies conducted with preterm or low birth weight infants have documented vagal suppression during feeding and vagal regulation or a "recovery" response following feeding, wherein the HF band of HRV rebounds, although not quite to prefeeding levels (e.g., Brown, 2007; Portales et al., 1997).

Maternal Factors

Previous research has shown that mothers of preterm infants are less actively involved with their newborns and engage in more negative dyadic interactions with their infants than do mothers of full-term infants (Beckwith & Cohen, 1980; DiVitto & Goldberg, 1979; Harrison & Magill-Evans, 1996), although it is unclear whether these patterns result from interacting with a less socially engaged baby or maternal stressors such as those related to SES.

Previous research has shown that fewer SES risks and more SES assets are associated with more maternal involvement and responsiveness in high risk children (Onufrak, Saylor, Taylor, Eyberg, & Boyce, 1995; Pelchat, Bisson, Bois, & Saucier, 2003). In addition, in a study of VLBW preterm infants, Doussard-Roosevelt and colleagues (1997) found that lower SES predicted less optimal child behavior regulation and social competence.

Feeding route is another important consideration because mother–child interaction quality has been shown to differ during breast and bottle-feeding. For example, Lavelli and Poli (1998) found that breastfeeding sessions were marked by more mutual touch and longer mutual gaze bouts within the dyad compared with those in bottle-feeding dyads. In addition, Else-Quest, Hyde, and Clark (2003) reported that infant–mother interaction quality at 12 months was more optimal for breastfed infants, compared with bottle fed infants, although no such difference existed at 4 months. Although both of these studies were conducted with samples of full-term infants, it is possible that feeding route may be related to interaction quality for preterm infants as well. Previous research has also shown that full-term breastfed infants exhibit higher HRV and vagal tone, compared with full-term bottle fed infants (Butte, O'Brian Smith, & Garza, 1991; DiPietro, Larson, & Porges, 1987; Jacob, Byrne, & Keenan, 2009), suggesting possible differences in early infant physiological regulation related to feeding that may also predict interaction quality.

Study Goals and Hypotheses

Previous research has documented the interactive challenges that preterm infants and their mothers frequently experience, and a number of studies have suggested the importance of examining such patterns over time, including how interactions are affected by early physiological and caregiving risks (e.g., Feldman & Edelman, 2007). Thus, the present study had three goals. First, rather than comparing preterm infants with full-term infants, the study sought to examine individual differences in dyadic interaction trajectories in preterm infants and their mothers at 4 months, 9 months, 16 months, and 24 months postterm. Although we expected that the average trajectory would increase (i.e., reflect improvements in interactional behaviors), we expected individual variation in trajectories over time. The second goal of the study was to examine infant gestational age, neonatal health risks, HRV, feeding route, and maternal SES risks as predictors of infant and maternal social interaction at 4 months and rates of change between 4 months and 24 months. We hypothesized that interaction trajectories would show greater increases over time for infants born later, infants with fewer neonatal health complications, infants exhibiting higher HRV prior to and following feeding, infants who were breastfed, and infants experiencing fewer maternal SES risks. The third goal of the study was to examine how maternal and infant interaction quality covaried over time. We expected that they would be strongly linked.

Method

Participants

A total of 120 infants and their mothers were drawn from a larger longitudinal study of families with infants born preterm or with a low birth weight (Poehlmann, Schwichtenberg, Bolt, & Dilworth-Bart, 2009). In the larger study, 181 mothers and their infants were recruited from three NICUs in southeastern Wisconsin between 2002 and 2005. A research nurse from each hospital invited families to participate in the study if (a) infants were born ≤35 weeks gestation or weighed <2500 grams at birth and (b) infants had no known congenital problems or significant neurological findings during the NICU stay (e.g., Down syndrome, Grade IV intraventricular hemorrhage, periventricular leukomalacia) or prenatal drug exposures and if mothers (c) were at least 17 years of age, (d) could read English, and (e) self-identified as the child's primary caregiver. For multiple births, one infant was randomly selected to participate in the study. Characteristics of participating families paralleled the population of Wisconsin during the years of data collection, although with more racial diversity in the sample.

The 120 infants in this subsample included those born preterm (≤36 weeks) who also completed the HRV recording prior to NICU discharge. The 120 infants did not significantly differ from the larger sample on any infant, maternal, or family variables except maternal employment. Mothers in this subsample were more likely to be employed than were mothers in the larger study. Although all of the study families spoke English, 10% spoke additional languages in their homes (mostly Spanish). Approximately 18% of the families lived in poverty (according to federal guidelines, adjusted for family size). Additional characteristics are presented in Table 1.

Infants and their families were assessed at five time points: just prior to the infant's NICU discharge (Time 1) and again at 4 months (Time 2), 9 months (Time 3), 16 months (Time 4), and 24 months (Time 5), corrected for prematurity. Corrected age was calculated on the basis of the infant's due date (DiPietro & Allen, 1991). At Time 1 data collection, infants ranged from 32 weeks to 44 weeks postconception age, with an average

Table 1
Sample Demographic Information

Item	*N*	Range	Frequency	%	*M*	*SD*
Infant						
Birthweight (grams)	120	564–3,328			1,752.33	581.53
NBW (>2,500 grams)			9	7		
LBW (<2,500 grams)			69	58		
VLBW (<1,500 grams)			23	19		
ELBW (<1,000 grams)			19	16		
Days in NICU	120	2–136			31.15	27.72
Gender (% female)	120		57	48		
Multiple birth[a]	120		23	19		
Racial heritage	120					
Caucasian			84	70		
African American			13	11		
Latina			2	2		
Asian			1	1		
More than one racial heritage			20	16		
Family						
Maternal						
Age (years)	120	17–42			29.92	6.30
Education (years)	120	8–21			14.28	2.56
Employment (% employed)	120		88	73		
Paternal						
Age (years)	120	19–44			31.43	6.29
Education (years)	118	7–21			13.88	2.81
Employment (% employed)	118		104	87		
Marital status (% Married)	120	85		71		
Income ($)	120	0–500,000			61,308	5,688
Living in poverty[b]	120		21	18		

Note. NBW = normal birthweight; LBW = low birthweight; VLBW = very low birthweight; ELBW = extremely low birthweight; NICU = neonatal intensive care unit.
[a] In multiple births, one infant was randomly chosen to participate. [b] Based on federal income levels adjusted for family size.

postconception age of 36 weeks (*SD* = 1.78). There was a 14% attrition rate across the 2 years of the study. Although mothers lost to attrition were younger, completed fewer years of education, and were more likely to be single and non-White than were mothers who completed the study, infants and families did not differ on any other health or demographic variables. Attrition rates were the same in the subsample as the larger study.

