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Mother-Infant Circadian Rhythm: Development of Individual Patterns and Dyadic Synchrony

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Abstract

Background—Mutual circadian rhythm is an early and essential component in the development of maternal-infant physiological synchrony.

Aims—To examine the longitudinal pattern of maternal-infant circadian rhythm and rhythm synchrony as measured by rhythm parameters.

Study Design—In-home dyadic actigraphy monitoring at infant age 4, 8, and 12 weeks.

Subjects—Forty-three healthy mother-infant pairs.

Outcome Measures—Circadian parameters derived from cosinor and non-parametric analysis including mesor, magnitude, acrophase, L5 and M10 midpoints (midpoint of lowest 5 and highest 10 hours of activity), amplitude, interdaily stability (IS), and intradaily variability (IV).

Results—Mothers experienced early disruption of circadian rhythm, with re-establishment of rhythm over time. Significant time effects were noted in increasing maternal magnitude, amplitude, and IS and decreasing IV ($p < .001$). Infants demonstrated a developmental trajectory

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The authors have no conflict of interest to report.

of circadian pattern with significant time effects for increasing mesor, magnitude, amplitude, L5, IS, and IV ($p < .001$). By 12 weeks, infant phase advancement was evidenced by mean acrophase and M10 midpoint occurring 60 and 43 minutes (respectively) earlier than at 4 weeks. While maternal acrophase remained consistent over time, infants became increasingly phase advanced relative to mother and mean infant acrophase at 12 weeks occurred 60 minutes before mother. Mother-infant synchrony was evidenced in increasing correspondence of acrophase at 12 weeks ($r = 0.704$), L5 ($r = 0.453$) and M10 ($r = 0.479$) midpoints.

Conclusions—Development of mother-infant synchrony reflects shared elements of circadian rhythm.

Introduction

Limited research has examined longitudinally the development of infant circadian rhythm, parallel changes in maternal circadian rhythm, and coordination of maternal and infant rhythm. Infant circadian rhythm is an early expression of temporal regulatory ability and characterized by development over time of twenty-four hour, diurnal pattern. Temporal coordination of infant and mother circadian rhythm represents physiological synchrony (1) which is foundational for further establishment of rhythmic, reciprocal maternal-infant interaction and infant regulatory ability (2-4). Infant establishment of the typical social day is an essential developmental achievement. The specific aims of this exploratory longitudinal study conducted with healthy mother-infant dyads were to: (1) Determine the longitudinal pattern of maternal and infant activity circadian rhythm derived from actigraphy (count/minute) recordings at infant age 4, 8, and 12 weeks, and (2) Examine the longitudinal pattern of maternal-infant physiological synchrony defined as the separate correlations between mother and infant circadian rhythm parameters at infant age 4, 8, 12 weeks.

Infants are born with the capacity for circadian rhythm however daily rhythm is poorly developed due to immaturity of the neural control mechanisms. The central pacemaker, the suprachiasmatic nuclei, oscillates before birth and the circadian timing system continues to develop postnatally (5, 6). Although this timing system is present in the fetus, the mother's circadian rhythm predominates with the uterine environment providing rich temporal cues (7). At time of birth, the neonate is abruptly separated from the mother's rhythm while at the same time possessing immature circadian timing (8). This immaturity is evidenced in activity patterns, observable as sleep-wake periods, which differ substantially from those of parents. Activity circadian rhythm changes dramatically over the first year of life and demonstrates a developmental trajectory characterized by increasing cycle amplitude, predominant cycle period lengthening to approximately 24 hours, cycle acrophase or peak time appropriately timed to daytime, and establishment of day-night diurnal pattern (5, 9, 10). While environmental light is a potent entrainer of infant rhythm the patterns of social interaction and feeding are also important timing cues (5, 11, 12) The development of infant circadian rhythm is essential for the infant temporal “fit” within the family and particularly coordination between mother and infant. Infant activity rhythm has far-reaching implications including infant health and development as well as parental physical and mental health. Few studies have examined the effects of infant circadian rhythm disturbance, such as suppressed cycle amplitude, altered cycle timing, or impaired entrainment (13), however disruption or delay of infant circadian rhythm development has been associated with colic and crying pattern as well as arrhythmic behavior and irregular sleep (14) suggesting untoward effects of impaired rhythm. Although there is a paucity of research on the consequences of rhythm alteration among infants and young children, substantial evidence supports the relation between circadian disruption and health outcomes in adults.

