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Mother–Infant Activity Synchrony as a Correlate of the Emergence of Circadian Rhythm

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Abstract

Objective: Entrainment to the day–night cycle is critical for infant sleep and social development. Synchronization of infant circadian systems with the social 24-hr day may require maternal activity signals as an entraining cue. This descriptive and exploratory research examines the activity level and circadian pattern in mothers and infants. Method: Twenty-two healthy mothers and their infants (postnatal age 49.8 $\pm$ 17.1 days) wore actigraph monitors for seven days. Daytime (06:00–21:59) and nighttime (22:00–05:59) activity levels and circadian parameters of rest–activity patterns (i.e., mesor, amplitude, acrophase, and 24-hr cosinor fit) were calculated. Results: Mothers and infants were significantly more active during the day than at night. The goodness-of-fit index for the model (R2) indicates that circadian rhythm accounted for a mean of 29 $\pm$ 10% and 12 $\pm$ 8% of the variability in maternal and infant activity, respectively. Acrophase of activity occurred at 15:46 $\pm$ 1:07 for the mothers and 15:20 $\pm$ 1:21 for the infants. The mean within-dyad correlation of activity counts was $r = .46 \pm .11$, and the within-dyad correlation was associated with the amplitude ($r = .66$, $p < .01$) and 24-hr cosinor fit of infant activity ($r = .67$, $p < .01$). Conclusions: Our findings suggest maternal rhythms as a possible exogenous influence on shaping an infant's emerging rhythms and synchronizing them with the external light–dark cycle. Strong pattern synchrony between maternal and infant activity may support infant circadian entrainment and enhance a regular 24-hr sleep–wake schedule during the early postnatal weeks.

Keywords

infants, mothers, activity, circadian rhythm, entrainment

An irregular sleep–activity pattern is the most common concern reported by parents in well infant visits. Such patterns may persist through infancy and contribute to sleep problems later in childhood (Touchette et al., 2005; Zuckerman, Stevenson, & Bailey, 1987). Infant entrainment to the 24-hr day–night cycle is critical for parental and infant sleep and ensures that the infant's physiologic functions and behaviors are properly timed with the environment. Fitting into the family's daily schedule also aids in infant social development. Mothers constitute the primary physical and social environment for young infants; therefore, synchronization of the infant circadian system with the social 24-hr day may require maternal activity signals as an entraining cue.

Circadian rhythms are approximately 24-hr rhythms observed in physiological, psychological, and behavioral functions. The human sleep–wake cycle is one of the most well-known circadian rhythms. The timing of sleeping and waking is regulated by the interaction of a homeostatic mechanism and a circadian timing system (Borbély, 1982; Borbély, Achermann, Trachsel, & Tobler, 1989; Daan, Beersma, & Borbély, 1984). The homeostatic component mediates the accumulation of sleep pressure during waking and its dissipation during sleep. The circadian component regulates the sleep–activity cycle into a 24-hr rhythm independent of prior sleeping and waking (Borbély, 1982; Dijk & Czeisler, 1995). Endogenous circadian rhythms with a period close to 24 hr are entrained by zeitgebers, which are the environmental factors that serve as the external clock providing time cues.

Human circadian systems develop during fetal life and continue to mature during the neonatal period (Mirmiran, Kok, Boer, & Wolf, 1992; Seron-Ferre, Torres-Farfan, Forcelledo, & Valenzuela, 2001; Swaab, Hofman, & Honnebier, 1990).

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Findings from studies in rodents suggest that the fetal biological clock can be entrained by maternal signals as early as the middle of gestation and that prenatal maternal entrainment extends into the postnatal period (Reppert, Weaver, & Rivkees, 1988). With the transition from fetal to extrauterine life, maternal entrainment is needed because newborns lose the mother's rhythmic, temporal input when separated at birth. Several studies in human infants have suggested that regular social stimuli provided by the caregiver augment the day–night organization of infant behavior. Sander, Julia, Stechler, and Burns (1972) demonstrated that infants cared for by a single caregiver under rooming-in conditions achieved day–night differentiation of rest and activity earlier than those cared for by multiple caregivers in a nursery environment. In an intensive single case study, McGraw, Hoffmann, Harker, and Herman (1999) suggested that maximizing daylight exposure and maintaining a fixed family daily schedule facilitate rapid establishment of infant circadian rhythms in temperature, melatonin, and sleep–wake behavior. Lohr and Siegmund (1999) further concluded in their review that maternal interaction provides the most important entraining signals before the infant's visual pathways are fully matured for photo-entrainment.