Procedure

An institutional review board-approved brochure was distributed to families in each NICU, and a research nurse from each hospital described the study to eligible families. Interested mothers returned the signed informed consent forms to nurses who alerted researchers when the infant was close to discharge. By appointment, a researcher met the mother at the NICU just prior to the infant's discharge to collect Time 1 data. At Time 1, mothers completed self-administered questionnaires including a demographic form, and infant HRV was recorded during a 10-min to 15-min resting period that occurred prior to feeding. Five electrodes were attached to the infant's chest with a two-channel ambulatory electrocardiogram (ECG) Holter monitor. Infant HRV was also recorded during feeding and for 20 min following feeding. Nurses completed a history of hospitalization form by reviewing the infant's medical records shortly after NICU discharge. Home visits were conducted with families when infants were 4 months and 9 months corrected age. At this visit, researchers asked mothers to complete self-administered questionnaires in addition to videotaping 15 min of mother–child play interactions, from which the first 5 min of active play were later coded. Mothers were asked to play with their infants as they normally would, using the materials and toys that were available in their homes. The home visits lasted approximately 1.5 hr, and mothers were paid $25 at the 4-months visit and $40 at the 9-months visit. When infants were 16 months and 24 months postterm, families visited our laboratory playroom. They were asked to play with their children as they normally would, using a standard set of developmentally appropriate toys. Subsequently, mothers completed self-administered questionnaires while their children participated in assessments. Each of the laboratory visits lasted 1.5– 2.5 hr. Mothers were paid $60 at the 16-months visit and $80 at the 24-months visit. See Table 2 for a summary of the longitudinal data collection used in the present study.

Measures

Mother and child play interactions. Infant–mother play interactions at 4 months (Time 2), 9 months (Time 3), 16 months (Time 4), and 24 months (Time 5) months postterm were coded with the Parent Child Early Relational Assessment (PCERA; R. Clark, 1985). Standard data collection recommendations for the PCERA include recording a 15-min play episode and coding 5 min of the video clip. Following the recommendation of Dr. Roseanne

Table 2
Data Collection From NICU to 2 Years Postterm and Descriptive Statistics for Level-2 (Person-Level) Predictors

Variable (Source)	NICU	4 Months	9 Months	16 Months	24 Months	Min	Max	*M*	*SD*	%
Outcome										
Parent–child interaction quality during play (videotaped observations coded with the PCERA)		X	X	X	X					
Infant factors										
Gestational age (review of medical records from NICU stay)	X					23.7	36.4	31.69	2.96	
Neonatal health risks (Review of medical records from NICU stay)	X					0	9	3.06	2.30	
Heart rate variability (ECG recordings using Holter monitor)	X									
HF prefeeding	X					1.87	5.55	3.43	0.87	
HF postfeeding	X					1.94	5.70	3.37	0.78	
Parent factors										
Socioeconomic risks (demographic questionnaire)	X					0	6	0.94	1.50	
Breastfeeding (observation/interview)	X									33.3

Note. The X denotes the time point at which these data were collected. PCERA = Parent-Child Early Relational Assessment; NICU = neonatal intensive care unit; Min = minimum; Max = maximum; ECG = electrocardiogram; HF = high frequency.

Clark, who developed the PCERA, the first 5 min in which each dyad was actively engaged in play were coded. Therefore, transitions from the previous task and initial toy or game set up were not coded.

The PCERA was designed to assess the frequency, duration, and intensity of affect and behaviors of parents and infants that occur during 5 min of face-to-face interactions. Each variable is coded on a scale ranging from 1 (*negative quality*) to 5 (*positive quality*). In the present study, we focused on the 29 parent variables and the 23 child variables that could be coded at all time points (five child variables cannot be coded for infants less than 6 months of age). Parental domains coded included tone of voice, affect and mood, attitude toward child, affective and behavioral involvement, and style. Child domains coded included mood and affect; adaptive abilities such as interest, attention, responding and initiating social behaviors, avoidance, and soothability; activity level; and communication (visual and vocal/verbal). Established parent and child subscales that have been used in previous research (e.g., Durik, Hyde, & Clark, 2000) were calculated. The three parent subscales were Positive Affect, Involvement, and Verbalizations (Parent Subscale 1), Negative Affect and Behavior (Parent Subscale 2; e.g., anger, criticism), and Intrusiveness, Insensitivity, and Inconsistency (Parent Subscale 3). The three child subscales were Positive Affect and Social and Communicative Competence (Child Subscale 1), Quality of Play, Interest, and Attention (Child Subscale 2), and Dysregulation and Irritability (Child Subscale 3). Items in each subscale are detailed in R. Clark (1985). Previous research has shown that although the parent subscales are correlated, they represent different aspects of parenting and relate to child outcomes in different ways. For example, in preterm infants who are easily distressed, parental expressions of anger or criticism (PCERA Parent Subscale 2) are associated with later toddler externalizing behavior problems, whereas intrusive and anxious parenting behaviors (PCERA Parent Subscale 3) are associated with later toddler internalizing behavior problems (Poehlmann et al., in press).

Table 3 presents subscale ranges, means, standard deviations, and internal consistency data for the PCERA at each time point. Cronbach's alphas were adequate for each subscale at each time point. Ten percent of the sample at each time point was independently coded by four trained research assistants, and interrater reliability ranged from .83 to .97 across codes and time points, with a mean of .88 (the PCERA standard).

The PCERA has an acceptable range of internal consistency, factor validity (R. Clark, 1999), and discriminate validity between high risk and well-functioning mothers (R. Clark, Paulson, & Conlin, 1993). The PCERA has been used previously with preterm infants (Brown, 2007; Pridham, Lin, & Brown, 2001) and has been linked to their subsequent developmental and behavioral outcomes (Poehlmann et al., in press).

Infant heart rate variability. Infant HRV was recorded prior to NICU discharge during a 10-min resting period prior to feeding, a feeding period, and a 20-min resting period following feeding (during which time infants had closed eyes, mostly regular breathing, and few movements). Short-term (e.g., 10–20 min) recordings of HRV are recommended for preterm infants because data can be obtained under constant conditions (Longin et al., 2006). Assessments of preterm infant HRV were obtained from a two-channel ambulatory ECG Holter recorder. ECG data were read by means of a MARS 5,000 Ambulatory ECG and Analysis System (General Electric, Milwaukee, WI). Analyses of ECG data were conducted by Jill Winters, an HRV expert who specializes in spectral analyses of such data. ECG data were recorded and digitized at 128 samples per second. The cubic spline interpolated RR interval (the time measurement between the R wave of one heartbeat and the R wave of the preceding heartbeat) function was sampled at 1,024 samples per 300 s, or 3.4 samples per second. This sampling rate translates to the highest observable frequency of HRV being 1.707 Hz.