The limited research describing infant activity circadian rhythm has involved varied analytic approaches (e.g., spectral analysis, autocorrelation, day-night differential, cosinor analysis) and has been conducted in small sample sizes. Typically the pattern of sleep-wake scored nominally (categorical scoring of sleep and wake) has been depicted rather than the circadian rhythm of raw activity counts. Although existing research provides evidence of inter-subject variability, general trends are supported. Infants demonstrate predominantly ultradian rhythm following birth, however day-night asymmetry of sleep is detected within the first month of life (15). Early work by Wulff and Siegmund detected circadian rhythm of sleep-wake state derived from actigraphy and frequency domain analysis at 3-14 days postnatal age (16). Longitudinal studies of maternal-infant dyads with actigraphy recordings at infant age 3, 6, 9, and 12 weeks, revealed circadian rhythm detected by autocorrelation at 2-3 weeks postnatal age with increasing rhythm amplitude over time and all infants demonstrating circadian rhythm at 12 weeks.

While sleep in postpartum women has been studied extensively, few studies have examined circadian rhythm during this period. Decreased circadian rhythm amplitude is reported after birth (16). The primary decrement in maternal amplitude occurs in the early postpartum period in response to infant night time care needs. In a longitudinal study of postpartum women, sleep cycle amplitude was dampened at infant age 3 weeks and increased through 12 weeks, the study endpoint (17). In one of few longitudinal studies following 11 pregnant women through the postpartum and comparing with non-pregnant women, circadian rhythm amplitude of sleep-wake pattern measured by actigraphy was decreased in postpartum women and was not fully recovered by 15 weeks postpartum (18). Decreased cycle amplitude occurs with interrupted sleep pattern and is characteristic of irregular sleep-wake rhythm disturbance, also termed circadian rhythm sleep disorder (19).

From a systems perspective, infants are uniquely dependent upon their mothers to shape the surrounding environment. Mothers serve a primary role entraining young infants' immature rhythm to a 24-hour period through both direct caregiving interaction and management of the physical home environment (20, 21) including control of light exposure (11). While parenting behavior is a strong determinant of infant rest-activity pattern, within the mother-infant dyad the influence is bidirectional in that infant activity pattern (i.e., waking, crying) disrupts parent sleep (22). Activity pattern, operationalized as state-dependent movement, is a critical representation of physiological synchrony within the mother-infant dyad and is the most relevant circadian rhythm predicting later interactive synchrony and infant regulation (2, 3).

The few existing studies of mother-infant rhythm synchrony have involved small sample sizes and varying analytic approaches (e.g., cross-correlation, correlation of rhythm parameters, correspondence of sleep periods). Mothers' wake state, recorded by polysomnography in a longitudinal study at 1, 3, and 6 weeks infant age, has been shown to be connected with categories of infant activity measured by actigraphy (23). Significant within dyad ($n = 22$) correlations have been reported between mother and infant circadian amplitude ($r = 0.66$) and acrophase ($r = .46$) obtained from cosinor analysis of actigraphy records at infant age 2-10 weeks. (24).

