

From Biological Rhythms to Social Rhythms: Physiological Precursors of Mother–Infant Synchrony

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Links between neonatal biological rhythms and the emergence of interaction rhythms were examined in 3 groups ($N = 71$): high-risk preterms (HR; birth weight < 1,000 g), low-risk preterms (LR; birth weight = 1,700–1,850 g), and full-term (FT) infants. Once a week for premature infants and on the 2nd day for FT infants, sleep–wake cyclicality was extracted from 4-hr observations and cardiac vagal tone was measured. At term age, infant orientation was tested with the Neonatal Behavior Assessment Scale. At 3 months, arousal modulation and emotion regulation were assessed, and mother–infant synchrony was computed from microanalysis of face-to-face interactions using time-series analysis. Sleep–wake amplitudes showed a developmental leap at 31 weeks gestation, followed by a shift in vagal tone at 34 weeks gestation. At term, differences among FT, LR, and HR infants were observed for biological rhythms in a linear-decline pattern. Sleep–wake cyclicality, vagal tone, newborn orientation, and arousal modulation were each uniquely predictive of mother–infant synchrony. The organization of physiological oscillators appears to lay the foundation for the infant’s capacity to partake in a temporally matched social dialogue.

Keywords: mother–infant synchrony, sleep–wake cyclicality, vagal tone, premature infants, arousal

Caregiver–infant face-to-face communication is a dynamic process that integrates the endogenous rhythms of parent and child, their interpersonal style and emotional signals, and the level of mutual involvement into a relational system with clear temporal parameters (Field, 1994; Fogel & Thelen, 1987; D. N. Stern, 1985; Tronick, 1989). The centrality of parent–infant synchrony for the development of the infant’s cognitive, social–emotional, and self-regulatory capacities has been well documented (Feldman & Eidelman, 2004; Feldman & Greenbaum, 1997; Feldman, Greenbaum, & Yirmiya, 1999; Jaffee, Beebe, Feldstein, Crown, & Jasnow, 2002). The precursors of synchrony, on the other hand, have not received empirical attention. Numerous authors have proposed that the periodic structure of face-to-face play reflects the infant’s biological rhythms and that interactional synchrony is built on the parent’s and child’s mutual adaptation to endogenous cycles of affective involvement (Cohn & Tronick, 1988; Lester, Hoffman, & Brazelton, 1985; Trevarthan, 1979; Wolff, 1967). As such, early communication systems develop through the ongoing integration of biological, emotional, and contextual components, which provide a temporal framework for the organization of cognitive and affective experiences (Fogel, 1993). Such systems are best studied by applying relational units of behavior, using longitudinal designs—preferably those including prenatal or neonatal assessments—and addressing change-related questions that examine the mutual effects of biology on context (Gottlieb, 1991; Lerner, 1991; Sameroff, 1995). Yet the biological foundations of early communication systems have not been examined in depth.

Prematurity and the Development of Physiological Oscillators and Interaction Synchrony

Prematurity provides a unique context in which to study the biological substrates of early social communication, in particular the relations between the development of physiological oscillators and the emergence of parent–infant coordinated timing. Although premature infants demonstrate a periodic structure of face-to-face play, as measured by spectral analysis, there are alterations in the temporal parameters of synchrony, including lower levels of coherence between maternal and infant’s time series and changes in the lead–lag relationship, which are thought to reflect disruptions in the biological underpinnings of social engagement (Lester et al., 1985). Premature infants display facial emotional signals that are poorly identified by adults (Malatesta, Culver, Tesman, & Shepard, 1989), their ability to tolerate high levels of negative or positive arousal during face-to-face encounters is limited (Eckerman, Hsu, Molitor, Leung, & Goldstein, 1999), and the lower level of dyadic adaptation is predicted by impaired neonatal orientation to social and nonsocial stimuli (Greene, Fox, & Lewis, 1983), findings that underscore the relations between neurobehavioral development and face-to-face coordination. Consistent with the predictions of transactional and systemic perspectives (Sameroff, 1995), the infant’s biological dysregulation affects parental behavior, and parents of premature infants show higher intrusiveness, more didactic behavior, and lower adaptation to the infant’s pace and rhythms (Brachfeld, Goldberg, & Sloman, 1980; Feldman, Weller, Eidelman, & Sirota, 2003; Minde, 2000). Differences in levels of social engagement were found between premature infants born at low and high biological risk, with the latter showing higher dependence on the mother’s sensitive approach (Landry, Smith, Miller-Loncar, & Swank, 1998). These findings point to significant difficulties in the early social engagement of premature in-

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infants, possibly related to the immaturity of physiological systems and closely linked to the level of infant biological risk.

It has been suggested that the infant's capacity to partake in face-to-face play at 3 months is built on structural and functional brain maturation that occurs at the late fetal and early neonatal period, including the assembly of brain nuclei, the rapid increase in synaptic growth, and the development of neurochemical systems, all of which are substantially altered in premature infants (Levitt, 2003). These same processes also support the emergence of physiological oscillators during the last trimester of pregnancy, such as sleep-wake cyclicality and parasympathetic control over heart rhythms (Groome, Loizou, Holland, Smith, & Hoff, 1999; Peirano, Algarin, & Uauy, 2003). Premature infants display irregular sleep-wake cycles and disorganized heart rhythms. Similar to the findings for social engagement, the biological rhythms of high-risk premature infants born prior to the last trimester of pregnancy were found to be especially disorganized (Mirmiran, Maas, & Ariagno, 2003; van Ravenswaaij-Arts et al., 1991).

To examine the association between biological and social rhythms, the present study followed the development of two physiological oscillators—sleep-wake cyclicality and heart rate variability—from mid-gestation to term age in high-risk premature infants and examined their contribution to the emergence of parent-infant interactive synchrony. The links between physiological oscillators in the neonatal period and interactive synchrony at 3 months were compared in three groups: high-risk premature infants, low-risk premature infants, and full-term infants. Such data may point to specific pathways in the effects of biological processes on early communication systems within a prenatal-to-infancy, change-oriented, systemic frame (Lerner, 1998; Sameroff, 1995).

Phase Shift at the Third Trimester of Pregnancy and Interaction Synchrony

Among the central controversies in development research is how developmental change in biological or behavioral systems comes about (Thelen & Smith, 1994). According to the dynamic systems perspective, systems self-organize from the ongoing interplay between subcomponents and context. Over time, natural fluctuations and the system's innate instability cross a critical cutoff, resulting in a phase shift in systemic functioning and reorganization of the system's parameters (Oyama, 1985; Prigogine & Stengers, 1984). In infancy, phase shifts and the emergence of novelty typically occur in conjunction with the development of specific biological systems (Emde, 1994; Kagan, 2003). During a phase shift variability among individuals is at its peak, and the performance of individual children is predictive of the system's functioning; thus, the study of systemic phase shifts is highly significant for understanding early development (Thelen & Smith, 1994). Modeling change in emerging systems is best achieved through frequent, repeated, longitudinal observations of a developmental phenomenon before, during, and following the expected transition (van Geert, 1994). This empirical design aims to chart the iterative growth curve of the system across its dynamic period and to describe both the nonlinear nature of gradual change and the specific point at which the phase shift has occurred. Few studies, however, have undertaken such modeling (e.g., Lavelli & Fogel, 2005; van den Boom & Hoeksma, 1994), and the growth curve of

biological functions has not yet been examined in relation to the dynamic parameters of early relational systems.

The notion that development occurs in phase shifts or "bio-behavioral transitions" (Emde, 1994) that follow the emergence of specific biological functions is consistent with current neuropsychological models on emotional development (Damasio, 1999; Tucker, Derryberry, & Luu, 2000). According to these evolutionary, hierarchical-integrative models, brainstem-mediated structures that serve a homeostatic function provide the foundation for the proper functioning of higher order limbic and cortical systems. The higher order systems, in turn, elaborate, fine-tune, and serve an inhibitory function for the lower level homeostatic systems, and thus, the development of each core function involves the reorganization of the entire system. Several periods of transition have been described across the first years of life, each following the emergence of a specific skill (Emde, Gaensbauer, & Harmon, 1976; Kagan, 2003).