Initially, each ECG complex was identified as to its morphology by computer software. Then, each recording was overread and edited to ensure proper identification of location and morphology

Table 3
Descriptive Statistics for PCERA Subscale Scores at Each Time Point

Statistic	Parent Subscale 1: Positive Affect, Involvement, & Verbalization	Parent Subscale 2: Negative Affect & Behavior	Parent Subscale 3: Intrusiveness, Insensitivity, & Inconsistency	Child Subscale 1: Positive Affect & Social & Communicative Competence	Child Subscale 2: Quality of Play, Interest, & Attention	Child Subscale 3: Dysregulation & Irritability
No. of items	11	5	8	8	9	5
4 months						
M	3.97	4.39	3.98	3.47	3.85	3.44
SD	0.63	0.55	0.58	0.72	0.66	0.46
Min	1.82	2.80	2.38	1.13	1.11	2.00
Max	5.00	5.00	5.00	5.00	5.00	4.00
α	.91	.86	.83	.91	.89	.77
9 months						
M	3.67	3.98	3.70	3.51	3.94	4.30
SD	0.75	0.75	0.60	0.64	0.52	0.63
Min	1.91	1.40	2.25	1.75	2.22	1.00
Max	4.91	5.00	4.75	4.63	4.78	5.00
α	.94	.91	.84	.88	.84	.90
16 months						
M	3.60	4.30	3.90	3.51	4.13	4.57
SD	0.60	0.56	0.40	0.59	0.42	0.50
Min	2.00	2.60	2.88	2.06	2.22	2.80
Max	4.73	5.00	4.75	4.75	5.00	5.00
α	.90	.90	.70	.87	.79	.84
24 months						
M	3.72	3.81	3.92	3.63	4.00	4.41
SD	0.64	0.74	0.52	0.67	0.49	0.55
Min	2.00	2.00	2.25	2.13	2.78	2.40
Max	4.91	5.00	5.00	4.88	5.00	5.00
α	.89	.89	.78	.85	.78	.81

Note. On all subscales, higher scores indicate more positive interactions (e.g., higher scores on Child Subscale 3: Dysregulation and Irritability reflect less dysregulation and irritability). Min = minimum; Max = maximum; PCERA = Parent-Child Early Relational Assessment.

of each ECG complex.[1] Computer software (MARS Unity Workstation Heart Rate Variability, Version 4) was then used to determine all RR intervals for ECG complexes originating in the sinoatrial (SA) node. Ectopic ECG complexes, artifact, and missed triggers were not included in the analyses because these do not reflect autonomic modulation of the SA node. A priori, it was determined that recordings with more than 10% unusable data would not be used in the analyses. No recording with usable data had greater than 1% ectopy, artifact, and/or missed triggers. To determine frequency-domain measures of HRV, power spectrum analysis with fast Fourier transform was performed on the edited ECG recordings.

Power spectrum analysis quantifies components in terms of their relative density or power within specified frequency bandwidths. Fast Fourier transform analysis provides a spectral density plot of high and low frequency power as a function of heart rate frequency. Spectral activity is expressed as the absolute power (milliseconds squared) in the high and low frequency bands (Pomeranz et al., 1985). PSNS influences are typically seen in the HF range (Beauchaine, 2001; Task Force of the European Society of Cardiology & the North American Society of Pacing and Electrophysiology, 1996). A Hanning window, also known as a raised cosine window, was used to perform the spectral analysis. This window allows spectral coefficients to be scaled to properly account for the attenuation of signal energy due to the window. We selected an HF bandwidth of 0.15 Hz to 1.10 Hz, similar to Longin et al. (2006) and Pizur-Barnekow, Kraemer, and Winters (2008), to capture the entire HF spectrum for premature infants, who tend to have rapid respiration rates. This band captures respiratory rates of 9–66 breaths per minute. The width of the HF band was determined for each participant, based on respiratory rates collected by the data collectors. The band was expanded to include the entire spectra of RSA.

Measurement of HRV via spectral analysis is a widely used, noninvasive measure of autonomic nervous system activity that estimates regulatory processes that cannot be observed directly in

[1] Cardiology experts have come to some consensus in the past 15 years regarding the assessment and analysis of HRV data, concluding that when using frequency- or time-domain measures,

> the complete signal should be carefully edited using visual checks and manual corrections of individual RR intervals and QRS complex classifications. Automatic "filters" based on hypotheses on the logic of RR interval sequence (e.g., exclusion of RR intervals according to a certain prematurity threshold) should not be relied on when ensuring the quality of the RR interval sequence. (p. 365, Task Force of the European Society of Cardiology & the North American Society of Pacing and Electrophysiology, 1996)

The recommended editing methods were used in the present study, similar to other recent infancy research (e.g., Brown, 2007; Pizur-Barnekow et al., 2008). In contrast, techniques that prevent the researcher from accessing and carefully editing the raw data (i.e., "black box" methods that are sometimes used in the field of infant development) may be problematic.

a noninvasive manner (Beauchaine, 2001). Variation of heart periods occur in a phasic relationship with inspiration and expiration because vagal cardiac neurons are inhibited during inspiration and appear to be mildly activated during the expiratory phase of respiration (Richter & Spyer, 1990; Saul, 1990; Saul & Cohen, 1994).

In the present study, we used two HRV variables: (a) HRV HF during the prefeeding resting period as a reflection of early vagal tone and (b) HRV HF during the postfeeding period as a reflection of early vagal regulation.[2] Because 22 (18%) of the prefeeding recordings did not last for a full 10 min as a result of the infants becoming hungry, the observations were coded as missing, and a multiple imputation procedure was used to address missingness (see below). Table 2 presents ranges, means, and standard deviations for predictor variables. HRV during pre- and postfeeding were correlated, $r(120) = .65$, $p < .001$, and thus entered in separate analyses.

Infant prematurity and neonatal health. Infant birth weight and gestational age were collected from infant NICU medical records. These variables were highly correlated, $r(120) = .87$, $p < .001$, so we chose one variable to use in the analyses. We chose gestational age because of its relation to HRV in preterm infants (Doussard-Roosevelt et al., 1996).

To create a neonatal health risk index (used in previous research with preterm infants; Poehlmann et al., 2010), we summed 10 medical variables, each dichotomized into 1 if present and 0 if absent: apnea, respiratory distress, chronic lung disease, gastroesophageal reflux, multiple birth, supplementary oxygen at NICU discharge, apnea monitor at discharge, 5-min Apgar score less than 6, ventilation during NICU stay, and more than 30 days hospitalization. Higher scores indicated more neonatal health risks. Cronbach's alpha was .70.