Parent–infant interactive synchrony is well documented in developmental psychology as contributing to the development of infant social–emotional adaptations and self-regulatory capacities in the first months of life (Feldman & Eidelman, 2004; Feldman, Greenbaum, & Yirmiya, 1999). Few studies, however, have examined the development of infant circadian rest–activity rhythms in relation to maternal rhythms and the mother's role of behavioral entrainment. Maternal polysomnographic and infant actigraphic data collected by Nishihara and Horiuchi (1998) showed that maternal nocturnal wakefulness corresponded with their infants' nocturnal activity levels from the 1st to the 6th week after birth. Their later work showed an inverse association between mother nocturnal activity levels and the strength of their infant's circadian rest–activity rhythms (Nishihara, Horiuchi, Eto, & Uchida, 2000). Longitudinal actigraphic recordings of mother–infant pairs further demonstrated a strong synchrony between maternal and infant diurnal rest–activity rhythms. This synchrony is thought to promote a rapid development of entrained rhythms in infants during the early postnatal period (Nishihara, Horiuchi, Eto, & Uchida, 2002; Wulff, Dedek, & Siegmund, 2001).

To date, most studies of mother–infant circadian rhythms have focused on the strength and length of the mother's and infant's rhythms. We found no data on circadian timing of activity in mothers and infants in the literature. The present study extends current knowledge about the concept of postnatal maternal entrainment using cosinor analysis of time-series data to quantify rhythmic properties of 24-hr circadian rest–activity patterns. The purpose of this exploratory study was to examine the potential influence of maternal rest–activity patterns on the development of infant diurnal and circadian rhythms in behavioral activity. The specific aims were to (a) describe the daytime and nighttime activity levels of mothers and infants, (b) describe the circadian rest–activity patterns in mothers and infants, and (c) examine the relation between maternal and infant activity levels and circadian rest–activity patterns.

Materials and Method

Participants

This study was part of a larger study examining light exposure and rest–activity pattern in mothers and infants. Mothers and infants were recruited from pediatric and maternal–infant care clinics in Seattle. Information about the study was also advertised in local childbirth classes, and study flyers were posted on a university research recruitment webpage and at several locations near the university. Eligible mothers were >18 years of age, biological first-time mothers, primary caregivers of their babies, not experiencing postpartum depression, and had no medical complications during pregnancy and the postpartum period. Eligible infants had been born a singleton in a vaginal birth at between 38 and 42 weeks' gestation, were between 2 and 10 weeks' postnatal age, and were the first born child in a family with only one child. We recruited 26 healthy mother–infant pairs, but only 24 pairs participated due to scheduling difficulties. Of the 24 pairs who participated in the study, 2 did not provide consistent data and were excluded from the analysis.

Procedures

Interested mothers called the investigator who explained the purpose of the study and discussed study procedures. Mothers provided the investigator with their demographic and health information to confirm eligibility. During the telephone interview, mothers gave oral consent to screening for postpartum depression using the Edinburgh Postnatal Depression Scale (EPDS; Cox, Holden, & Sagovsky, 1987). Mothers were not enrolled in the study if they scored 13 or above on the EPDS. Once the mother and her baby's eligibility was confirmed, the investigator arranged a home visit. During the home visit, the investigator further explained the study procedures and obtained a signed informed consent form from the mother. Over the course of the 7-day in-home monitoring, mothers were instructed to wear an actigraph on their nondominant wrist and to keep another actigraph on their infant's ankle at all times. Each mother was given a diary to record her infant's and her own sleep–wake times and the times when the monitor was removed and when the infant was exposed to external motion, such as infant swings and caregiver walking. To reinforce protocol compliance and answer any questions that the mother might have, the investigator made two follow-up phone calls during the 7 days of home monitoring. After the week of data collection, the investigator returned to the home to collect the monitors and diaries. Due to potential adjustment of sleep schedules, eligible mothers and infants were not studied within the 2 weeks after the transition into or out of daylight savings time. The study was approved by the Institutional Human Subjects Review Board.

Instruments

EPDS. The EPDS (Cox et al., 1987) is the most widely used self-report screening tool for postpartum depression. We administered the scale as part of the telephone screening because previous researchers have reported that maternal depression was associated with altered sleep patterns in infants and postpartum women (Armitage et al., 2009; Posmontier, 2008). The EPDS has 10 items scored using Likert-type scales (0–3) based on reported severity of symptoms during the past week. The total score is between 0 and 30. A cutoff score of $\geq$13 has been used to indicate possible postpartum depression (Boyce, Stubbs, & Todd, 1993; Cox et al., 1987; Murray & Carothers, 1990). Using a cutoff score of 13, at 6 weeks and 3 months postpartum, the sensitivity, specificity, and positive predictive value of the EPDS were 68% and 86%, 96% and 78%, and 67% and 73%, respectively, when compared with diagnoses of major depression made using Goldberg's Standardized Psychiatric interview (Cox et al., 1987; Murray & Carothers, 1990). The EPDS has high internal consistency (Cronbach's $\alpha = .87$) and split-half reliability ($r = .88$; Cox et al., 1987). The Cronbach's α of the EPDS in this study was .75.