Circadian rhythm, a predominant rhythm governing multiple physiological functions, undergoes major development over the first 12 weeks of life (2, 3, 5, 9). Infant physiological rhythm sets the stage for the social interactional synchrony, the capacity to interact temporally with mother and other caregivers. Findings from prior research demonstrate prediction of maternal-infant interactional synchrony by infant physiologic rhythm including sleep-wake pattern, vagal tone, orientation, and modulation of arousal (2). Maternal-infant interactional synchrony is antecedent to infant regulation (2, 3, 25, 26), the organization and integration of physiological, cognitive, emotional, and behavioral processes (2). Several areas of research describe consequences of maternal-infant rhythm synchrony. Based on long term actigraphy recordings, early postnatal cross correlation between mother and infant is associated with infants' development of entrained diurnal pattern (27). Failure to establish organized circadian rhythm is associated with infant feeding difficulties, poor weight gain, altered parent-infant interaction, and erratic sleep-wake pattern (5, 21, 28, 29). De Graag et al. report mother-infant interaction at infant age five months is predicted by pattern of infant sleep (consolidation, timing of longest sleep), suggesting importance of biological rhythm shaping social rhythm (30). In elegant research, fMRI has been used to examine the neurohormonal basis of maternal organizing and entraining behaviors such as maternal gaze and pacing of social cues that influence physiological synchrony, attachment, and maternal interaction style (26).

Our research adds to the body of knowledge regarding development of mother and infant circadian rhythm and synchrony in several ways. In addition to using a longitudinal design to examine developing synchrony, our work involves a larger sample than in previously reported studies. Our analysis uses both a cosinor as well as non-parametric circadian rhythm analysis (NPCRA) approaches to examine circadian rhythm, and we have controlled for external motion influencing infant actigraphy monitoring (31).

Methods

Design and Subjects

Mother-infant dyads were studied in their naturalistic home environments using a longitudinal, single group exploratory design with three times of measure at infant age 4, 8, and 12 weeks. These time points were chosen to capture developmental transitions in infant sleep pattern. Inclusion criteria were: gestation 38-42 weeks, singleton birth, maternal age 18 to 40 years. Maternal exclusion factors included depression at time of enrollment, history of sleep disorder, medications altering circadian rhythm, chronic health problems, ante- and postpartum complications. Infants experiencing pre- or postnatal complications were excluded. Forty-six healthy mothers and their biologic infants, recruited through a registry of parents interested in research participation and public advertisement, were enrolled with 43 dyads completing data collection at infant age 12 weeks. The registry contacts parents based on birth certificate records and provides investigators with listing of potential parent contacts. Three dyads withdrew during or following the initial data collection due to time constraints.

Instruments

Actigraphy. Activity exhibits robust circadian rhythm (32, 33) and actigraphy provides a feasible and acceptable means of measuring activity continuously in the home environment, supporting naturalistic study of mother and infant entrained rhythm. Mother and infant activity were recorded continuously as counts per one minute epoch over a 72-hour period using actigraphy monitors (Respironics Actiwatch Spectrum or Actiwatch-L, Bend, OR). The accelerometry-based monitor devices, similar in design to a digital watch, provide a sampling rate of 32 Hz and sensitivity of 0.05 g-force.

Diary—Mothers recorded both their infant's and their own sleep-wake pattern in 15 minute epochs over three days using a paper-and-pencil log form. Infant feeding episodes and periods when the infant was held or exposed to external motion were recorded as well as periods when watches were removed. The diary was used to corroborate actigraphy recording.

Procedure

Data collection was performed in the home environment and scheduled when the infant was + 2 days from target recording age. During the home visit mothers were instructed by research staff in application of actigraphy monitors and completion of diary recording. Infant monitors were placed on the ankle. Mothers wore actigraphy monitors on the non-dominant wrist. Approval for study procedures was obtained from the human subjects review board and informed consent obtained from mothers.