Feeding route. Mothers were asked to feed their infants during the second part of the HRV recording. On the basis of our observations of the first 10–15 min of feeding, we coded the feeding as a 1 if mothers ever breastfed their infants ($n = 40$, 33.3%) and a 0 if mothers exclusively bottle-fed their infants ($n = 80$, 66.7%). According to interviews, mothers who indicated that they ever breastfed their newborns during the NICU stay did so during the recording.

Socioeconomic risks. Mothers completed a demographic questionnaire at the NICU visit (Time 1). On the basis of previous research with children with a multiple risk model (e.g., Burchinal, Roberts, Hooper, & Zeisel, 2000), one point was given for each of the following risks: family income was below federal poverty guidelines adjusted for family size, both parents were unemployed, the mother was single, the mother gave birth to the target child as a teen, the family had four or more dependent children, the mother did not complete high school, and the father did not complete high school. This index could range from 0 to 7, with higher scores reflecting more SES risks. Cronbach's alpha was .75. Family SES risks at all other time points were highly correlated with NICU SES risks; we used the NICU SES risk index to minimize missing data.

As noted, missing values existed for some variables. To address this, we used a multiple imputation procedure that generated five datasets, in which missing values for all person-level variables (e.g., prefeeding HRV) were randomly generated conditional on all other person level variables in the analysis (SPSS Version 16.0). Subsequent modeling procedures were applied to all five datasets, with aggregated results reported for the final prefeeding HRV models.

Results

Variables were screened for outliers and violations of distributional assumptions (Raudenbush & Bryk, 2002). No transformations or removal of outliers was necessary.

We used two-level hierarchical linear models to study individual change in mother and child interaction quality over time (Raudenbush & Bryk, 2002; Raudenbush, Bryk, & Congdon, 2005). The Level-1 (unconditional) model specified individual change (i.e., intercept and linear growth rate) in each PCERA subscale. The Level-2 models explained variability in individual change with maternal and infant variables (labeled maternal and child models below). Finally, a model was specified to assess the covariation between mother and child trajectories over time. Restricted maximum likelihood estimation was used in all models, with robust standard errors with generalized estimating equations (GEE; Liang & Zeger, 1986) used in performing significance tests. Separate models were run for HRV prefeeding and postfeeding and for each PCERA subscale.

Unconditional Models

We examined unconditional models to quantify variance in trajectory parameters across the PCERA Parent and Child subscales. These models included the Level-1 predictor of time (i.e., months) but no predictors at the individual level. Mothers showed significant variability with respect to the intercept (i.e., 4-month interaction quality) for Parent Subscales 1: Positive Affect, Involvement, and Verbalizations, $\chi^2(114) = 196.98$, p $< .001$, and 3: Intrusiveness, Insensitivity, and Inconsistency, $\chi^2(114) = 157.84$, p $< .01$, but not for Parent Subscale 2: Negative Affect and Behavior, $\chi^2(114) = 119.49$, p $= .34$. Children showed such variability with respect to the intercept for Child Subscales 1: Positive Affect and Social and Communicative Competence, $\chi^2(114) = 162.70$, p $< .01$, and 2: Quality of Play, Interest, and Attention, $\chi^2(114) = 162.87$, p $< .01$, but not for Child Subscale 3: Dysregulation and Irritability, $\chi^2(114) = 92.90$, p $> .5$. These findings suggest that some of the mother and child intercept parameters may possess variability that can be explained by Level-2 predictors.

In regard to the effects of time (slopes), results from the unconditional models were used to evaluate both the average and variability of slopes across persons. The average slopes for Parent Subscales 1 and 2 significantly differed from 0 in a negative direction, $t(119) = -3.37$, $p < .05$, and $t(119) = -6.34$, $p < .05$, respectively, whereas the average slope for Parent Subscale 3 did not significantly differ from 0, $t(119) = .44$, $p = .66$. In contrast, the average slopes for Child Subscales 2 and 3 significantly differed from 0 in a positive direction, $t(119) = 2.43$, $p < .05$, and $t(119) = 12.73$, $p < .05$, respectively, whereas the average slope

[2] We also calculated change in HRV HF between prefeeding and feeding and between feeding and postfeeding; because these variables were unrelated to interaction quality, they were omitted from our final models.

for Child Subscale 1 did not significantly differ from 0, $t(119) = 1.66$, $p = .10$.

Chi-square tests suggested significant variability in the slopes for Child Subscales 1, $\chi^2(114) = 149.81$, $p < .01$, and 2, $\chi^2(114) = 143.23$, $p < .05$, but neither for Child Subscale 3, $\chi^2(114) = 92.89$, $p > .5$, nor for any maternal subscales, $\chi^2(114) = 107.95$, $p > .5$, $\chi^2(114) = 101.53$, $p > .5$, $\chi^2(114) = 104.17$, $p > .5$ (Parent Subscales 1–3, respectively). These results suggest potential to find significant predictive effects related to slopes for children but limited potential to identify such predictors for mothers.

Maternal Models

For each maternal PCERA subscale, we studied two models: HRV during prefeeding (i.e., vagal tone) as a predictor and HRV during postfeeding (i.e., vagal regulation) as a predictor. The direction of effects seen for the pre- and postfeeding was the same, although only postfeeding HRV reached statistical significance. Findings for the postfeeding HRV maternal models are presented in Table 4 and discussed below.

PCERA Parent Subscale 1: Positive Affect, Involvement, and Verbalizations. Examination of the coefficients and associated *t* tests indicated that HRV significantly predicted mothers' slopes. As shown in Table 4, higher infant vagal regulation corresponded to a less negative slope. Figure 1a illustrates the nature of the HRV effect on Parent Subscale 1 for a hypothetical mother at a level of 0 on all other predictors, namely, a mother with a bottle-fed child in the lowest SES risk and health risk categories and approximately at the sample mean for gestational age. The two trajectories thus distinguish mothers of this type who had children who were 1 standard deviation above versus below the mean in terms of vagal regulation. The magnitude of the effect can be interpreted in comparison with the variability of slopes observed for this subscale in the unconditional model. Specifically, a 1 standard deviation increase in HRV corresponded to a 2.55 standard deviation decrease in the slopes; although seemingly sizable, this effect should be understood in reference to the relatively small variability in slopes found for this subscale in the unconditional analyses.

Figure 1b illustrates the significant effect found for SES risk on the intercepts for Parent Subscale 1, suggesting that mothers experiencing fewer SES risks showed more positive affect, involvement, and verbalizations during interactions with their children at 4 months, compared with mothers experiencing more SES risks, effects that tended to be sustained over time as a result of negligible effects of SES risk on the slopes. Specifically, 1 standard deviation increase in SES risk corresponded to a 0.62 standard deviation decrease in the intercept.