Actigraphy. Maternal and infant activity was measured using an ambulatory monitoring system (Actiwatch-L, MiniMitter-Respironics Co., Inc., Bend, OR, USA). The actigraphic monitor is a lightweight, wristwatch-like, computerized device with an accelerometer sensitive to body movement in all directions. It can provide continuous activity recordings with minimal disruption of an individual's ongoing behavior. The device records activity counts by integrating the degree and speed of motion. Activity counts that vary in magnitude were stored and accumulated over a designated interval. Prolonged actigraphic recordings for multiple days provide important chronobiological information on rest–activity rhythms, which can be analyzed by mathematical/statistical methods such as cosinor analysis. Actograms, a graphical display of the raw activity counts recorded by an actigraphy device, also facilitate visual assessments of activity patterns. For the current study, maternal and infant activity data were collected concurrently at 30-s intervals. This sampling rate and length for activity data acquisition is substantially higher than the minimal requirement to capture a cycle with a 24-hr period (Lentz, 1990; Thomas & Burr, 2008).

Sleep–activity record. Mothers completed a sleep–activity record (Barnard, 1999) of their own and their infants' sleep–wake behaviors at 15-min intervals using alphabetical codes (S = sleep; W = wake; O = watch off). Although mothers were not expected to complete the activity record continuously throughout the night, they were asked to record in the diary times at which they were awakened by their infants during their nocturnal sleep period. Mothers also recorded their own behavior with respect to their infant, such as feeding, carrying, rocking, or moving the infant (e.g., in a stroller or in a car). These recorded data were used to assist in analyzing the actigraphy data, because identification of potential artifacts enhances the validity of actigraphic assessment of activity counts (Tsai, Burr, & Thomas, 2009). Mothers also reported their sleeping arrangements with their infants every night during the week. Parent diaries are widely used in infant behavior research and are accurate sources for reporting daily activities. Significant correlations have been found between diary-reported and actigraphy-derived infant sleep onset time ($r = .88$–$.96$) and nocturnal sleep duration ($r = .74$–$.87$; Sadeh, 1996, 2004). In adults, sleep-diary data were found to have a high percentage of agreement (Kappa = .87) with polysomnography recordings (Rogers, Caruso, & Aldrich, 1993).

Data Treatment and Analysis

Activity data were downloaded to a personal computer at the end of the study week. Short periods when the monitor was not worn due to showers and baths, as documented in the diary, comprised 1.3% of the total recording time for the mothers and 1.6% for the infants across the sample. These data were coded as missing and then replaced by the mean value of the two adjacent activity counts calculated from within each subject. Infant activity data from 37.8% of the total recording time were excluded from analysis because the infants were exposed to external motion, including riding in a car or stroller, infant swings, and other holding and bouncing, and so on. Although these artifact epochs were omitted, the cosine-fitting function is robust to unequally spaced data points when measurements are obtained over several cycles (Monk, 1987; Nelson, Tong, Lee, & Halberg, 1979). Mean, median, and maximum activity (counts per 30-s interval) were calculated across all epochs for the 7 days of recording by day (defined as 06:00–21:59) and night (22:00–05:59) for each subject and then reported as a group. The daytime and nighttime intervals were arbitrarily chosen because these are the typical adult wake and sleep hours and because the bedtimes and rise times of mothers of 2 to 10-week-old infants may not be readily distinguishable from awakenings during the beginning and end of their in-bed sleep periods. Descriptive group data were presented as mean $\pm$ standard deviation.

Circadian activity patterns in each mother and infant were examined using cosinor analysis to evaluate how well their activity patterns fit to a 24-hr period. Cosinor analysis is a statistical method of modeling cyclic behavior that involves a curve-fitting procedure to estimate the average level, magnitude, and timing of an individual's rhythm. The parameters that characterize a rhythm determined by cosinor analysis include cycle mesor (the mean value of a rhythm estimated by the cosinor curve), amplitude (the differences between the cosinor-estimated mean and maximum value), acrophase (timing of the peak cosine-fitted value), and R^2 cosinor fit (a goodness-of-fit measure indicating the percentage of variance in the data explained by the fitted cosine curve).