Overlooked in current developmental research, however, are the phase shifts that occur prior to birth and their implications for later development. One such transition can be detected at the beginning of the third trimester, between 30 and 34 weeks gestational age (GA), with the rapid increase in synapse formation, dendritic growth, myelination, and synaptic remodeling (Levitt, 2003; Sampaio & Truwit, 2001). The second period of transition is defined by birth itself. At birth, a new encounter between the infant and its environment forces the emergence of new skills. Among the skills the newborn must acquire for survival are the integration of respiration with heart rhythms, the entrainment of circadian rhythms (i.e., alignment of sleep with the light-dark cycle), and the proper orientation to the external environment. These brainstem-controlled functions, which develop at the late fetal and early neonatal period, are thought to provide critical support for the development of limbic-mediated capacities, such as emotional signaling and affect sharing that emerge at the 3- to 6-month stage (Levitt, 2003; Porges, 2003; Prechtle, 1992; Schore, 1996; Tucker et al., 2000). Such associations emphasize the connection between systems implicated in the maintenance of physiological homeostasis and those involved in the development of social engagement.

Sleep-Wake Cyclicality and Parent-Infant Synchrony

The circadian timing system, which monitors the biological clock, is located in a small region of the hypothalamus—the suprachiasmatic nucleus (Richter, 1967; Yamazaki et al., 2000)—with recent evidence pointing to the existence of several oscillators working in concert located at various nuclei in the brain, including the cerebellum (Isope, Dieudonne, & Barbour, 2002). The biological clock emerges at around 30 weeks GA and consolidates further during the last trimester of pregnancy (Mirmiran & Lunshof, 1996). At that point, the fetal spontaneous movements of the second trimester reorganize into distinct rest-activity cycles, and longer periods and higher amplitudes of quiet sleep states are observed. The consolidation of quiet sleep from the immature active sleep state reflects the integration of inhibitory and excitatory mechanisms and coincides with the formation of thalamocortical and intracortical patterns of innervation (L. Curzi-Dascalova et al., 1993; Peirano et al., 2003). Following birth, the development of day-night rhythmicity in the first postnatal weeks marks a shift

from ultradian (i.e., shorter than the 24-hr cycle) to circadian rhythmicity (Rivkees, 2003).

Sleep–wake cycles have been detected in fetuses, highly premature infants, and full-term neonates, and a similar progression in the development of sleep–wake cyclicity has been observed in the fetus and the preterm infant (de Vries, Visser, & Prechtel, 1982; Diambra & Menna-Barreto, 2004; Olischar et al., 2004). Weekly observations of sleep–wake states in premature infants prior to term, measured by electroencephalograph recording, continuous state observations, and 24-hr videotaping, showed longer sleep bouts and more predictable sleep sequences with increased gestation (Holditch-Davis & Edwards, 1998; Ingersoll & Thoman, 1999; Olischar et al., 2004). The state organization of premature infants reaching term provides a useful index of infant growth and has been shown to predict the infant’s cognitive skills, exploratory behavior, and emotion regulation across infancy (Anders, Keener, & Kraemer, 1985; Beckwith & Parmelee, 1986; Feldman, Weller, Sirota, & Eidelman, 2002). Moreover, the sleep–wake oscillator is an open dynamic system that is highly sensitive to environmental inputs, such as maternal hormones (Seron-Ferre et al., 2002), variations in the intrauterine environment (Moore-Ede, Sulzman, & Fuller, 1992), patterns of maternal care (Anders, 1994), and intervention practices such as Kangaroo Care (parent–infant skin-to-skin contact) or cycled lighting (Feldman et al., 2002; Rivkees, Mayes, Jacobs, & Gross, 2004). These findings suggest that the organization of the biological clock may support the emergence of arousal and emotion regulatory structures (Dahl, 1996), systems that are central for the development of parent–infant synchrony (Feldman, 2003).

Cardiac Vagal Tone and Parent–Infant Synchrony

Cardiac vagal tone, which measures the effects of respiration on heart rate variability as mediated by the parasympathetic system, is another pacemaker that serves as an index of maturity in term and preterm infants. Porges (1995) theorized that vagal tone reflects the mammalian brainstem organization and its adaptive capacity to differentially mobilize or save energy in response to external or internal stresses. Vagal tone plays a role in the achievement of physiological homeostasis and provides the foundation for the appearance of complex behaviors such as orientation, learning, and social engagement (Porges, 2003). Studies of fetal heart rate variability showed links between vagal tone and measures of prenatal parasympathetic development, pointing to its role in the emergence of inhibitory structures (Groome et al., 1999). The development of sleep–wake cyclicity and heart rate variability are thought to work in synchrony (Mirmiran & Lunshof, 1996), and the emergence of ultradian rhythmicity in heart rhythms at 32 weeks GA (Pillai, James, & Parker, 1992) may suggest that the phase shift in the development of the vagal tone follows the consolidation of the sleep–wake cycle.

Similar to sleep–wake cyclicity, respiratory sinus arrhythmia and vagal tone at term age provide an index of optimal growth that correlates with the degree of newborns’ medical risk, as measured by objective risk indices (Spassov et al., 1994; van Ravenswaaij-Arts et al., 1991), and with cognitive outcomes and emotion regulation in the first years of life (Doussard-Roosevelt, Porges, Scanlon, Alemi, & Scanlon, 1997). The growth rate of the vagal tone between 33 and 35 weeks GA has similarly been shown to

predict postnatal weight gain (DiPietro & Porges, 1991) and social–emotional adaptation up to 6 years of age (Doussard-Roosevelt, McClenny, & Porges, 2001). Higher vagal tone and better regulation of the vagal brake at 3 months were associated with better regulation of negative arousal during the presentation of aversive stimuli (Huffman et al., 1998) and with higher levels of mother–infant synchrony (Moore & Calkins, 2004). Similar to the biological clock, the cardiac pacemaker is open to environmental inputs, and caregiving practices, such as Kangaroo Care, improve the growth rate of vagal tone during the last trimester of pregnancy (Feldman & Eidelman, 2003). It thus appears that the development of the vagal tone may be an important indicator of the infant’s later orientation, social engagement, and emotion regulation, capacities that support the emergence of parent–infant synchrony.

The Present Study

In light of the above, the present study charted the developmental trajectory of two physiological oscillators—sleep–wake cyclicity and heart rate variability—from 25 weeks GA to term age in a group of high-risk premature infants observed weekly. Guided by dynamic systems principles, the period between 30 and 34 weeks GA—the beginning of the third trimester—was conceptualized as a period of a phase shift for the two oscillators, characterized by a short period of rapid growth followed by a longer period of stabilization (Thelen & Smith, 1994). It was expected that the two pacemakers would synchronize their developmental transition and that the emergence of parasympathetic control over heart rhythms would follow the consolidation of the biological clock. The period of 30 weeks GA has been highlighted as important for the organization of sleep–wake rhythmicity (Mirmiran & Lunshof, 1996), and the time between 33 and 35 weeks GA has been pinpointed as significant for the development of the vagal tone (Doussard-Roosevelt et al., 2001). These time points were thus examined as potential periods of transition for the two pacemakers. At term age, the development of sleep–wake cyclicity and vagal tone in the high-risk group, who were deprived of the entire last trimester of pregnancy, was compared with that of two control groups: (a) full-term infants and (b) low-risk premature infants, who were born after the phase shift in sleep and heart rhythms was expected to have occurred. Sleep–wake cyclicity and vagal tone were expected to be differentially organized in high-risk premature infants as compared with low-risk premature infants and full-term controls, and these infants were expected to show a less organized sleep–wake cycle and a lower vagal tone index as compared with both full-term infants and premature infants who experienced the developmental transition in utero.

The second goal of the study was to assess the contribution of neonatal biological rhythms to the development of social rhythms. Links between the individual’s endogenous cycles and interaction synchrony have been proposed in theories of communication systems for both caregiver–infant and adult–adult interactions (Fogel, 1993; Lester et al., 1985; D. N. Stern, 1985; Warner, 1992) but have received little empirical support. Synchrony was defined as an ongoing match in the mother’s and infant’s direction of involvement in the interaction, a measure that addresses the degree of coordination in the “dance” between the two partners (Tronick, 1989). Time-series analysis was used to assess mother–infant synchrony, and three dynamic parameters of early communication

systems were examined in line with previous research (Cohn & Tronick, 1988; Feldman, 2003; Field, Healy, Goldstein, & Guthertz, 1990; Lester et al., 1985). These include the coherence between the mother's and infant's time series, indicating the strength of the lagged associations between the partners' behavior; the lead-lag relationship, addressing who is "driving" the interaction; and the time lag to synchrony, referring to responsivity lags between change in one partner's behavior and parallel change in the other's. It was hypothesized that more organized biological rhythms would support a more synchronous mother-infant dialogue. Specifically, higher sleep-wake amplitudes and a higher vagal tone index were expected to predict a closer coherence between the mother's and infant's affective states and to correlate with the infant "leading" the interaction. The infant-leads/mother-follows interaction is considered a more optimal form of synchrony at 3 months and implies that the mother is responsive to microlevel shifts in the infant's affective state (Feldman et al., 1999).