In addition, mothers of preterm infants with more neonatal health risks exhibited more positive affect, involvement, and verbalizations during interactions at 4 months than did mothers of preterm infants with fewer neonatal health risks. Figure 1c illustrates the effect. In this instance, a 1 standard deviation increase in health risks corresponded to a 0.42 standard deviation increase in the intercept. No other variables predicted maternal intercepts or slopes.

PCERA Parent Subscale 2: Negative Affect and Behavior. For Parent Subscale 2, feeding route was a significant predictor of the slope, with mothers who breastfed their infants at least some of the time during the NICU stay showing less decline in the PCERA Negative Affect and Behavior Score (indicating fewer negative behaviors over time) between 4 months and 24 months postterm, compared with mothers who exclusively bottle fed. The difference in slopes for the two curves represents a 1.24 standard deviation difference with respect to the overall variability of slopes. However, this seemingly large effect should be understood in reference to a relatively small amount of overall variability in the slopes across mothers.

PCERA Parent Subscale 3: Intrusiveness, Insensitivity, and Inconsistency. The patterns of results observed for Subscale 3 were largely the same as those observed for Subscale 1 (although

Table 4
Linear Estimates for Maternal Models: HRV HF Postfeeding

	Parent Subscale 1: Positive Affect, Involvement, & Verbalizations				Parent Subscale 2: Negative Affect & Behavior				Parent Subscale 3: Intrusiveness, Insensitivity, & Inconsistency			
Variable	Coefficient	*t*	*df*	*p*	Coefficient	*t*	*df*	*p*	Coefficient	*t*	*df*	*p*
B00												
Intercept	2.78	3.51	114	.001	3.23	4.91	114	<.001	3.09	4.89	114	<.001
SES risk	−0.16	−4.16	114	<.001	−0.05	−1.59	114	.115	−0.13	−4.36	114	<.001
Feeding route	0.05	0.46	114	.645	−0.10	−1.12	114	.265	0.04	0.48	114	.630
Gestational age	0.03	1.47	114	.145	0.03	1.53	114	.128	0.02	1.05	114	.296
Neonatal health	0.07	2.64	114	.010	0.03	1.30	114	.196	0.06	2.36	114	.020
HRV HF	−0.02	−0.31	114	.757	0.05	0.92	114	.360	0.03	0.53	114	.595
B10												
Intercept	−0.05	−0.83	114	.409	−0.04	−0.72	114	.471	−0.02	−0.34	114	.733
SES risk	0.00	1.03	114	.305	−0.00	−1.10	114	.276	0.00	1.15	114	.254
Feeding route	0.00	0.44	114	.657	0.02	2.59	114	.011	0.01	0.86	114	.394
Gestational age	0.00	0.07	114	.946	−0.00	−0.05	114	.959	0.00	0.28	114	.780
Neonatal health	−0.00	−0.48	114	.628	0.00	0.21	114	.838	−0.00	−1.20	114	.233
HRV HF	0.01	2.03	114	.044	0.01	1.10	114	.275	0.00	0.67	114	.503

Note. $N = 115$. B00 = intercepts in the HLM model; B10 = slopes in the HLM model; HRV = heart rate variability; HF = high frequency; SES = socioeconomic status.

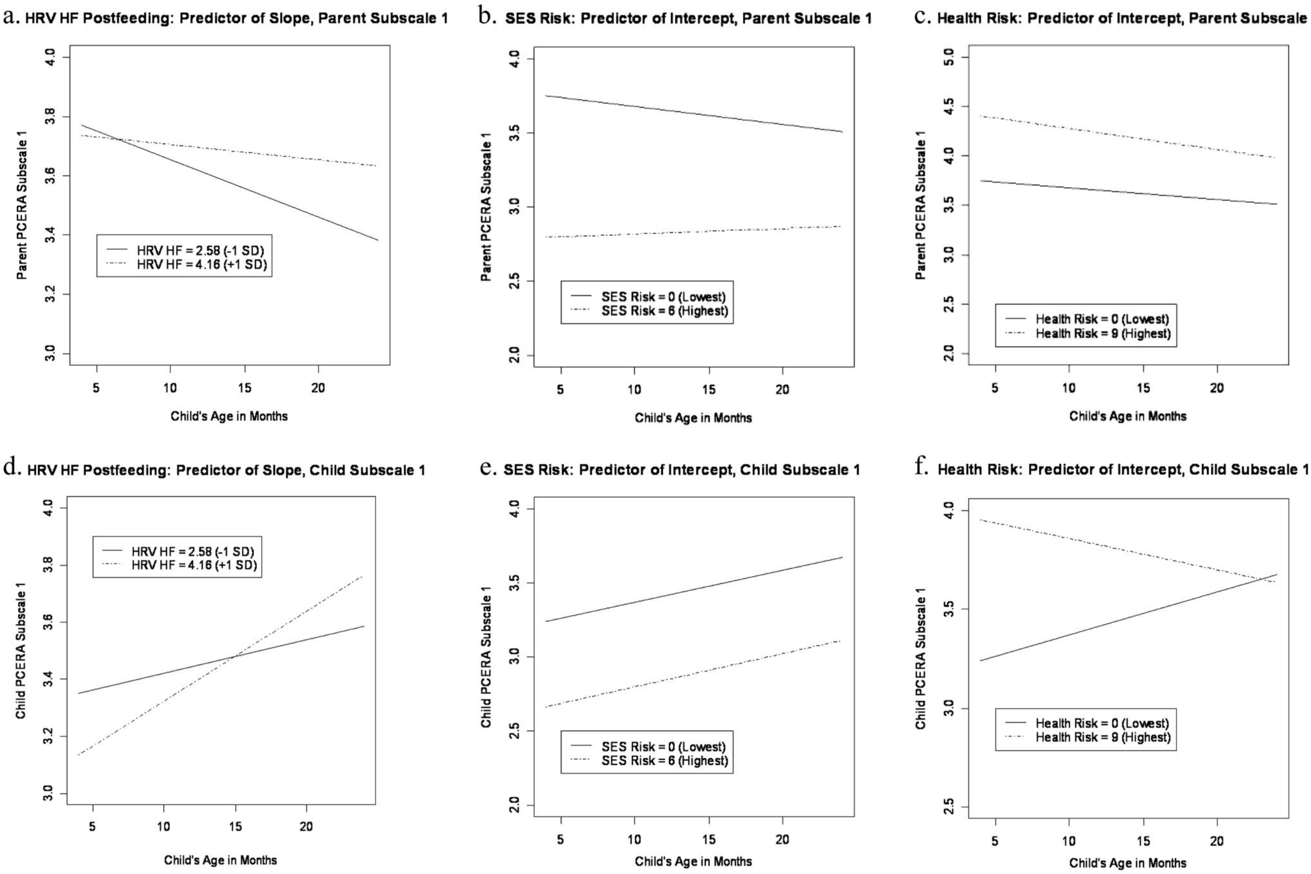

Figure 1. Mother and child interactive trajectories between 4 months and 24 months postterm for Parent Subscale 1: Positive Affect, Involvement, and Verbalizations and Child Subscale 1: Positive Affect and Social and Communicative Competence. HRV = heart rate variability; HF = high frequency; SES = socioeconomic status; PCERA = Parent Child Early Relational Assessment.