The 7 days of activity data collected for each mother and infant were log-transformed (base e) to normalize the data distribution and then fitted with a single 24-hr period (tau) using

Table 1. Maternal and Infant Activity Level and Circadian Pattern of Activity ($N = 22$)

	Mother		Infant	
	Day	Night	Day	Night
Activity level				
Mean[a]	144 ± 31	44 ± 23	72 ± 33	21 ± 10
Median[a]	80 ± 35	0 ± 3	12 ± 12	0 ± 0
Maximum[a]	1,967 ± 725	1,238 ± 776	1,395 ± 625	910 ± 484
Circadian pattern of activity				
Mesor, ln[count][b]	2.73 ± 0.27		1.96 ± 0.36	
Amplitude, ln[count][b]	1.89 ± 0.37		1.06 ± 0.44	
Acrophase, clock time	15:46 ± 1:07		15:20 ± 1:21	
R^2 cosinor fit	.29 ± .10		.12 ± .08	

[a] Activity counts were significantly different between day and night for mothers ($p < .001$) and for infants by paired t test ($p < .001$).
[b] ln[count] = $\log_e$[count], the natural logarithm of count.

least square regression analysis. Although a more complex cosinor model including various harmonic components (i.e., a period of 12, 8, or 6 hr, etc.) can be used to fit the data, only the fundamental 24-hr circadian periodicity was examined because it is the most clinically important for parents who want to synchronize their infant's rhythms to the normal 24-hr day. Cycle mesor, amplitude, acrophase, and the percentage of variance in the time-series activity data explained by the fitted cosine curve (R^2) were calculated for each mother and infant. The group means were computed on the above cosinor parameters derived from each mother and infant's data. Pearson correlation between each mother–infant pair activity series, infant postnatal age, and the aforementioned maternal and infant activity cosinor parameters was calculated to examine the relation between maternal and infant activity patterns. Two-tailed statistical significance was set at $\alpha < .05$.

Results

Sample Characteristics

Our final analysis consisted of 22 mother–infant pairs (12 female infants). Of the mothers, 21 (95.4%) had some college education and were married and living with the father of the baby. The mean age for mothers was 30.5 ± 4.3 years. The mean postnatal age for infants was 49.8 ± 17.1 days. Race and ethnicity distribution of the pairs was as follows: African American, 1; Asian, 4; Caucasian, 16; Hispanic, 1. Regarding the arrangement of night sleeping, 3 mother–infant pairs (13.6%) slept in the same bed, 8 (36.3%) slept in the same room but not the same bed, 9 (40.9%) had mixed sleeping arrangements (using both room-share and bed-share), and only 2 infants (9.1%) were solitary sleepers who slept in their own bedrooms. All infants were exclusively breastfed and the mean number of feeding episodes per day was 9.50 ± 2.14. Five mothers provided their infant with pumped breast milk for a total of 59 feeding episodes over the 7-day study period. The mean time spent per feeding was 25.3 ± 6.0 min. All mothers were either on maternity leave or had not returned to their work outside the home when they were studied. None of the women suffered from postnatal depression (mean EPDS total score 3.73 ± 2.96; a cutoff score of 13 indicated depression).

Activity Levels

Table 1 illustrates maternal and infant daytime and nighttime activity counts. Mothers and infants had significantly more activity during the day than at night, and mothers had about twice the mean activity count of infants. All infants and 20 mothers spent approximately half of the night immobile with zero activity. Figure 1 shows the actogram illustrating the activity record of one mother–infant pair in which the mother's activity pattern was in synchrony with the infant's. Figure 2 shows another actogram of a mother–infant pair that was less in synchrony in which the infant was up frequently throughout the night.

Circadian Activity Rhythmicity

Table 1 shows maternal and infant 24-hr pattern of activity. The goodness-of-fit index for the model (R^2) indicates that the circadian rhythm accounted for a mean of 29 ± 10% and 12 ± 8% of the variability in maternal and infant activity, respectively. We arbitrarily chose 10% variance to establish the definition of rhythm because it is consistent with a moderate correlation coefficient of ∼.35 (Cohen, 1987). The 24-hr cosinor fit for all mothers and 16 (72.7%) infants was >10%, supporting the presence of a circadian rhythm to various degrees in this sample. Maternal and infant peak activity levels occurred during afternoon hours, and their peaks were approximately 25 min apart. One infant had an inverse day–night rhythm with its acrophase occurring at approximately 7 p.m. Figure 3 shows the activity acrophase for mothers and infants. The activity acrophases in 5 mothers occurred before those of their infants, while 17 mothers' acrophases occurred after those of their infants. Figures 4 and 5 show the mean cosinor fit of activity count for the mother–infant pairs whose actograms are shown in Figures 1 and 2, respectively.