To further explore the pathway from biological to social rhythms, functions that may mediate the link between physiological pacemakers and parent-infant synchrony were tested, including newborn orientation to social and nonsocial stimuli and infant arousal modulation and emotion regulation. The proper modulation of positive and negative arousal is required for the infant's participation in en-face interactions, is disturbed in premature infants (Eckerman et al., 1999), and is related to cardiac vagal tone (Huffman et al., 1998). In this study, a dynamic measure of arousal modulation was used, one that evaluates changes in infant arousal in response to the onset and termination of environmental events. This measure of arousal modulation has been shown to predict a more efficient information-processing system (Feldman et al., 2002) and was examined here as a potential moderator of the relations between physiological rhythms and the rhythms of mother-infant face-to-face dialogue.

Method

Participants

Seventy-one infants and their mothers participated in the study. The study used an extreme-case design and included three groups. Group 1 consisted of 17 high-risk (HR) infants born at extremely low birth weight of below 1,000 g and before 30 weeks GA. Group 2 included 25 low-risk (LR) infants born at a birth weight of 1,700–1,850 g and between 34 and 35 weeks GA. Group 3 included 29 full-term (FT) infants born at term

(>36 weeks GA) with a birth weight of 2,500 g and above and with no medical complications. All infants were born in a singleton birth, and those born prematurely received standard incubator care. Premature infants were excluded from the study if they had intraventricular hemorrhage Grades III or IV (i.e., large bleeding in the brain ventricles with extension into the brain parenchyma) or suffered from perinatal asphyxia, metabolic, or genetic disease.

Demographic and medical information appears in Table 1 and shows no differences in parental age and education among the three groups. All parents had graduated high school, mothers were at least 20 years old, and all mothers were married to the child's father. Parents were Israeli Jews, and all families were considered middle class by Israeli standards (Harlap, Davis, Grower, & Prywes, 1977). Infants were recruited from a hospital nursery. No mothers of HR infants born in the Neonatal Intensive Care Unit during the study period declined participation. Two mothers of LR infants and 4 mothers of FT infants declined, citing time constraints and father refusal as reasons. These infants and mothers did not differ on demographic or medical factors from the participating families. Mean length of hospitalization was 10.26 weeks for the HR group ($SD = 3.11$), 3.42 weeks for the LR group ($SD = 1.14$), and 2 days for the FT infants. Premature infants remained in the Neonatal Intensive Care Unit until discharge, typically at 37 weeks GA. The study was approved by the Institutional Review Board, and all participating families signed an informed consent.

Procedure

Once a week for all infants born prematurely (<36 weeks GA) a 4-hr state observation was conducted in the hospital and a 10-min sample of electrocardiogram (ECG) was collected. State and heart rate data were collected within the same 24-hr period. State observation and ECG for FT infants were collected once, on the second postbirth day prior to discharge. Thus, each premature infant in the HR and LR groups entered the study shortly after birth, and weekly observations continued for this child until 37 weeks GA. At term age, all infants were tested with the Neonatal Behavior Assessment Scale (NBAS; Brazelton, 1973) by a trained neonatologist. The final state observation was conducted on the evening prior to discharge, and the ECG recording and NBAS testing were conducted on the day of discharge for all infants. All state and ECG data were collected in the hospital. At 3 months (corrected age for premature infants, i.e., 40 weeks gestation plus 3 months), mother-infant interaction was videotaped and infant reactivity and emotion regulation were assessed during a home visit. Mean number of observations was 10.55 ($SD = 1.67$) for the HR group and 3.42 ($SD = 1.13$) for the LR group.

Neonatal Period

State observation. During 4 consecutive evening hours (7 p.m. to 11 p.m.), trained coders observed the infant's state in 10-s epochs in the

Table 1
Demographic Information

Variable	High-risk preterm ($n = 17$)			Low-risk preterm ($n = 25$)			Full term ($n = 29$)		
	<i>M</i>	<i>SD</i>	<i>SEM</i>	<i>M</i>	<i>SD</i>	<i>SEM</i>	<i>M</i>	<i>SD</i>	<i>SEM</i>
Birth weight (g)	831.44	140.39	34.05	1,793.84	109.69	21.93	3,186.41	539.02	55.09
Gestational age (weeks)	27.17	1.46	0.35	34.32	1.18	0.48	39.17	2.37	0.44
Medical risk (CRIB)	5.11	3.51	0.85	0.68	1.22	0.23	0.00	0.00	0.03
Mother age (years)	29.62	6.12	0.82	28.11	5.97	0.49	28.83	6.36	0.88
Mother education (years)	14.17	2.33	0.47	14.24	1.65	0.29	14.03	2.64	0.51
Father age (years)	32.45	6.92	1.18	31.82	7.24	0.68	31.02	6.31	1.19
Father education (years)	14.55	3.46	0.61	14.93	2.94	0.45	13.65	3.11	0.75

Note. CRIB = Clinical Risk Index for Babies.

neonatal intensive care unit (for premature infants) or the nursery (for FT infants) and entered the data into a computerized program. Because sleep cycles last approximately 60 to 70 min in term infants (D. Curzi-Dascalova, Peirano, & Inserm, 1988; E. Stern, Parmelee, & Harris, 1973), a 4-hr period was observed to enable the detection of several sleep-wake cycles. States were defined according to Brazelton (1973) and Holditch-Davis (1990) as follows: *quiet sleep*—infant's eyes are closed, breathing is regular, motor activity is minimal; *active sleep*—infant's eyes are closed, respiration is irregular, motor activity and rapid eye movements occur sporadically; *sleep-wake transition*—eyes are typically closed but may open occasionally, motor activity is typical, behaviors of both sleep and wakefulness are observed; *unfocused wakefulness*—eyes are typically open but may occasionally close, motor activity is typically high; *alert wakefulness*—eyes are open and scanning, motor activity is medium range; *fuss/cry*—eyes are typically open, motor activity is typical, the infant emits clear fuss vocalizations or a full cry. Observations took place between feedings, and arrangements were made to diminish interruptions. In cases of interruption, the observation was terminated and was resumed when the infant returned to a calm state.

A training program for state observation was developed. Coders were first introduced to the six states and spent time in the nursery freely observing infants. Following this, coders scored a training tape of infants in their cribs, including infants of different ages and medical risk, in real time, using a hidden beeper that beeped every 10 s. When 85% reliability was reached on the tape, coders were trained in the nursery. Reliability of each coder (eight students of psychology) was measured against the program manager, who was trained by the chief neonatologist. Reliability on 30 infants at different ages averaged 92% ($\kappa = .85$).

Cardiac vagal tone. Approximately 10 min of heart rate were recorded when the infant was in a quiet sleep state from the cardiac monitor, using a special A/D adaptor that samples heart rate, and transferred into a special computerized system that registered the R waves and computed the R-R interval (heart period in ms). Vagal tone, the amplitude of respiratory sinus arrhythmia, was quantified with Porges's MXEdit system (Porges, 1985) by a research assistant trained to reliability at Porges's lab. After editing to remove artifacts, the MXEdit system converts heart period data into time-based data sampled in 200-ms intervals, determines the periodicities of heart rate with a 21-point moving polynomial, filters the time series to extract the heart period within the frequency band of spontaneous breathing of neonates, and calculates the vagal tone index (Vna).

Neurodevelopmental status at term age. At 37 weeks GA for premature infants and on the second day for FT infants, infants were examined with the NBAS by a trained neonatologist. The orientation cluster (Lester, 1984) was used in this study, which addresses the infant's skill at orienting to social and nonsocial stimuli.

Three Months

Mother-infant interaction. Five minutes of mother-infant face-to-face interactions were videotaped at home. A camera was situated to capture the infant's face while the mother's face was filmed through a mirror positioned in front of her. The final picture showed a frontal view of both the mother's and the infant's face.