HRV did not affect the slope). Mothers experiencing fewer SES risks showed less intrusiveness, insensitivity, and inconsistency during interactions with their preterm infants at 4 months, compared with mothers experiencing more SES risks, effects that tended to be sustained over time as a result of negligible effects of SES risk on the slopes. In this instance, a 1 standard deviation increase in SES risk corresponded to a 0.73 standard deviation decrease in the intercept. In addition, mothers of preterm infants with more neonatal health risks exhibited less intrusiveness, insensitivity, and inconsistency during interactions at 4 months than did mothers of preterm infants with fewer neonatal health risks. A 1 standard deviation increase in health risk corresponded to a 0.47 standard deviation increase in the intercept. No other variables predicted maternal intercepts or slopes for Parent Subscale 3.

Child Models

Like the maternal models, we studied two models for each PCERA child subscale: infant vagal tone as a predictor and infant vagal regulation as a predictor. The findings for the models were again similar, and again vagal tone did not reach statistical significance. Findings for vagal regulation are presented in Table 5 and discussed below.

PCERA Child Subscale 1: Positive Affect and Social and Communicative Competence. Examination of the coefficients and associated *t* tests indicated that HRV predicted children's slopes and intercepts. Although infants with higher vagal regulation exhibited less optimal positive affect and communication at 4 months, they also showed significantly greater increases in positive affect and social and communicative competence over time, so that by the toddler period, their skills exceeded those of infants with lower vagal regulation.

Like the mother models, Figure 1d illustrates the nature of the HRV effect on Child Subscale 1 for a hypothetical child at a level of 0 on all other predictors, namely, a bottle-fed child in the lowest SES risk and health risk categories and at approximately the sample mean for gestational age. One standard deviation increase in vagal regulation corresponded to 0.43 standard deviation increase in slope.

Figure 1e similarly displays the significant effect seen for the SES risk index in relation to the children's intercepts (with HRV now fixed to its mean of 3.37); children experiencing

Table 5
Linear Estimates for Child Models: HRV HF Postfeeding

Variable	Child Subscale 1: Positive Affect & Social & Communicative Competence				Child Subscale 2: Quality of Play, Interest, & Attention				Child Subscale 3: Dysregulation & Irritability			
	Coefficient	*t*	*df*	*p*	Coefficient	*t*	*df*	*p*	Coefficient	*t*	*df*	*p*
B00												
Intercept	2.31	2.62	114	.010	2.38	3.57	114	.001	3.99	5.59	114	<.001
SES risk	−0.10	−2.56	114	.012	−0.09	−2.54	114	.013	−0.04	−1.52	114	.131
Feeding route	0.16	1.45	114	.149	−0.02	−0.16	114	.871	0.03	0.39	114	.697
Gestational age	0.04	1.77	114	.079	0.05	2.46	114	.015	0.01	0.34	114	.735
Neonatal health	0.08	2.42	114	.017	0.05	1.88	114	.063	−0.02	−0.70	114	.484
HRV HF	−0.14	−2.15	114	.033	−0.03	−0.48	114	.628	−0.10	−1.95	114	.053
B10												
Intercept	0.01	0.13	114	.893	0.05	0.89	114	.375	−0.00	−0.05	114	.959
SES Risk	0.00	0.35	114	.726	0.00	0.47	114	.637	−0.00	−0.22	114	.827
Feeding Route	−0.01	−0.82	114	.416	0.01	0.98	114	.330	−0.00	−0.32	114	.749
Gestational Age	−0.00	−0.44	114	.658	−0.00	−1.08	114	.284	0.00	0.05	114	.438
Neonatal Health	−0.00	−1.52	114	.132	−0.00	−1.09	114	.276	0.00	0.78	114	.447
HRV HF	0.01	2.47	114	.015	0.01	1.43	114	.155	0.01	2.79	114	.007

Note. $N = 115$. B00 = intercepts in the HLM model; B10 = slopes in the HLM model; HRV = heart rate variability; HF = high frequency; SES = socioeconomic status.

fewer SES risks showed more optimal interactions with their mothers at 4 months, compared with children experiencing more SES risks, a difference that was largely sustained across time as a result of the negligible effect of SES risk on the slope. Again, in reference to the unconditional model, a 1 standard deviation increase in SES corresponded to a 0.48 standard deviation decrease in the intercept.

Unexpectedly, preterm infants with more neonatal health risks showed more positive affect and social and communicative behaviors during interactions with their mothers at 4 months,compared with preterm infants with fewer health risks. Figure 1f illustrates the effect in reference to the highest and lowest possible health risk categories. Although the effect of health risk on the slope was not statistically significant, it appears that the effect of health risk was largely driven by differences at an early age (that were not maintained over time). A 1 standard deviation increase in health risk corresponded to a 0.58 standard deviation increase in the intercept.

PCERA Child Subscale 2: Quality of Play, Interest, and Attention. None of the variables examined predicted children's slopes for Subscale 2. However, gestational age and SES risks predicted children's intercepts. Preterm infants born closer to term had higher quality play, interest, and attention during interactions with their mothers at 4 months postterm than did preterm infants born earlier. Specifically, a 1 standard deviation increase in gestational age corresponded to 0.54 standard deviation increase in the intercept. Moreover, children experiencing more SES risks exhibited poorer quality play, interest, and attention at 4 months than did children experiencing fewer SES risks. A 1 standard deviation increase in SES risk corresponded to a 0.51 standard deviation decrease in the intercept.

PCERA Child Subscale 3: Dysregulation and Irritability. Infant vagal regulation predicted children's slopes on Subscale 3, with higher vagal regulation associated with more positive slopes, implying a significantly greater reduction over time in dysregulated behavior and irritability. The effect is quite sizable. In reference to the unconditional model, a 1 standard deviation increase in vagal regulation corresponded to a 1.04 standard deviation increase in the slopes. No other variables predicted Subscale 3 intercept or slope.