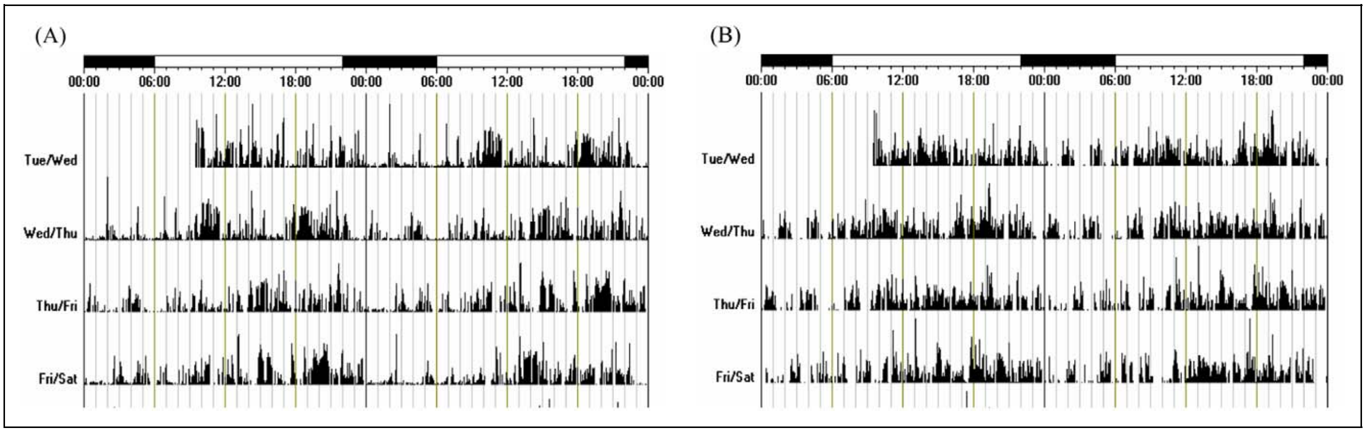

Figure 1. Sample double-plotted actograms show the daily rest–activity patterns of a 29-day-old infant (A) and his mother (B) over the first 72–96 hr of the study period. The vertical axes list the observation days and show the activity counts on an arbitrary scale with higher values suggesting more activity. The horizontal axes represent the time of day from midnight one day (0 hr) to midnight the next day (24 hr). The actograms indicate that the mother's activity pattern was in synchrony with the infant as both were relatively more active during the day than during the night.

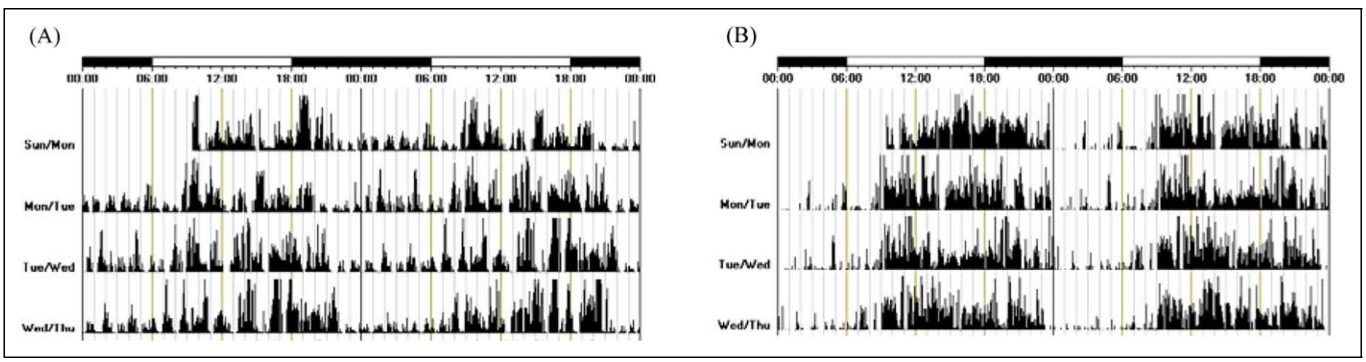

Figure 2. Sample double-plotted actograms show the daily rest–activity pattern of a 70-day-old infant (A) and his mother (B) over the first 72–96 hr of the study period. The vertical axes list the observation days and show the activity counts on an arbitrary scale with higher values suggesting more activity. The horizontal axes represent the time of day from midnight one day (0 hr) to midnight the next day (24 hr). The activity pattern of this mother–infant dyad showed less synchrony than the one depicted in Figure 1, with the infant being up frequently throughout the *night*.