Infant reactivity and regulation. Reactivity and regulation were assessed with the Behavior Response Paradigm (BRP; Garcia-Coll et al., 1988). In this procedure, infants are presented with 17 stimuli in various modalities (e.g., sound, light). Each stimulus is presented for 20 s, with a 10-s break between stimuli. Stimuli are organized in a sequence of increasing complexity and intrusiveness, ranging from simple unimodal (e.g., bell sound, flashlight) to aversive, multimodal stimuli (e.g., a fast-moving car flashing its lights and making loud noises). Infants sat in an infant seat, and a trained examiner presented the stimuli in a predetermined order.

Coding and Measures: Neonatal Period

Infant medical risk. The Clinical Risk Index for Babies (CRIB; International Neonatal Network, 1993) is an objective quantitative measure of neonatal risk for infants born prematurely that evaluates the degree of medical risk and has been shown to be a better predictor of mortality and morbidity than birth weight alone. The CRIB consists of six sections, and scores within each section are predetermined. Scores are summed to create the total CRIB score, and higher scores indicate greater risk.

Sleep-wake cyclicity. Each time series of states, consisting of 1,440 data points (10 s epochs over 4 hr), was analyzed with spectral analysis according to a procedure detailed by Gottman (1981) and used in research on sleep-wake cyclicity in neonates (Diambra & Menna-Barreto, 2004). Prior to spectral analysis, linear trends were removed, to improve stationary conditions (i.e., consistency of mean and variance across time). The residualized time series were analyzed with Blackman-Tukey Fourier analysis. Fourier analyses decompose the time series into separate cycles, superimposed on a constant, and each cycle is defined by its power (amplitude) and frequency. Spectral analysis was computed using a Tukey-Hanning smoothing function. The variable used to index sleep-wake cyclicity was the amplitude of the basic cycle, the tallest "spike" in the periodogram. High amplitude of the basic cycle implies that more variance in the infant's states is accounted for by rhythmic oscillations between sleep and wakefulness (i.e., higher cyclicity). Higher cyclicity measured with spectral analysis has been shown to index more optimal physiological development in term and preterm infants (Diambra & Menna-Barreto, 2004; Feldman et al., 2002).

Coding and Measures: 3 Months

Mother-infant synchrony. Three minutes of mother-infant interaction were coded in 1-s frames using the Monadic Phase Manual (Tronick, Als, & Brazelton, 1980). Monadic phases represent a continuum ranging from negative to positive engagement and include the following phases: protest, avert, object attend, social attend, object play, social play, and talk. Coding was conducted for the 2nd, 3rd, and 4th minutes of play, to enable a 1st minute of orientation to the play setting and in light of research showing that the most pronounced period of play at this age occurs between the 2nd and 5th minutes (Feldman et al., 1999). Mother's and infant's affective states were coded separately, and the two time series of 180 data points each were then examined for synchrony. The monadic phases system uses a widely accepted scaling approach to the study of synchrony, in which affect is organized on a continuum from negative to positive involvement in play. This approach enables the definition of synchrony as a match in the *direction* of change, not necessarily as a match of phase. The coding, length of observation, and data analysis used in this study are consistent with previous research using the monadic phases system (Cohn & Tronick, 1988; Field et al., 1990; Lester et al., 1985) that demonstrated lower synchrony in cases of maternal or child risk. Two coders, unaware of the infant group membership, observed the tape at normal speed, approximated the time of phase change, and returned to determine the exact time of phase change while the tape was running in slow motion. Coding of a mother and her infant was not performed successively so as to ensure unbiased assessment. Coders were trained extensively with the monadic phases coding system on a pilot sample until 80% reliability was achieved on all categories. Reliability for the present sample was examined on 20 time series of mothers and 20 time series of infants. Reliability kappa was .82 for the infants' time series and .84 for the mothers' time series.

Prior to the assessment of synchrony, time series were examined for stationarity, and in the rare cases when conditions of stationarity were not observed, series were differenced once (i.e., recomputed as the difference between two consecutive observations) to enable time-series analysis that requires stationarity conditions. Next, the autocorrelated component in each time series (i.e., the tendency to cycle between states regardless of the partner's behavior) was estimated using separate

autoregressive integrated moving averages (ARIMAs). ARIMA is a univariate time-domain technique that estimates the autoregressive component in a time series by fitting a best model on the basis of the autocorrelation and partial correlation functions and diagnosing the series of residuals for lack of autocorrelations (Gottman, 1981). All time series included a significant autocorrelated component defined by either an AR1 (i.e., behavior is predicted from the immediately preceding event) or an AR2 (i.e., behavior shows a stochastic-cyclic pattern) structure. These findings are consistent with previous research in infants (Cohn & Tronick, 1988; Feldman, 2003) and adults (Warner, 1992) and show endogenous periodicities in the behavior of each partner. Prior to the assessment of synchrony, the autocorrelated component in each time series was partitioned out, resulting in two series of residuals for each dyad. Finally, the lagged association between the mother's and infant's series of residuals was examined with cross-correlation functions (CCF), to evaluate the level of synchrony.

Three types of synchrony may be observed on the CCF plot. Positive spikes on the CCF plot imply an infant-leads/mother-follows relation. Negative peaks suggest a mother-leads/infant-follows relationship. When both positive and negative peaks appear on the CCF, mutual synchrony is inferred, suggesting that mother and infant are each responsive to changes in the partner's play. Four parameters of synchrony were examined here in light of previous research (Feldman, 2003):

1. *Synchrony*: This binary variable indexed whether a significant peak, of any direction, appeared on the CCF plot.
2. *Degree of synchrony (coherence)*: This variable measures the strength of the lagged associations between the two time series and was indexed by the size of the largest cross-correlation coefficient on the CCF plot. Scores range from 0, implying no associations between the two time series, to 1, describing a perfect match between the two time series. The coherence variable was used in this study as a criterion variable.
3. *Lead-lag relationships*: This variable took on a positive value only when significant relations were found between the time series and was indexed as a binary variable. It indicated whether synchrony was of an infant-leads/mother-follows type, a mother-leads/infant-follows type, or the mutual synchrony type.
4. *Time lag to synchrony*: This measure refers to responsiveness lags (in seconds) between change in one partner's behavior and corresponding change in the other's. It took on a positive value only when synchrony was found.

Arousal modulation and motion regulation. Microanalytic coding was conducted for the BRP procedure (Garcia-Coll et al., 1988) using a computerized system (The Observer, Noldus Co.); approximately 3–4 observations were required to code each session. Coding considered five general categories of behavior (gaze, affect, reactivity, fine motor, and gross motor), and codes within each category were mutually exclusive. In addition, periods of "stimulus on" and "stimulus off" were marked. In this report, the three codes from the *reactivity* category and the cry code from the *affect* category were used. Reactivity was coded on the basis of facial expressions, eye movements, hand and body movements, orientation, muscle tone, and level of arousal. Three codes were included in this category: (a) No reactivity implied that the infant showed no signs of reaction to the stimulus or to any internal or external input; (b) midrange reactivity indicated that the infant showed interest and moderate levels of excitement, as demonstrated by gaze, body orientation, neutral or positive facial expressions, and fine and gross motor movements; and (c) high reactivity implied a high level of negative (e.g., crying combined with body arching and leg movements) or positive (laugh, enjoyable vocalizations, exuber-

ance) arousal. The following variables were computed on the basis of these codes.

Arousal modulation was based on the reactivity codes and addressed the infant's capacity to organize arousal in accordance with the presentation and termination of external stimuli. Arousal modulation was indexed by two conditional probabilities: (a) Midrange reactivity during "stimulus on" was the relative proportion of time the infant spent in midrange reactivity during the "stimulus on" period, and (b) no reactivity during "stimulus off" was the relative proportion of time the infant showed no reactivity during the "stimulus off" period.

Emotion regulation was indexed by two variables based on the cry code of the affect category: (a) Negative emotionality was the proportion of time the infant spent in crying or fussing during the procedure, and (b) threshold was defined by the latency to the first cry. Because stimuli were getting progressively more intrusive, longer latencies to the first cry implied that the infant was able to tolerate higher levels of environmental intrusion and began to cry during the more aversive stimuli. The threshold variable was log-transformed prior to data analysis.