Covariation in Child and Maternal PCERA Subscale Trajectories

Table 6 reports results of the multivariate model jointly analyzing all six subscales and their trajectories over time. As the model included no person-level predictors, results in terms of the mean slope and mean intercept, as well as the slope and intercept variances, are similar to those seen in the unconditional analyses described earlier. Of greater interest are the correlations between parent–child intercepts and parent–child slopes across subscales. In regard to subscale intercepts, across all six subscales, the correlations were positive and statistically significant, as expected. There was, however, noticeable variability in the size of correlations, with Parent Subscale 2 Negative Affect and Behavior appearing to show lower correlations in the intercept, with both the other parent subscales and the child subscales. A similar pattern of results was seen in the slope correlations across subscales, such that change in Parent Subscale 2 appeared more differentiated from change in the other subscales.

Discussion

In this prospective longitudinal study of preterm infants, we found that on average, children's quality of play, interest, and attention improved between 4 months and 24 months postterm, whereas average levels of dysregulation and irritability declined. However, there was significant variability in individual rates of

Table 6

Fixed and Random Effect Estimates for Trajectory Covariation Model

Parameter	Coefficient	*T*	*df*	*p*	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11
Fixed effect parameter estimates															
G10, Slope, Parent Subscale 1	−0.011	−2.862	119	.005											
G20, Intercept, Parent Subscale 1	3.831	66.707	119	<.001											
G30, Slope, Parent Subscale 2	−0.021	−5.800	119	<.001											
G40, Intercept, Parent Subscale 2	4.311	92.120	119	<.001											
G50, Slope, Parent Subscale 3	0.001	0.385	119	.700											
G60, Intercept, Parent Subscale 3	3.854	77.279	119	<.001											
G70, Slope, Child Subscale 1	0.007	1.609	119	.110											
G80, Intercept, Child Subscale 1	3.456	61.484	119	<.001											
G90, Slope, Child Subscale 2	0.009	2.129	119	.035											
G100, Intercept, Child Subscale 2	3.895	75.730	119	<.001											
G110, Slope, Child Subscale 3	0.044	11.895	119	<.001											
G120, Intercept, Child Subscale 3	3.766	85.481	119	<.001											
Correlation															
U1, Slope, Parent-1					—										
U2, Intercept, Parent-1					−.48*	—									
U3, Slope, Parent-2					.62*	.01	—								
U4, Intercept, Parent-2					−.25*	.69*	.14	—							
U5, Slope, Parent-3					.96*	−.58*	.69*	−.39*	—						
U6, Intercept, Parent-3					−.43*	.96*	.07	.86*	−.55*	—					
U7, Slope, Child-1					.93*	−.46*	.43*	−.32*	.88*	−.43*	—				
U8, Intercept, Child-1					−.85*	.78*	−.29*	.41*	−.82*	.71*	−.75*	—			
U9, Slope, Child-2					.98*	−.46*	.54*	−.35*	.94*	−.45*	.96*	−.81*	—		
U10, Intercept, Child-2					−.86*	.67*	−.33*	.40*	−.81*	.64*	−.73*	.98*	−.83*	—	
U11, Slope, Child-3					.86*	−.39*	.74*	−.44*	.91*	−.44*	.73*	−.68*	.86*	−.74*	—
U12, Intercept, Child-3					−.82*	.63*	−.31*	.54*	−.80*	.66*	−.71*	.91*	−.83*	.96*	−.79*

Note. $N = 120$. Child-1 = Positive Affect and Social and Communicative Competence; Child-2 = Quality of Play, Interest, and Attention; Child-3 = Dysregulation and Irritability; Parent-1 = Positive Affect, Involvement, and Verbalizations; Parent-2 = Negative Affect and Behavior; Parent-3 = Intrusiveness, Insensitivity, and Inconsistency.

* $p < .01$, based on Fisher r-to-z approximation.

change in such skills, and this individual variation was predicted by infant vagal regulation assessed during the NICU stay.

Unlike previous research in the infant literature, prefeeding resting HRV (i.e., vagal tone) did not reach statistical significance in the models predicting child or maternal interaction quality. Rather, postfeeding vagal regulation significantly predicted rates of growth in child and maternal interaction quality over time. Infant physiological adaptation following the normative but challenging feeding experience for preterm infants during the NICU stay predicted decreases in infant dysregulation and irritability as well as rates of gain in infant positive affect and social and communication skills during dyadic play between 4 months and 24 months postterm. Although children with higher vagal regulation during postfeeding showed less optimal positive affect and communication at 4-months postterm, they also showed significantly greater improvements in positive affect and communication as well as significantly greater decline in dysregulation and irritability than did children with lower vagal regulation, suggesting continuing effects of individual differences in early physiological regulation beyond that of gestational age or medical risk in this sample of preterm infants who did not have significant neurological findings during the NICU stay. In addition, mothers of preterm infants showed significantly less decrease in their positive affect, involvement, and verbalizations over time when infants exhibited higher postfeeding vagal regulation during the NICU stay.

Feldman (2007) has discussed the role of biological foundations of mother–infant interactions, which has implications for children's subsequent social development. Feldman's research has documented links between lower vagal tone in preterm infants and maternal interaction quality, including mother–infant synchrony (Feldman, 2006; Feldman & Eidelman, 2007). However, in previous studies, researchers have not examined vagal tone in relation to rates of growth in infant or maternal social interaction over time. In the present study, although vagal tone in the prefeeding condition was not significantly associated with rates of growth in interaction quality, postfeeding vagal regulation predicted infant and maternal trajectories. We speculate that higher vagal regulation during the postfeeding period may have helped to dissipate the stress response associated with feeding in preterm infants, suggesting greater adaptability to environmental challenges. The HF band of postfeeding HRV, which appears to reflect vagal regulation as opposed to vagal tone, may be particularly important for preterm infants' rates of growth in social development over time. In future studies, researchers should examine this possibility by assessing growth in other domains (e.g., cognitive, language) in relation to early vagal regulation following a stressor in infants born preterm.

The finding that child and mother interaction quality strongly covaried over time highlights the bidirectional nature of dyadic interactions in emerging mother–child relationships, though the analyses presented do not address causal links (e.g., we do not know whether the child's interactive behaviors became more positive because the mother's interactive behaviors became more positive or less negative). One would expect such covariation, in part because mother and child interaction ratings were not independent (they were coded from the same interaction segment), but also because of theorized influences of parental interactions on children's development and children's influences on parenting (e.g., Bronfenbrenner & Ceci, 1994; Sameroff & Fiese, 2000). There was less correspondence between maternal negative affect and behavior and children's interaction quality at 4 months and across time, however.