Relation Between Maternal and Infant Activity Patterns

The mean within-dyad correlation of activity counts was $r = .46 \pm .11$ across the sample, suggesting that these time series were temporally correlated. Table 2 shows the correlation between maternal and infant circadian activity parameters, infant postnatal age, and within-dyad correlation of activity counts. The within-dyad correlation of activity counts showed significant positive correlations with the amplitude and 24-hr cosinor fit of infant activity. Significant positive correlation coefficients were obtained for mother–infant activity mesor, amplitude, acrophase, and 24-hr cosinor fit, indicating a high degree of synchronization. Infant postnatal age was significantly correlated with the mesor, amplitude, and 24-hr cosinor fit of maternal activity. Postnatal age was also moderately correlated with infant activity mesor, amplitude, and 24-hr cosinor fit, but these correlations did not reach statistical significance.

Discussion

The current study was one of a very few actigraphy studies to examine the 24-hr circadian rest–activity patterns simultaneously in mothers and infants during the early postnatal weeks. Our findings indicate that 2- to 10-week-old infants have beginning circadian rhythms and the acrophase for their activity shows an adult-like phase relationship, suggesting that most infants are entrained to the day–night cycle even during the early neonatal stage. In our study, mother and infant acrophases occurred at a comparable time in the afternoon hours, which may be due to mother–infant interaction. Similar to the findings of Nishihara and colleagues (2002), all mothers and infants in our study were more active during the day than during the night, and mothers of older infants had stronger circadian patterns. As evidenced in our cosinor parameters, there was a strong within-dyad correlation of activity as well as a strong correlation between mother and infant circadian activity patterns. The

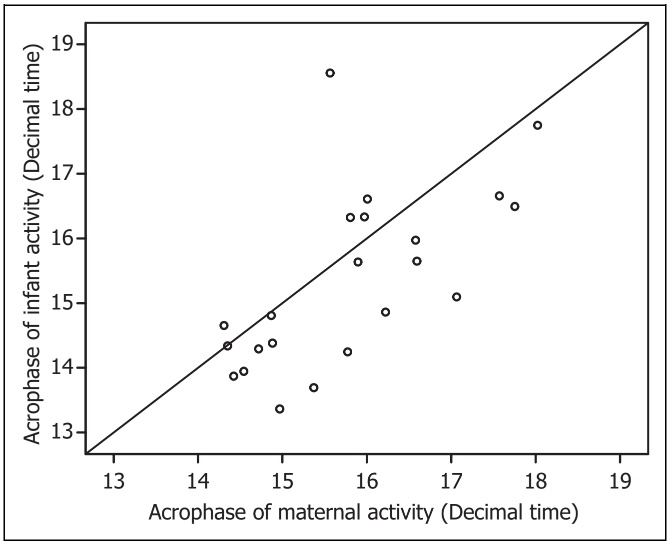

Figure 3. Scatterplot of the acrophase of activity in mothers and infants ($N = 22$). The diagonal line represents a perfect correlation. The timing of the maximum activity in each mother–infant pair was correlated ($r = .65$, $p < .01$), and mother–infant maximum activity occurred at a comparable time.

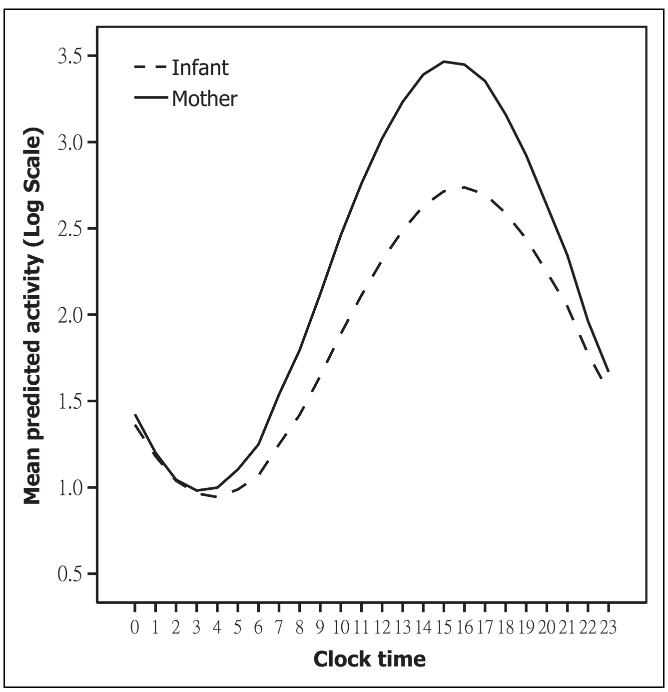

Figure 4. Mean values of natural log transformed data for each measurement point approximated by a single 24-hr cosine curve of rest–activity of one mother-infant pair. The actogram of this pair was shown in Figure 1. The mesor, amplitude, acrophase (clock time) and R^2 cosinor fit of the mother's activity pattern ($\log_e$[count]) were 2.22, 1.25, 15:48, and 0.15 respectively; those of the infant's activity pattern were 1.84, 0.89, 16:19, and 0.10, respectively.

strong pattern synchrony between maternal and infant activity suggests that infants raised in their natural home environments are behaviorally entrained to the 24-hr day by their mothers.