Two individuals coded the BRP while the tape was running in real time, shifting to slow motion to determine the beginning and end of states or short events. Reliability was examined for 15 infants and exceeded 87% on all channels. Mean reliability was 92% ($\kappa = .81$).

Results

Results are reported in three sections. In the first, the growth curve of sleep-wake cyclicality and vagal tone from 25 weeks GA to term age is charted for the HR infants and tested with trend analysis. In the second, mean-level differences between groups are examined. In the neonatal period, group differences were examined for sleep-wake cyclicality, cardiac vagal tone, and neurobehavioral orientation. At 3 months, differences were assessed for mother-infant synchrony, arousal modulation, and emotion regulation. In the third section, physiological, neurobehavioral, and emotion-regulatory predictors of mother-infant synchrony are examined. This section also includes moderating models that tested the role of arousal modulation in moderating the relations between physiological rhythms and mother-infant synchrony.

Developmental Trajectories of Physiological Oscillators Prior to Term in HR Preterms

Sleep-wake cyclicality. Figure 1 presents the developmental trajectory of sleep-wake cyclicality from 25 weeks GA to 37 weeks GA. A total of 266 observations were conducted. Of these, 9 observations could not be included. In 5 cases, infant medical procedures cut the observation short, and in 4 cases data were not available owing to technical computer problems. The remaining 257 observations were included in the graph and in the following analyses. Missing observations were as follows: one observation each at 27, 28, 29, 31, 33, 35, and 36 weeks GA and two observations at 34 weeks GA.

To examine the trajectory of sleep-wake cyclicality for the entire HR group during the dynamic transition period, a trend analysis of the observations at 30, 31, 32, 33, and 34 weeks GA was carried out. Trend analysis examines mean-level changes in a series of repeated observations from the same subjects and assesses (a) whether significant change has occurred during the observation period; (b) at which point in time the change has occurred (phase

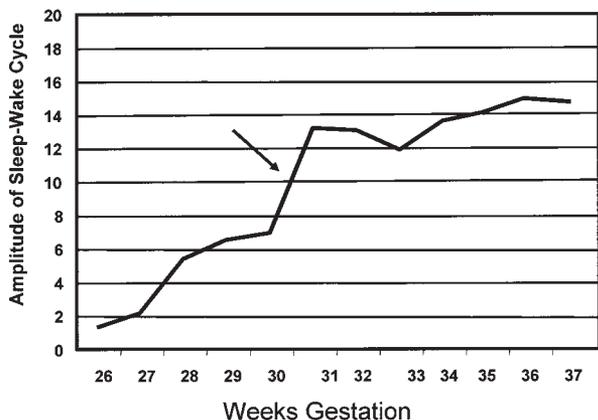


Figure 1. Developmental trajectory of sleep-wake cyclicality from 25 weeks gestational age to 37 weeks gestational age in high-risk premature infants.

shift); and (c) whether the curve is best described by a linear, quadratic, or cubic trend or a combination of these trends. Results showed a linear trend for sleep-wake cyclicality, indicating that a developmental shift in sleep-wake cyclicality had occurred between 30 and 34 weeks GA; within-subject sphericity assumed $F(4, 13) = 2.82, p < .05$, effect size (ES) = .16. A significant effect was found for the linear component, $F(1, 16) = 6.04, p < .05$, with no significant quadratic or cubic effects, indicating that the curve is best described as a linear increment. Planned contrast between subsequent observations showed only one significant contrast, between the first (30 weeks GA) and the second (31 weeks GA) observations, $F(1, 16) = 8.05, p < .05$, indicating that a phase shift in the development of the sleep-wake cycle occurred during that week. Examination of the means showed that at 30 weeks GA, the mean amplitude of sleep-wake cyclicality was 7.16 ($SD = 1.03$) and at 31 weeks the mean amplitude was 13.47 ($SD = 1.35$). To examine the development of the sleep-wake oscillator following the period of transition, trend analysis was conducted for the observations at 35, 36, and 37 weeks GA for the HR group. This analysis showed no linear, quadratic, or cubic trends, within-subject sphericity assumed $F(2, 15) = 1.24, ns$. Thus, the data mark the period between 30 to 34 weeks GA as a specific time window for the organization of the sleep-wake cycle, with a growth spurt between 30 and 31 weeks GA. Subsequent to the period of developmental shift, there appears to be a period of consolidation with no major changes.

To ascertain that no significant changes in sleep-wake cyclicality occurred prior to 30 weeks GA, paired-sample *t* tests with Bonferroni corrections were computed between the amplitudes of the sleep-wake cycle for each pair of consecutive weeks prior to 30 weeks (e.g., cyclicality at 27 weeks compared with cyclicality at 28 weeks GA) for infants who had data on these two time points. Because each child entered the study immediately after birth, the number of infants observed at each time point prior to 30 weeks GA was different, and trend analysis could not be computed for that period. Results of the *t* tests showed no significant changes in sleep-wake cyclicality between any consecutive observations from 25 to 30 weeks GA, pointing to the period of 30 to 34 weeks GA as the dynamic period of growth for the sleep-wake oscillator.

As to the maturation rates of individual infants, at 30 weeks, only 4 infants scored within one standard deviation of the mean that was observed at 31 weeks GA (i.e., demonstrated a sleep-wake cycle similar to the one observed at term age for that group). On the other hand, at 31 weeks GA, 15 infants showed a cycle that is similar to term age, $\chi^2(1, N = 17) = 3.97, p < .05$, indicating that for most infants, the developmental shift occurred between 30 and 31 weeks GA. No gender effects were found in sleep-wake cyclicality amplitudes at any time point.

Mean-level differences between sleep-wake cyclicality of the HR and LR groups at 34, 35, 36, and 37 weeks GA were examined with univariate analysis of variance. At 34 and 35 weeks GA, no differences were found. However, at 36 and 37 weeks GA the LR group showed a more organized sleep-wake cycle: $F(1, 40) = 4.51, p < .05$, ES = .11, at 36 weeks GA, and, $F(1, 39) = 12.22, p < .01$, ES = .21, at 37 weeks GA. These data suggest that around term age, differences between the high- and low-risk groups begin to emerge.

Vagal tone. The developmental trajectory for vagal tone is presented in Figure 2. Of a total of 266 samples collected, 18 ECG samples were unanalyzable owing to technical problems. Missing observations included one each at 28, 30, 32, and 33 weeks GA; two each at 29, 31, and 34 weeks GA; and three each at 36 and 37 weeks GA.

Similar to sleep-wake cyclicality, trend analysis for the vagal tone data of the HR group was carried out during the transition period, at 30, 31, 32, 33, and 34 weeks GA. The developmental trajectory of the vagal tone between 30 and 34 weeks gestation was significantly more complex than that of the sleep-wake cycle, showing several highly significant trends: a linear trend, within-subject sphericity assumed $F(4, 13) = 33.11, p < .01$, ES = .67; a quadratic trend, within-subject sphericity assumed $F(4, 13) = 13.46, p < .01$, ES = .45; and a cubic trend, within-subject sphericity assumed $F(4, 13) = 19.24, p < .01$, ES = .54. These multiple trends suggest that the regulation of the vagal brake first declines, then returns to baseline, and only subsequently goes through a developmental reorganization. Planned contrasts revealed a significant change between 30 and 31 weeks GA, when the vagal tone decreases, $F(1, 16) = 28.05, p < .01$; a significant change between 31 and 32 weeks GA, when the vagal tone returns to baseline, $F(1, 16) = 16.73, p < .01$; no change between 32 and 33 weeks GA, $F(1, 16) = 0.20, ns$; and a significant increase

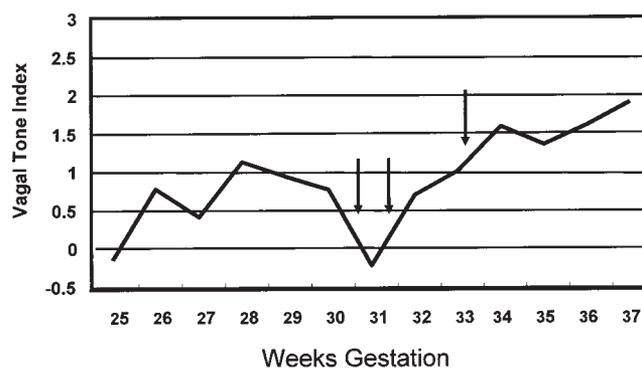


Figure 2. Developmental trajectory of cardiac vagal tone from 25 weeks gestational age to 37 weeks gestational age in high-risk premature infants.

between 33 and 34 weeks GA, $F(1, 16) = 5.87, p < .05$. Mean Vna was 1.02 ($SD = 0.42$) at 33 weeks GA and 1.59 ($SD = 0.59$) at 34 weeks GA. Trend analysis for vagal tone at 35, 36, and 37 weeks GA showed no significant trend, within-subject sphericity assumed $F(3, 14) = 1.46, ns$, indicating that following the very dynamic period in the development of the vagal tone, there is a period of consolidation with no developmental change.