Analysis

Actigraphy records were first examined visually and periods of infant external motion were excluded. For infants a mean of 2.96% (+ 4.78) of data points were missing per recording due either to exclusion or failure to record. In mothers this rate was 2.80% (+ 4.92). Actigraphy data were transformed using natural log function followed by fitting a cosine curve representing a 24-hour period to the data using regression analysis. Three cosinor analysis parameters were then derived: mesor, magnitude, and acrophase and the R^2 as a goodness of fit index within subject was also determined (further definition provided in Table 1). Cosinor analysis is based on the assumption that the underlying rhythm is sinusoidal in shape. When this cannot be assumed, NPCRA is an alternate approach that does not include assumptions about the shape of the underlying model. Given criticism that cosinor model does not adequately portray rest-activity rhythms (34) and reports of improved estimates of infant actigraphy rhythm with non-parametric circadian rhythm analysis (NPCRA) (35) we employed both approaches. NPCRA parameters included amplitude, M10 midpoint, L5 midpoint, Intradaily Variability, and Interdaily Stability (Table 1). Both employed rhythm analysis approaches are robust in relation to missing data (34, 36, 37). Change in maternal and infant circadian parameters over time was analyzed using ANOVA for repeated measures. Maternal-infant synchrony was determined by correlation between mother and infant circadian parameters.

Results

Subject Description

Descriptive information (mean (SD)) for the sample of 43 mother-infant dyads follows: gestational age 39.8 (1.17) weeks, postnatal age at entry 29.5 (1.64) days, birth weight 3574 (396.2) grams, maternal age 31.7 (3.63) years, and 19 (44.2%) infant subjects were female. Racial and ethnic distribution frequency of mothers were: Hispanic 1 (2.3%), Asian 5 (11.6%), Native Hawaiian & Pacific Islander 1 (2.3 %), black 3 (7.0%), white 34 (79.1%). Infant values included: Asian 7 (18.6%), Native and Pacific Islander 1 (2.3%), black 5 (11.6%), American Indian, Alaskan Native 1 (2.3%), white 29 (67.4%). At entry 26 (60.5%) of the infants were exclusively breast fed while at 12 weeks this was reduced to 11 infants (25.6%).

Infant and Mother Circadian Rhythm Development

Findings from cosinor analysis (Figures 1 and 2, Table 2) show that while infant mesor or average activity increased across 4, 8, and 12 weeks of age, mothers’ mesor remained consistent. The magnitude or amplitude of mother rhythm increased from 4 to 8 weeks and then was unchanged at 12 weeks. Infant magnitude increased steadily from 4 to 12 weeks of age. Mothers’ acrophase or timing of cycle peak was stable across the eight week study period (mean 15.2 - 15.4 decimal time [3:12 to 3:24 pm]), however infants demonstrated wider variation and phase advancement, a move toward increasingly earlier mean acrophase (4 weeks 15.2 [3:12pm], 12 weeks 14.2 [2:12 pm]) (Figure 2). Acrophases derived from NPCRA are similar to those based on cosinor analysis. Both mother and infant increasing interdaily stability values (IS) and decreasing intradaily variability (IV) over time reflect increasing 24-hour pattern consistency, however infant IS values are lower and IV values are higher than those of mothers throughout as a result of rest-activity pattern fragmentation.

Synchrony of Mother and Infant Circadian Rhythm Over 12 Weeks

At infant age 4 weeks correlations between mother and infant mesor, magnitude, acrophase, amplitude, M10 midpoint, IS, and IV were moderate ($r = 0.231$ to 0.514) (Table 3). Over time the dyadic correlation of mother-infant acrophase ($r = 0.704$) and L5 and M10 midpoints increased ($r = 0.453$ and 0.479, respectively) at infant age 12 weeks, providing evidence of synchronizing of circadian diurnal pattern timing.