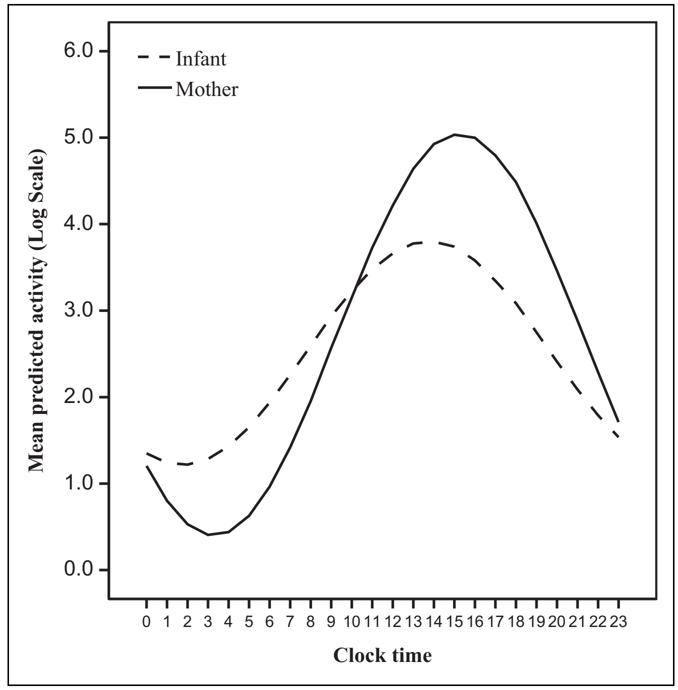

Figure 5. Mean values of natural log transformed data for each measurement point approximated by a single 24-hr cosine curve of rest–activity of a mother–infant dyad that is out of synchrony, as the actogram in Figure 2 showed. The mesor, amplitude, acrophase (clock time), and R^2 cosinor fit of the mother's activity pattern ($\log_e$[count]) were 2.72, 2.32, 15:46, and .41 respectively; those of the infant's activity pattern were 2.51, 1.30, 14:15, and .13 respectively.

Infant rest–activity rhythms are characterized by various ultradian periodicities (period < 24 hr) or by mixed ultradian and circadian periodicities (Korte, Hoehn, & Siegmund, 2004; Nishihara et al., 2002; Shimada et al., 1999; Wulff et al., 2001). Developmental strengthening of infant rest–activity and sleep–wake rhythms and the large degree of individual variability in rhythmicity reported in the literature (Freudigman & Thoman, 1994; Jenni, Deboer, & Achermann, 2006; Nishihara et al., 2002; Wulff et al., 2001) was supported by our investigation. The connection between maternal and infant activity found in this study was considered a prerequisite for infant circadian entrainment (Nishihara et al., 2002). It also supports the view that maternal entrainment of infant developing rhythms is a process of mutual regulation (Sander, 1977; Sander, Stechler, Burns, & Julia, 1970; Wulff et al., 2001). The strong correlation between maternal and infant activity levels, as well as their circadian rest–activity patterns, suggests that the fundamental 24-hr pattern of rest–activity behaviors in infants may be driven by the mothers, who already have a 24-hr rhythm. In this study, we used correlation and cosinor results to examine the possible rhythm synchronization of maternal–infant activity. These analyses do not enable exploration of the lead–lag relationships between mother–infant pairs. However, results from Shimada et al. (1999) would support our explanation, asserting that most infants are entrained to their mother's day–night schedule, although the ultradian cycles

Table 2. Correlation Between Maternal and Infant Circadian Activity Parameters, Infant Postnatal Age (PNA), and Within-Dyad Correlation of Activity Counts ($N = 22$)