Paired-samples t tests with Bonferroni corrections were computed for vagal tone between subsequent time points prior to 30 weeks GA for infants with data on these two time points. No significant changes between any two time points were found, underscoring the period between 30 and 34 weeks GA as the stage of reorganization for both oscillators: the sleep-wake cycle and the vagal tone. With regard to individual infants, it was found that at 33 weeks GA, only 3 infants showed a Vna similar to the one observed at term age for that group, as compared with 14 infants who showed such a Vna at 34 weeks GA, $\chi^2(1, N = 17) = 4.01, p < .05$.

Differences between the HR and LR groups were not observed at 34 weeks GA. Marginal differences emerged at 35 weeks GA, $F(1, 40) = 3.25, p < .07$, and significant differences were found at 36 weeks GA, $F(1, 40) = 5.34, p < .05, ES = .13$, and at 37 weeks GA, $F(1, 39) = 11.02, p < .01, ES = .20$. It thus appears that the growth rate of these oscillators differentiates premature infants born at high and low biological risk.

Group Differences at Term Age and at 3 Months

Term age: Sleep-wake cyclicity, vagal tone, and orientation. Differences between the three groups in sleep-wake cyclicity, vagal tone, and NBAS orientation were examined with univariate analyses of covariance. Data from the final assessment at 37 weeks GA were used for premature infants, and data from the second

postbirth day were used for FT infants. All infants in the study were tested in the day of discharge from the hospital. However, although all infants reached full term by the time of the final assessment (i.e., >36 weeks GA), there were differences between the preterm and FT groups in the infant's actual GA at the final assessment (premature infants, $M = 37.4$ weeks GA; FT infants, $M = 39.1$ weeks GA). To control for the infant's postconceptual maturity, the infant's GA at the final assessment was entered as a covariate. Following significant findings, post hoc comparisons with Duncan's tests were applied. These data are presented in Table 2.

As seen in Table 2, sleep-wake cyclicity and cardiac vagal tone showed a linear-decline pattern, with FT infants scoring most optimally, LR premature infants scoring lower, and HR infants displaying the poorest maturation. In neurobehavioral orientation, differences were found only between the HR group and the other two groups.

Associations between the three neonatal indices at term age are presented in Table 3. The three neonatal measures were interrelated: More organized sleep-wake cyclicity was related to better orientation; vagal tone correlated with better orientation; and sleep-wake cyclicity was related to higher vagal tone.

Three months: Synchrony, arousal modulation, and emotion regulation. Differences in the parameters of synchrony were examined among the three groups. At this stage, the postconceptual age of the three groups was identical, as premature infants were examined at 3 months corrected age, which was corrected to full gestation. Synchrony of all types was more prevalent in the FT group as compared with the two premature groups, $\chi^2(1, N = 71) = 4.70, p < .05$, but no differences were found between the LR and HR groups. Differences between the FT and the premature groups were related to differences in the infant-leads/mother-

Table 2
Group Differences in Study Variables at Term Age and at 3 Months

Variable	High risk (A)			Low risk (B)			Full term (C)			Univariate F	ES
	M	SD	SEM	M	SD	SEM	M	SD	SEM		
Term age											
Sleep-wake cyclicity ^a	13.13	4.78	.98	16.82	5.50	.94	19.95	8.68	.91	9.63** a<b<c	.17
Vagal tone	0.96	0.45	.11	1.85	1.01	.19	2.67	1.42	.15	18.56** a<b<c	.37
Orientation (NBAS) ^b	5.02	0.88	.19	5.41	0.68	.13	5.57	0.73	.12	3.47* a<b,c	.08
3 months											
Synchrony											
Synchrony (coherence) ^c	.13	.07	.03	.15	.08	.01	.18	.10	.01	3.95* a<b,c	.09
Time lag to synchrony	3.04	2.01	.33	2.77	1.65	.31	2.45	1.18	.21	1.44	<i>ns</i>
Emotion regulation											
Threshold (s)	141.17	84.13	24.20	152.60	65.62	8.09	237.27	93.10	10.98	8.62** a,b<c	.16
Negative emotionality	.13	.09	.03	.06	.05	.02	.02	.03	.02	12.33** a>b>c	.20
Arousal modulation											
Mid-range reactivity ^d	.44	.21	.05	.52	.29	.02	.63	.31	.01	7.44** a<b<c	.11
No reactivity ^e	.39	.27	.04	.48	.21	.04	.55	.33	.03	8.28** a<b<c	.12

^a Measured by the amplitude of the basic cycle on the power spectra. ^b NBAS = Neonatal Behavior Assessment Scale. ^c Numbers represent the largest coefficient on the cross-correlation functions plot. ^d Numbers represent proportion of time infant was in mid-range reactivity during "stimulus on." ^e Numbers represent proportion of time infant was in no reactivity during "stimulus off."

* $p < .05$. ** $p < .01$.

Table 3
Bivariate Correlations Between Study Variables

Variable	1	2	3	4	5	6
1. Mother–infant synchrony (3 months)	—	.27*	.37**	.35**	.34**	-.10
2. Sleep–wake cyclicality (term age)		—	.39**	.34**	.30*	-.27*
3. Vagal tone (term age)			—	.32**	.24*	-.41**
4. Orientation (term age)				—	.15	-.30*
5. Arousal modulation (3 months)					—	-.12
6. Negative emotionality (3 months)						—

* $p < .05$. ** $p < .01$.

follows type of synchrony, $\chi^2(1, N = 71) = 4.70, p < .05$, the more optimal form of synchrony at this age. Mutual synchrony was observed in 1 dyad of the HR group, in 2 dyads of the LR group, and in 5 dyads of the FT group, with no significant differences between groups, $\chi^2(1, N = 71) = 1.79, p > .10$. As seen in Table 2, the coherence (degree of synchrony) variable showed a significant main effect of group. Post hoc comparisons indicated significant differences between the HR and FT groups, with LR infants scoring in the middle. No differences in the time lag to synchrony were found between groups.

To examine whether synchrony of all types was more prevalent among infants who displayed higher vagal tone in the neonatal period, infants were divided into high- and low-vagal-tone groups using the median split (median $V_{na} = 1.80$). Among the low-vagal-tone group, synchrony was observed in 13 dyads, and in 23 dyads no synchrony was detected. On the other hand, among the high-vagal-tone group, synchrony was observed in 25 dyads, as compared with 10 dyads that did not display any form of synchrony, $\chi^2(1, N = 71) = 8.89, p < .01$.

Similar links were examined between sleep–wake cyclicality and mother–infant synchrony. The cyclicality variable was divided using the median split (median amplitude of basic cycle = 14.23) into organized and disorganized sleep–wake cycle groups. Among the infants of less organized cyclicality, 21 did not show any form of synchrony, whereas in 15 dyads synchrony was observed. Among the more organized sleep–wake cyclicality group, 12 infant–mother dyads did not show any form of synchrony, as compared with 23 synchronous dyads, $\chi^2(1, N = 71) = 4.12, p < .05$. These data indicate that the organization of physiological rhythms in the neonatal period contributes to the formation of mother–infant synchrony in early infancy.

To examine the relations between the development of sleep and heart rhythms in individual infants and later mother–infant synchrony, the 4 infants who did not show a phase shift in the development of the sleep–wake cycle or vagal tone following the transition period for that pacemaker (within one standard deviation of the mean) were tested for the existence of synchrony. These included 1 infant with a low amplitude of sleep–wake cyclicality at 31 weeks GA, 2 infants with a low V_{na} at 34 weeks GA, and 1 infant who had low cyclicality and a low V_{na} . No synchrony of any type was observed in any of these children at 3 months corrected age, suggesting that a delay in the development of physiological oscillators during the dynamic period may impinge on the development of mother–infant affective matching.