Discussion and Conclusion

Study results depict infant rhythm development characterized by increasing activity level (mesor), increasing cycle excursion (magnitude, amplitude), and gradual establishment of diurnal pattern (acrophase, L5 and M10 midpoint, IS, IV). With age typically developing infants express an increasingly circadian pattern with increasing night-day differentiation and reducing cycle disruption at night. From the standpoint of sleep-wake pattern, over time infants demonstrate longer daytime awake periods, more sleep occurring during typical nighttime hours, and longer and more consolidates nighttime sleep periods (20, 21, 38, 39).). Previous research has not shown effects of gestational age, birth order, season, birth weight, or breastfeeding duration on the trajectory of rhythm strength increase with age (15). Similar to previous reports, our findings attest initial development of circadian rhythm in the newborn period with evidence of continuing developmental trajectory in early infancy (15, 16, 35, 40, 41) and magnitude of infant circadian rhythm increasing across infant age (15, 17, 40). Additionally results provide evidence of maternal rhythm disruption following birth (magnitude, amplitude, IS, IV) although maternal mesor, M10 and acrophase did not change appreciably over time. Thus the circadian rhythm center or mean and timing of mother's peak activity remained consistent and while the amount of change over 24 hours was reduced, stability across days increased, and there was less fragmentation of sleep. Dampened maternal rhythm has also been reported in previous research (16-18, 40). Circadian rhythm is an early manifestation of developing mother-infant synchrony, however research examining relation of dyadic rhythm characteristics is incomplete. Compared to work by Tsai and others (23), we employed a larger sample size and used a longitudinal design to capture change over time, however our methods are comparable and the across time of measure correlations between mother and infant circadian parameters mirror similar findings with correspondence of mother and infant magnitude and acrophase. Our study is one of few examining development of both maternal and infant acrophase and timing of circadian rhythm. Our findings show increasing correlation between mother and infant acrophase despite the seeming paradox of the growing phase shift between mothers and infants and infant phase advancement. By infant age 12 weeks both mother and infant circadian rhythms are progressively robust and the correlation between mother and infant acrophase increases over time. While maternal acrophase remained consistent, infant acrophase occurred progressively earlier with infants becoming phase advanced in relation to mother. By 12 weeks of age the average difference between infant and mother peak activity was 1.3 hours (M10 midpoint difference) or 1.7 hours (acrophase difference) (infant “ahead” of the mother). This phase difference between mother and infant is also seen in L5, the period of least activity. By 12 weeks of age the midpoint of the infants’ lowest activity (reflecting night sleep) occurs an average of 1.1 hours earlier than that of the mother's. This rhythm difference is consistent with infant waking during mother's longest sleep period and may also result in infant morning awakening earlier than mother.

Mother and infant rhythm synchrony is implicated in several areas. The infants “fit” into the typical 24-hour, diurnal pattern improves maternal sleep and that of other family members. Although there is substantial research documenting family sleep disruption following birth of an infant there is minimal interventional emphasis on entraining circadian rhythm through home lighting and pattern of social interaction and environmental stimulation. Physiological rhythm is foundational for quality of mother-infant interaction which is essential to infant development (3, 25, 26). Further mother-infant interaction contributes to infant development of self regulation which is cardinal for cognitive and emotional development (42-46). Our study is strengthened by sample size larger than those supporting previous research on maternal and infant circadian rhythm. Actigraphy is well established as a tool for determining circadian rhythm (32) and a three-day recording period provides acceptable estimates of mother and infant rhythm (47). Mothers in our study were adherent to study protocol which restricted missing data. The combination of cosinor and NPCRA analytic approaches produced additive insights not provided by a single approach. The study sample however was limited to maternal age 18 to 40 years and may not be generalizable to adolescent or mid-age women. Additionally findings are restricted to healthy mother-infant dyads and biological children. Future studies would benefit from inclusion of spouses and partners, family structure, as well as other aspects of the home social environment. Further research is needed connecting circadian rhythm synchrony with infant and maternal outcomes with particular emphasis on effects of timing among infants and mothers with substantial phase differences.