	Mother					
Infant	Mesor	Amplitude	Acrophase	R^2 Cosinor Fit	PNA	Within-Dyad Corr[a]
Mesor	0.45[b]	0.50[b]	0.01	.54[c]	0.37	0.35
Amplitude	0.31	0.58[c]	−0.29	.58[c]	0.38	0.66[c]
Acrophase	−0.07	−0.26	0.65[c]	−.23	−0.05	−0.12
R^2 cosinor fit	0.35	0.61[c]	−0.38	.61[c]	0.36	0.67[c]
PNA	0.43[b]	0.59[c]	−0.16	.55[c]	—	−0.05
Within-dyad corr[a]	0.08	−0.06	−0.14	−.07	−0.05	—

[a] Within-dyad correlation of activity count.
[b] Correlation is significant at the .05 level.
[c] Correlation is significant at the .01 level.

may be driven by the infant. Our results and interpretations also agree with the observation that increased maternal presence and physical contact, including kangaroo care, neonatal rooming-in, and co-sleeping, provide beneficial regulatory effects on the development and entrainment of infant circadian rhythm (Feldman & Eidelman, 2003; Keefe, 1987; Sander et al., 1972; Thomas & Burr, 2002).

Our correlation analysis further demonstrated that stronger within-dyad correlation of activity was associated with greater amplitude and the robustness of the infant's rhythm. These results indicate that the development of the 24-hr rest–activity pattern in infants may be associated with the reciprocal behavior between the mother and her infant or with sharing a simultaneous daily schedule, which may include the mother's bedtimes and rise times. In an actigraphic study, Wulff et al. (2001) found that the leading position of the mother promotes, in addition to synchronized activity, a rapid development of infant circadian rhythms. In a study by Nishihara and Horiuchi (1998), investigators observed poor synchronization between mothers' wakefulness and infants' activity in one mother–infant pair in which the mother suffered from maternal depression. This suggests that women with postpartum mood disorders may have difficulty maintaining an optimal mother–infant mutual regulation relationship. These women have also been reported to have an altered rhythm of hormone secretion (Parry et al., 2006), which may in turn affect a mother's ability to entrain her infant. Because of our small and highly selected sample of mothers and infants, findings in this study may not be generalized to more at-risk populations. Whether infants of mothers with mood disorders would experience delayed entrainment due to failure to achieve early social synchronization warrants further investigation.

Given our findings on maternal rhythms as a possible exogenous influence on the development of infant diurnal and circadian rhythmicity, another vulnerable population is infants of shift-working parents because these infants may be exposed to an irregular social and family schedule as well as a chaotic light–dark cycle. In a study by Shimada et al. (1999), one infant, whose parents were shift workers, did not entrain to the normal 24-hr day and maintained a free-running rhythm until 3 years of age. Possible delayed circadian entrainment in infants of shift-working parents should also be explored in future studies. When mothers' rest–activity rhythms do not have optimum entraining effects, the input from the normal light–dark cycle may become crucial.

This study demonstrated that external motion is a predominant experience for infants by 3 months of age. The activity counts recorded from infants were pervasively confounded by the behavior of mothers in relation to their infants, such as holding and carrying. Previous studies using continuous actigraphic recordings in infants have included the exogenous activity counts for analysis (Korte et al., 2004; Nishihara & Horiuchi, 1998; Nishihara et al., 2000, 2002; Wulff et al., 2001), with few acknowledging this undocumented external motion as a study limitation (Jenni et al., 2006). Consistent with our previous report (Tsai et al., 2009), results from this study indicate the need to use diaries along with actigraphy to carefully document passive movements and correct for external motion.

This study had several limitations worth noting. First, all infants in this study were the only child in the family. In families with more than one child, the potential for disrupted maternal rest–activity pattern is increased. Second, observations from this study were based on healthy mothers and infants, so the results may not be generalized to mothers and/or infants with health problems. Third, because this study was conducted in natural home environments, it would be difficult to totally dissociate the entraining effect of the maternal rest–activity behaviors from that of the light–dark cycle.

Conclusions

Becoming a new mother is joyful and exciting, but the unpredictability of the timing of an infant's rest and activity can create tremendous stress for the mother. Although this research was descriptive and exploratory in nature, our findings suggest that cyclic maternal activity patterns provide important social time cues in shaping an infant's emerging rhythms and synchronizing them with the external light–dark cycle. Strong synchrony of activity between the mother and her infant, or sharing the same day–night schedule, may support infant circadian entrainment and enhance a regular 24-hr sleep–wake schedule during the early postnatal weeks. Findings suggest that health care professionals should encourage new mothers to maintain a regular diurnal pattern of rest and activity. To better understand the correlates for mother–infant synchrony and their implications for infant entrainment, future studies should include variables about maternal mood and employment. Possible effect of maternal behavioral entrainment of circadian rhythms in preterm infants should also be explored in future studies.

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