In contrast to child trajectories, average maternal interaction quality on Parent Subscales 1 and 2 gradually declined between 4 months and 24 months postterm. In other words, mothers gradually exhibited less positive affect, involvement, and verbalizations and gradually displayed more negative affect and behavior (e.g., anger) as children grew older, although average levels of intrusive and insensitive behaviors (Parent Subscale 3) remained relatively constant. Similarly, in her study of preterm infants, Brown (2007) reported that quality of maternal interactions decreased between the NICU stay and 4 months postterm, as measured by the Parent Subscale 1 of the PCERA. Mothers of preterm babies may, on average, exhibit declining interaction patterns because of the interactional difficulties that preterm infants exhibit early in life (e.g., Cohen & Beckwith, 1979). It is possible that this pattern may also be present for mothers of full-term infants, although additional research is needed to document such a pattern. As infants grow into toddlers, they may become more active, initiating, and mobile, and a broader repertoire of behaviors may be required of mothers as they respond to these behaviors. Individual variation in maternal interactive trajectories regarding positive affect, involvement, and engagement was related to infant HRV (i.e., vagal regulation), suggesting that when mothers interact with more physiologically adapted babies, mothers show less decline in interaction quality.

In contrast to infant and maternal rates of growth over time, different variables predicted 4-month interaction quality in this sample of preterm infants (i.e., the intercept in the hierarchical linear models). Infants who were born closer to term engaged in higher quality play and showed higher levels of interest and attention during dyadic play than did infants born earlier. Prior studies have shown that higher birth weight infants experience fewer interactional difficulties than did lower birth weight infants when both preterm and full-term infants were compared (e.g., Fiese et al., 2001), and in preterm infants, birth weight tends to correlate strongly with gestational age.

Unexpectedly, mothers of infants who experienced more neonatal health risks engaged in less intrusiveness, insensitivity, and inconsistency during dyadic play at 4 months postterm than did mothers of infants with fewer neonatal health risks, and this difference persisted over time. Several previous studies have shown that more medically fragile infants engage in less optimal interactions when compared with healthy full-term infants (e.g., Poehlmann & Fiese, 2001). However, in a study of high and low risk preterm infants and full-term infants, Feldman (2006) found that higher neonatal medical risk was associated with more mother–infant synchrony at 3 months. Similarly, we found that infants with more neonatal health risks engaged in more positive affect and social and communicative competence at 4 months postterm, compared with infants with fewer neonatal health risks; however, unlike the pattern for mothers, this difference was not maintained over time.

Our findings regarding neonatal health may be the result of the present study's within-group design (i.e., no full-term infants), possibly resulting in diminished variability in neonatal risk. In this sample, 86% of infants experienced at least one health risk and 56% of the sample experienced three or more health risks during the NICU stay. However, infants with more severe problems such as periventricular leukomalacia were not included in the study.

Because we adjusted for infant gestational age and HRV in the analyses, the potential effects of these variables also should be considered in addition to neonatal health. For example, prematurity and poor infant health can attenuate HRV (Rosenstock, Cassuto, & Zmora, 1999). It is also possible that within families of preterm infants, mothers of infants who have experienced relatively mild or moderate health risks early in life may exhibit heightened sensitivity to their infants' cues and fewer intrusive behaviors relative to mothers of healthier preterms born at the same gestational age, thus facilitating children's social engagement at an early age. This information is potentially important for interventions in which one seeks to improve developmental and social outcomes for children born preterm through a focus on improving maternal sensitivity and interaction quality.

Results of the present study also indicated that early SES risks predicted both maternal and child 4-month interactive behaviors, with mothers and preterm children who experienced more SES risk factors showing less optimal social interactions at 4 months, compared with mothers and children experiencing fewer SES risks. This finding is consistent with research that has demonstrated links between SES risk and maternal responsiveness and negativity (Onufrak et al., 1995; Pelchat, 2003), which may in turn influence child interactive quality. Socioeconomic risk did not predict interactive trajectories of either mothers or children, however, so that rates of change in social behaviors did not differ for infants and mothers on the basis of SES risk. Rather, the difference that was present at 4 months continued across the duration of the study.

Feeding route was related to change in maternal negative interactive behaviors, with mothers who breastfed their infants at least some of the time during the NICU stay showing fewer negative behaviors over time, compared with mothers who exclusively bottle fed. Feeding route was coded as breastfeeding if infants were breastfed during the 10-min to 15-min feeding portion of our HRV recording that occurred during the child's NICU stay. This measure reflected all mothers who were attempting to breast feed their infants in the NICU (at least some of the time). It is possible that mothers who tried to breastfeed their newborns during the NICU stay changed feeding route following NICU discharge or at a later point in the child's development. Moreover, it was relatively common for mothers to alternate between feeding methods in this sample of preterm infants (i.e., part of feeding occurred via breast and part of feeding occurred via bottle or tube), suggesting the social benefits of even attempting to breastfeed a preterm infant during the child's NICU hospitalization. Moreover, at least one study with full-term infants found that the association between breastfeeding and maternal interaction quality only occurred at certain times in development (e.g., 12 months but not 4 months; Else-Quest et al., 2003), so this should be examined in future research with preterm infants. Feeding issues and choices may differ for preterm and full-term infants because of medical fragility or respiratory issues.

The limitations of this study should be considered when interpreting and applying our findings. Although attrition was relatively low, families who dropped out of the study or could not be located were slightly more socioeconomically disadvantaged than families remaining in the study. We only assessed infant–mother interactions during unstructured play rather than in other situations, such as contexts that become increasingly important as children grow older (e.g., problem solving) or those that may elicit negative emotional reactions from children (e.g., restraint). We did not include a full-term control group so that we could focus on factors that facilitate development within preterms (an approach that attempts to examine resilience processes within a high risk group; see Poehlmann, Schwichtenberg, Shah, et al., 2010, for additional explanation). The inclusion of a full-term comparison group would help elucidate the extent to which interactional trajectories (and predictors) in preterm infants and their mothers may differ from healthy full-term children and their mothers. An additional limitation of the study is the relatively large number of prefeeding resting HRV recordings that were unusable because of infants becoming agitated or fussy in anticipation of feeding. In future research featuring prefeeding with preterm newborns, researchers may want to either shorten the ECG recordings (e.g., first 5 min only) or time their recordings differently regarding the infant's feeding schedule to minimize data loss. Finally, we did not focus on fathers or siblings, who may also be significant interactional partners for preterm infants as they grow older.

Despite these limitations, our investigation provided important information about infant–mother interactions over time in a sample of preterm infants, including identification of infant and maternal variables that are implicated in children's emerging social development.

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