In summary both cosinor and NPCAR analysis were used to examine circadian rhythm of activity recorded by actigraphy monitoring in mother-infant dyads at infant age 4, 8, and 12 weeks. Mothers demonstrated aspects of early rhythm disruption followed by stabilization of pattern, while infants demonstrated continual development of circadian rhythm. Synchrony between mother and infant rhythm was evidenced in increasing strength of correlation of acophase and mutual adoption of diurnal pattern.

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Highlights

Mother-Infant Circadian Rhythm: Development of Individual Patterns and Dyadic Synchrony

Increasing strength of infant activity circadian rhythm development occurs between 4 to 12 weeks of age.

Maternal activity circadian rhythm is disrupted in the early postpartum then stabilizes.

Maternal-infant circadian timing are increasingly correlated however infant acrophase is phase advanced in relation to mother.

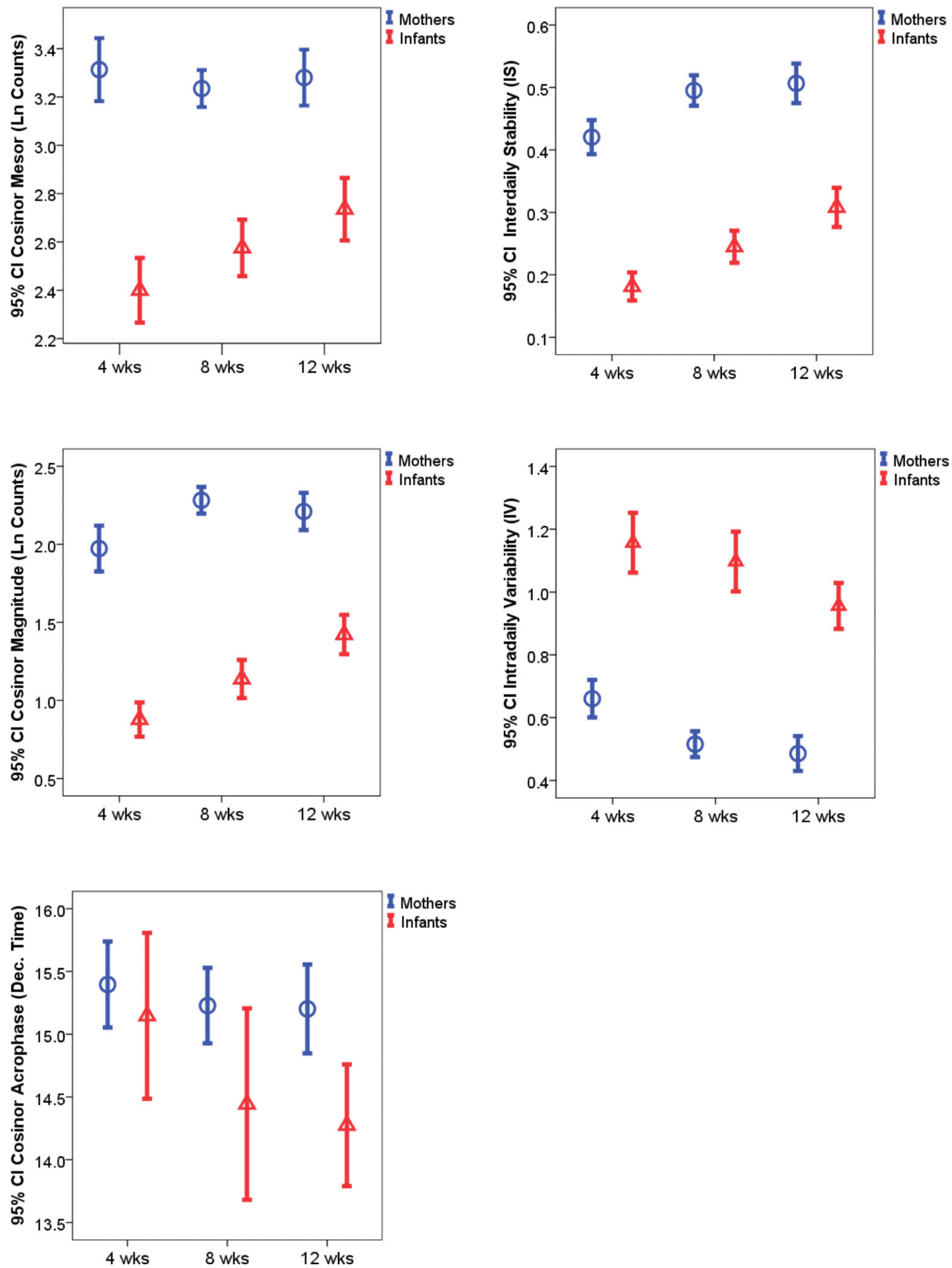

Figure 1.
Mother and infant circadian rhythm parameters at infant age 4, 8, and 12 weeks (n = 43 dyads).

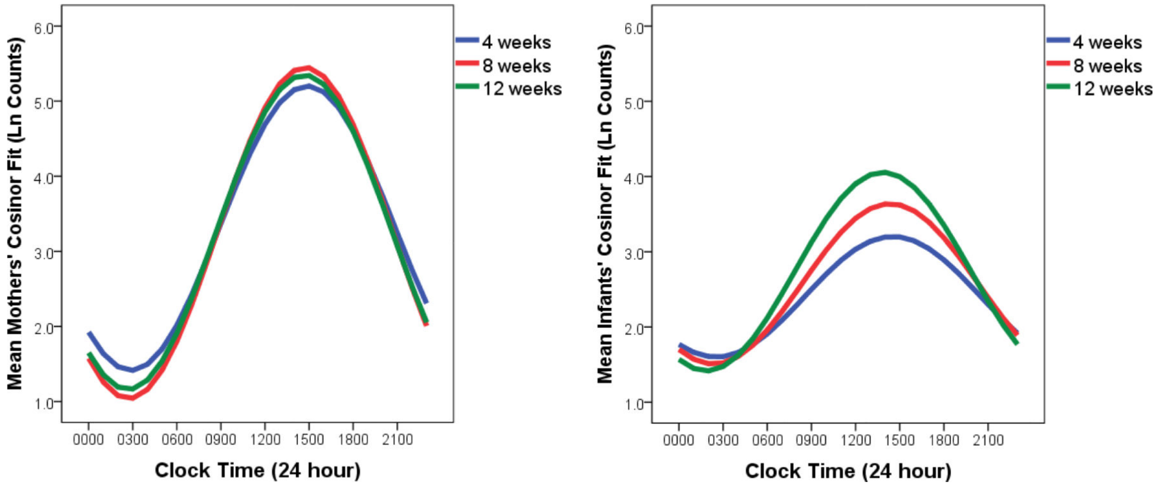

Figure 2.
Mother and infant circadian rhythm derived by cosinor analysis.

Table 1

Circadian rhythm parameters derived from mother and infant actigraphy recordings.

Fixed Period 24 hour Cosinor Model Parameters:	
Mesor pattern	Midpoint level or mean activity count of the fitted 24 hour rhythm
Magnitude	Difference between the model fit peak value and the mesor; the amount of change from mesor to peak of the cycle
Acrophase	Decimal clock time of fitted cycle peak; the time of highest activity in the cycle
R^2 GOF	Goodness of Fit Index, R-square of the within-subject model fit; measure of fit with 24-hour period, variance explained by the fitted curve
Non-Parametric Circadian Rhythm Analysis (NPCRA) Descriptors:[*]	
L5 midpoint	Decimal clock time for the midpoint of the L5 block; timing of lowest activity
M10 midpoint	Decimal clock time for the midpoint of the M10 block; timing of highest activity
Amplitude	Difference between L5 and M10 segments average levels; difference in activity level of highest and lowest periods
IS	Interdaily Stability, normalized index of the similarity of activity patterns across days, strength of coupling with 24-hour environment; values from 0 to 1.0 with 1.0 indicating exact coupling.
IV	Intradaily Variability, measure of the fragmentation of the rest/activity pattern; frequency of transitions in activity, values from 0 (near perfect sine wave) to ≥ 2 (noise or ultradian rhythm)