Differences between the three groups emerged for emotion regulation and arousal modulation. As seen in Table 2, differences were found in emotion regulation, indexed by the threshold to the first cry and by the proportions of negative emotionality. The two preterm groups showed lower thresholds to negative affect and cried during the more mild stimuli as compared with the FT group. In negative emotionality, a linear-decline pattern was found, with the FT group displaying the least negative affect, the LR group scoring lower, and the HR group showing the most negative affect. These findings emphasize the role of higher infant gestational age at birth in buffering against aversive environmental stimuli.

In general, more preterm than FT infants cried during the procedure. In the HR group, 12 infants cried and 5 did not; in the LR group, 15 infants cried and 10 did not; and in the FT group, 10 infants cried and 19 did not during the procedure, $\chi^2(1, N = 71) = 6.04, p < .05$. The frequencies of cry episodes also differentiated the three groups, with the HR infants crying on average 2.55 ($SD = 2.18$) times during the procedure, the LR group averaging 1.33 ($SD = 2.23$) cries, and the FT group crying on average 0.44 ($SD = 0.98$) times during the procedure, $F(1, 36) = 4.08, p < .05, ES = .09$.

Assessing the relations between physiological rhythms and emotion regulation, it was found that significantly more infants in the low-vagal-tone group cried during the procedure as compared with infants in the high-vagal-tone group, $\chi^2(1, N = 71) = 4.12, p < .05$. Similar associations between sleep–wake cyclicality and threshold were examined but were not found.

Predicting Mother–Infant Synchrony

Prior to computing the regression, bivariate correlations between the predictor variables were computed and are presented in Table 3. As seen in the table, the three neonatal indices at term age—sleep–wake cyclicality, vagal tone, and neurobehavioral orientation—were interrelated. Mother–infant synchrony was related to each of these indices as well as to arousal modulation, and sleep–wake cyclicality and vagal tone at term age were each related to lower negative emotionality at 3 months.

Predicting synchrony from neonatal and 3-month variables. A hierarchical regression equation was used to predict the level of mother–infant synchrony. The criterion variable was the coherence variable (degree of synchrony), indexed by the largest cross-correlation coefficient on the CCF plot. Predictors were entered in six blocks in a theoretically determined order. In the first block, the infant's medical risk was entered, indexed by the CRIB score. Medical risk was entered first to partial out variance related to biological risk in the prediction of synchrony. The next three blocks included the neonatal measures. Sleep–wake cyclicality at term was entered as a measure of the biological clock in the second block, and vagal tone at term age was entered in the third block. In the fourth block, the orientation cluster of the NBAS was entered. The two oscillators were entered prior to the orientation variable owing to their central importance for the present investigation. In the final two blocks, the 3-month measures of arousal modulation and negative emotionality were entered, to examine the contribution of the infant's current ability to regulate emotions to the development of synchrony above and beyond the physiological and neurobehavioral measures collected at the neonatal period. Results of the regression model are presented in Table 4.

Table 4
Predicting Mother–Infant Synchrony

Predictor	β	R	ΔR^2	ΔF	df
Medical risk (CRIB)	.11*	.17	.03	2.18	2, 69
Sleep–wake cyclicality	.05	.29	.05	3.97*	3, 68
Vagal tone	.32*	.40	.08	6.04*	4, 67
Orientation	.25*	.46	.05	4.22*	5, 66
Arousal modulation	.27*	.52	.07	5.95*	6, 65
Negative emotionality	–.13	.53	.01	1.20	7, 64

Note. R^2 total = .29; $F(7, 64) = 4.35$, $p < .001$. CRIB = Clinical Risk Index for Babies.

* $p < .05$.

As seen in Table 4, sleep–wake cyclicality, vagal tone, orientation, and arousal modulation were each uniquely predictive of mother–infant synchrony at 3 months. Negative emotionality did not contribute to the prediction of synchrony above and beyond these measures. The findings thus demonstrate that the organization of biological rhythms, the infant’s capacity to orient to the environment, and the ability to regulate arousal efficiently all contribute meaningfully to the formation of mother–infant second-by-second synchrony.

Moderator models in the prediction of synchrony. Finally, the moderating role of arousal modulation on the relations between the two physiological oscillators and mother–infant synchrony was tested with two moderating regression equations. In each regression, synchrony was predicted by the oscillator (sleep–wake cyclicality or vagal tone), by arousal modulation, and by their interaction. The moderator model for vagal tone was significant and is presented in Table 5.

As seen in Table 5, vagal tone, arousal modulation, and their interaction were each uniquely predictive of mother–infant synchrony at 3 months. This suggests that the infant’s arousal modulation capacities moderate the relations between neonatal vagal tone and mother–infant synchrony at 3 months (Baron & Kenny, 1986). To examine the interaction, arousal modulation was divided at the median into two groups: infants scoring high and low on arousal modulation. Among infants low in neonatal vagal tone, differences in the degree of mother–infant synchrony between those low on arousal modulation ($M = .11$) and those high on arousal modulation ($M = .20$) was significant, $F(1, 34) = 19.07$, $p < .01$, $ES = .21$. On the other hand, among infants with high neonatal vagal tone, differences in synchrony between infants exhibiting low ($M = .17$) and high ($M = .17$) arousal modulation were not significant. These findings point to the importance of the infant’s acquired capacity to regulate arousal in accordance with environmental events for the emergence of interaction rhythms, particularly among infants with an initial slow development of the vagal brake. A similar moderating model for sleep–wake cyclicality was examined, but no significant moderating relationships were found.

Discussion

Systemic models of infant development propose that developmental milestones are achieved through the integration of biological, affective, relational, and contextual components as they dynamically organize in time (Fogel, 1993; Gottlieb, 1991; Lerner,

1998). Little research, however, has focused on biology–affect–relationships links across two periods of very early transition: the third-trimester prenatal transition in biological rhythms (Peirano et al., 2003) and the 2-month transition in social communication (Lavelli & Fogel, 2005). The present study provides a first account on the trajectories of two physiological pacemakers prior to term, their dynamic involvement in relation to each other, and their contribution to mother–infant coordination. The concept of time has been an important component in philosophical inquiries that perceive human existence as defined by the experience of time (Bergson, 1907), in biological perspectives that claim that living systems can be understood only in reference to their involvement in time (Edelman, 1989), and in dynamic systems models that consider time an indispensable parameter of emerging systems (van Geert, 1994)—but it has received relatively little attention in developmental science. To integrate the concept of time into the study of early development, the present study focused on the temporal parameters of biological and affective phenomena. Second-by-second changes in sleep–wake states and in maternal and infant’s affective behavior were coded; arousal modulation was assessed on the basis of microlevel reactivity to changing events; and weekly observations addressed the development of physiological pacemakers during their dynamic transition. Such a focus on time afforded new insights on the relations of biological and social processes and further supports the central role of biological rhythms in the study of infant development (Sollberger, 1965; Thelen, 1979; Winfree, 1980).

The growth curves of sleep–wake cyclicality and cardiac vagal tone provide examples of a dynamic system during its developmental transition. According to dynamic systems notions (Prigogine & Stengers, 1984; Thelen & Smith, 1994; van Geert, 1994), the development of living systems occurs in phase shifts—that is, short periods of growth spurts followed by longer periods of stabilization. As seen, little change in either sleep or heart rhythm was observed before the dynamic period, between 25 and 30 weeks GA. Growth during that time was gradual, nonlinear, and cumulative without significant changes from one week to the next. During the period of transition, however, development was rapid, and functioning on both pacemakers changed significantly within a short period of time. Following this dynamic period, the system stabilized and no quick changes were observed until term age. It can thus be suggested that the period between 30 and 34 weeks GA functions as a unique period of transition in early development, related in part to the emergence of physiological pacemakers. This period appears to provide a crucial foundation for the development

Table 5
Moderating Role of Arousal Modulation on the Relations of Biological Rhythms and Mother–Infant Synchrony

Predictor	β	R	ΔR^2	ΔF	df
Sleep–wake cyclicality	.30	.27	.07	5.55*	2, 69
Vagal tone	.69**	.39	.08	6.84*	3, 68
Arousal modulation	.77*	.46	.06	5.95*	4, 67
Cyclicality \times Arousal Modulation	.33	.47	.01	.81	5, 66
Vagal Tone \times Arousal Modulation	–.88**	.60	.13	11.58**	6, 65

Note. R^2 total = .36; $F(6, 65) = 7.33$, $p < .01$.