[*] reference: Van Someren EJ, Swaab DF, Colenda CC, Cohen W, McCall WV, Rosenquist PB. Bright light therapy: improved sensitivity to its effects on rest-activity rhythms in Alzheimer patients by application of nonparametric methods. Chronobiol Int. 1999;16(4):505-18.

Table 2

Mother and infant circadian parameters mean (SD) and change over time (n = 43 dyads).

		Mother				Infant			
Model	**Parameter**	**4 wk**	**8 wk**	**12 wk**	**F; p**[a]	**4 wk**	**8 wk**	**12 wk**	**F; p**[a]
Cosinor	Mesor (Ln counts)	3.31 (.437)	3.24 (.251)	3.28 (.379)	F=.644;p=.531	2.37 (.415)	2.58 (.384)	2.73 (.424)	F=31.0;p<.001
	Magnitude (Ln counts)	1.96 (.486)	2.29 (.269)	2.20 (.391)	F=14.1;p<.001	.856 (.355)	1.13 (.399)	1.42 (.411)	F=36.9;p<.001
	Acrophase (dec. hours)	15.4 (1.15)	15.2 (.982)	15.2 (1.16)	F=1.26;p=.295	15.2 (2.21)	14.5 (2.50)	14.2 (1.57)	F=3.18;p=.052
	R-squared GFI	.297 (.100)	.367 (.075)	.357 (.105)	F=16.4;p<.001	.082 (.057)	.123 (.078)	.175 (.091)	F=22.9;p<.001
NPCRA (L5:M10)	Amplitude (Ln counts)	3.64 (.793)	4.21 (.441)	4.14 (.560)	F=13.1;p<.001	1.64 (.545)	2.22 (.643)	2.63 (.651)	F=52.1;p<.001
	L5 midpoint (dec. hours)	3.55 (2.53)	2.52 (1.79)	2.82 (1.61)	F=3.19;p=.052	2.49 (2.72)	1.75 (2.66)	.685 (1.78)	F=12.9;p<.001
	M10 midpoint (dec. hours)	15.1 (1.95)	15.2 (1.43)	14.8 (1.87)	F=1.23;p=.302	14.2 (2.55)	13.5 (2.77)	13.5 (1.41)	F=1.36;p=.267
	IS	.420 (.092)	.498 (.078)	.504 (.103)	F=25.0;p<.001	.176 (.070)	.245 (.084)	.306 (.103)	F=37.1;p<.001
	IV	.659 (.200)	.510 (.130)	.485 (.183)	F=16.5;p<.001	1.17 (.314)	1.10 (.312)	.959 (.240)	F=9.86;p<.001

[a]ANOVA-repeated measures time effect

Table 3

Correlation Between Mother and Infant Orcadian Rhythm Parameters Over Time (n = 43 dyads).

Model	Parameter	4 wk	8 wk	12 wk
Cosinor	Mesor (Ln counts)	0.231	0.059	0.059
	Magnitude (Ln counts)	0.482	0.154	0.211
	Acrophase (dec. hours)	0.514	0.483	0.704
	R^2 GOF	−0.163	−0.124	−0.005
NPCRA (L5:M10)	Amplitude (Ln counts)	0.366	0.148	0.154
	L5 midpoint (dec. hours)	0.129	0.227	0.453
	M10 midpoint (dec. hours)	0.348	0.306	0.479
	IS	0.475	0.291	0.108
	IV	0.446	0.295	0.169