* $p < .05$. ** $p < .01$.

of social engagement and interpersonal coordination. Because very few studies have followed infants longitudinally from the prenatal or neonatal periods, much further research is required to examine the links between the development of physiological oscillators during the third trimester of pregnancy and developmental outcomes.

It is interesting to note that within this dynamic period of growth, the two pacemakers synchronized their phase shift, with the sleep–wake cycle consolidating between 30 and 31 weeks GA and the shift in vagal tone following between 33 and 34 weeks GA. Moreover, during the period of rapid growth in sleep–wake organization, there was a delay in the development of the vagal brake. Circadian rhythms are thought to resemble cardiac rhythmicity, as the two systems involve the hierarchical organization of several oscillators and both are highly sensitive to environmental inputs (Healy, 1991). The present data further show that the growth spurts of these two systems occur in concert. The notion that a developmental function may be periodically inhibited after an initial appearance and prior to its full-blown expression has been described for various functions, such as walking (Thelen & Ulrich, 1991), and the period of inhibition is hypothesized to enable the development of other functions and to provide a nesting period after which the specific function appears under higher mechanisms of control. A somewhat similar pattern was observed here, with inhibition of the vagal brake during the reorganization of the sleep–wake cycle and a developmental leap in vagal tone appearing shortly thereafter. Moreover, it has been suggested that during the dynamic period of systemic transition, variability among individuals is at its peak and predicts later functioning (Emde, 1994; Thelen & Smith, 1994). The present data are consistent with this view and indicate that the infants who did not show a timely phase shift in the two oscillators also did not engage in a synchronous interaction with their mother at 3 months. Thus, interventions that have been shown to improve sleep–wake cyclicality and vagal tone in HR premature infants, such as Kangaroo Care or cycled lighting, should be targeted to the sensitive period of the beginning of the third trimester, especially as such interventions were found to speed the growth rate of the two oscillators (Feldman & Eidelman, 2003; Feldman et al., 2002; Rivkees, 2003). In timing these interventions, both the general period of transition, that is, the time between 30 and 34 weeks GA, and the precise timing of development for each pacemaker, that is, 30 weeks GA for the biological clock and 33 weeks GA for vagal tone, should be taken into consideration.

More generally, the findings contribute to our understanding of the dynamic, process-oriented nature of physiological and social growth. They suggest that physiological systems, such as the biological clock, develop on the basis of intrauterine conditions, the exact time of birth, the nature of the interaction between the organism's state at birth and the environment, and specific environmental provisions, such as focused interventions that are targeted to a sensitive period for the development of specific functions.

The associations between mother–infant synchrony at 3 months and the infant's later cognitive and symbolic skills, self-regulation, and social–emotional adaptation have been well validated. The present study examined the antecedents, rather than the consequences, of mother–infant synchrony, and the data seem to suggest that interpersonal synchrony is rooted in biological pacemakers. In

combination, these studies chart a neurodevelopmental trajectory from brainstem-mediated systems that maintain physiological homeostasis to limbic structures implicated in the processing of affectively charged stimuli to prefrontal systems that inhibit, represent, and regulate emotional behavior and symbolic thought. Consistent with the formulations of Hofer (1995), it is possible that the initial openness of the infant's endogenous pacemakers to the external regulation of the mother affords the possibility that physiological pacemakers can facilitate the emergence of interactive synchrony between two separate timing systems within an attachment relationship.

HR premature infants displayed disorganized biological rhythms, lower levels of mother–infant synchrony, a limited capacity for arousal modulation, and lower thresholds to negative emotionality. As seen, effect sizes for sleep–wake cyclicality and vagal tone at term age were large. This reflects the extreme-case prospective design used here, which has been recommended as a method of choice for research in developmental psychopathology (Lewis, 1990). The numbers of HR premature infants born prior to the third trimester are continuously on the rise, as a result of rapid advances in medical technology. Such infants miss the intrauterine development of both the biological clock (Mirmiran et al., 2003) and the parasympathetic control over heart rhythms (Groome et al., 1999). In addition, typical neonatal intensive care conditions that include continuous light and aversive sound further disrupt the development of the biological clock (Hao & Rivkees, 1999). Possibly, one of the detrimental outcomes of extremely premature birth is the permanent damage to biological pacemaker systems and their homeostatic impact. Consequently, the infant's preparedness to engage in critical experiences with the environment, such as synchronous parent–infant interactions, is diminished, and the child's brain is less competent at extracting formative experiences from the social and nonsocial environment. Still, at 3 months, effect sizes for mother–infant synchrony and infant arousal modulation were medium. This suggests that with development, biology and context shape each other in a mutually influencing manner, and more favorable environments may function to attenuate the effects of major physiological delays (Sameroff, 1995). The decrease in effect size was especially notable in mother–infant synchrony, which depends as much on the mother's sensitive attunement as on the infant's biological preparedness.

The main reason for including the LR premature group was to compare the emergence of biological and interaction rhythms, as well as other regulatory capacities, when pregnancy is truncated before or after the consolidation of physiological pacemakers. In general, premature infants born 1 or 2 weeks prior to term and at a birth weight of 1,750 g and above are not considered to be at high developmental risk, and most current studies focus on infants born at very low birth weight or at substantially higher risk. The data, however, show that these supposedly low-risk infants do not function at the level of their full-term peers on most measures of physiological and emotion regulation. Sleep–wake cyclicality amplitudes and vagal tone of the LR infants were significantly lower than those of the FT group. Although the LR group did not differ from the FT group on the continuous measures of synchrony and on neonatal orientation, on negative emotionality and arousal modulation LR infants scored significantly below the FT group. Moreover, in thresholds to negative emotionality—the degree of environmental intrusion required to elicit negative affect—LR

preterm infants did not differ from the HR group. These findings underscore the buffering effect of a full gestation for the development of the infant's capacity to screen aversive environmental inputs. Because of the critical importance of emotion regulatory experiences for the infant's neuromaturation, it is important to keep monitoring these low-risk premature infants on the more fine-grained indices of negative affect, regulation, arousal, and stress reactivity, although such infants may show typical development on global measures of cognition and social adaptation.

Similar to the measures of biological and interaction rhythms, the measure of arousal modulation used here was time based. It assessed the infant's capacity to flexibly adjust the level of arousal to the presentation and termination of environmental stimuli. Previous studies have shown that efficient information processing at 3 months is associated with more predictable cyclic oscillations between medium and low arousal during the presentation of new stimuli (Feldman & Mayes, 1999). As demonstrated, arousal modulation was related both to the broader shifts in arousal between sleep and wake states and to the more finely tuned organization of heart rhythms under the regulatory control of the parasympathetic system (i.e., vagal tone) and to the dyadic synchronous matching of internal cycles of affective engagement and disengagement. Similar to synchrony, arousal modulation is organized in stochastic (probabilistic) rhythmicity and represents a rhythmic structure that is more closely dependent on the interaction between the infant and its environment than on predetermined periodic rhythms. The moderator model demonstrates that the infant's acquired capacity to regulate arousal in accordance with the changing environmental demands is especially important for infants with lower neonatal vagal tone in order to develop mother–infant synchrony. Biological rhythms provide the foundation for the emergence of interaction synchrony. When the infant's endogenous rhythms are immature, arousal modulation—a skill that depends on the mother's sensitive style as much as on the infant's inborn regulation (Feldman, 2004)—may provide an additional avenue for the child to engage in a temporally matched social dialogue.

The relations between biological and social rhythms, between periodic and stochastic time-keeping mechanisms, and between inborn pacemakers and attachment relationships require much further research in healthy and at-risk infants. Future research should follow children longitudinally and examine the interactive contributions of endogenous rhythms and synchronous relationships to the development of symbolization, creativity, empathy, and social adaptation. The synchronization of the developmental transition in the two oscillators may suggest that the body functions as a dynamic system that continuously evolves through the ongoing interaction with the external environment, and future research might explore other links among various physiological systems and between those systems and the caregiving context. The organization of events along the continuum of time is among the most fundamental experiences of human existence. Understanding the infant's entrance into a time-bound existence, which synchronizes inborn pacemakers with the changing environment, may be among the most intriguing topics for developmental research.

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