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Original Article

A longitudinal study of sleep-wake patterns during early infancy using proposed scoring guidelines for actigraphy

Elizabeth L. Adams [a, b], Lindsay Master [c], Orfeu M. Buxton [c, d, e, f], Jennifer S. Savage [a, b, *]

[a] Center for Childhood Obesity Research, Penn State University, University Park, PA, United States
[b] Department of Nutrition Sciences, Penn State University, University Park, PA, United States
[c] Department of Biobehavioral Health, The Pennsylvania State University, University Park, PA, United States
[d] Department of Social and Behavioral Sciences, Harvard Chan School of Public Health, Boston, MA, United States
[e] Division of Sleep Medicine, Harvard Medical School, Boston, MA, United States
[f] Division of Sleep and Circadian Disorders, Departments of Medicine and Neurology, Brigham and Women's Hospital, Boston, MA, United States

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ABSTRACT

Objective/Background: We describe developmental and day-to-night sleep patterns across the first six months of life using actigraphy and compare these to mother-reported perceptions of infant sleep.
Patients/Methods: This observational, burst design included three, one-week bursts of data collection at six, 15, and 24 weeks of age. Infants wore an actigraphy device (Actiwatch Spectrum) on their right ankle for each one-week period. Data were scored using a SAS-based hierarchical, algorithmic methodology and independently assessed for necessary corrections by two trained scorers in a Visual Basic. Mothers completed the Brief Infant Sleep Questionnaire (BISQ) at each burst. Mixed models tested developmental patterns over time and multilevel models examined day-to-night sleep patterns at each burst.
Results: Daytime nap sleep duration decreased over time ($p = 0.02$) with marginal significance for nighttime sleep interval duration increasing over time ($p = 0.09$). Total 24-h sleep duration was time invariant ($p > 0.05$). These longitudinal patterns were similar when examining mothers' perception of infant sleep. Daily variations demonstrated nighttime sleep interval and maintenance efficiency did not predict next-day nap sleep duration. Yet, at 24 weeks of age, daytime nap sleep was associated with that nights' sleep interval. For every 1-h above infants' average total daytime nap sleep duration, infants slept ~15 min longer and 1.0% less efficiently that night ($p \leq 0.05$). Mothers overestimated daytime nap sleep and total 24-h sleep, when compared to actigraphy ($p < 0.01$).
Conclusion: Changes to infants' usual daytime sleep duration impacted subsequent sleep bouts and mothers tended to overestimate infants' sleep. These patterns should be explored in relation to parenting practices.

1. Introduction

Infant sleep patterns develop rapidly throughout the first year of life. Shortly after birth, sleep is fragmented and less predictable, as the central circadian pacemaker takes several months to establish the connection from the retina and for light signals to synchronize to the external light and dark cycle [1]. As infants age, sleep consolidation emerges with a more prolonged sleep at night and more sustained wakefulness during the day. Healthy sleep patterns have important implications on later health outcomes including physical growth and the development of a healthy body mass index (BMI) [2,3]. Therefore, accurate measurements of these infant sleep-wake patterns are essential for evaluating intervention outcomes, providing guidance in clinical care, and understanding how sleep impacts other behaviors such as feeding.

When quantifying infant sleep patterns, much of the existing literature has relied on parent-reported measures, such as questionnaires or sleep diaries [4,5]. These are biased by subjective report and limited to what parents are able to recall. Instead, actigraphy is a measure in which motor activity is continuously

Abbreviations: PSG, Polysomnography; BISQ, Brief Infant Sleep Questionnaire; WASO, Wake After Sleep Onset.

* Corresponding author. Center for Childhood Obesity Research, 129 Noll Laboratory, The Pennsylvania State University, University Park, PA, 16802, United States.
E-mail addresses: eka5159@psu.edu (E.L. Adams), lmaster@psu.edu (L. Master), orfeu@psu.edu (O.M. Buxton), jfs195@psu.edu (J.S. Savage).

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quantified over time using a wrist-worn wearable device. This noninvasive method uses activity counts to infer states of sleep and wake. Actigraphy may be more accurate than parent-report given its objective nature, while also more feasible than polysomnography (PSG) for natural settings like the home environment. Actigraphy has been used widely in sleep research among adults and older children, yet less in infants [6]. Of the studies that include infants, actigraphy has been shown to be a valid measure with agreement rates ranging 72–95% when compared to PSG or observer-identified states of sleep and wake [7–9].

Like all forms of measurement, actigraphy is not without limitations. The wide variety of devices, scoring algorithms, device placement sites, and definitions of key variables pose a challenge to interpreting results across studies [10]. In particular, there is little guidance available for researchers and clinicians on how to score and interpret infant actigraphy data. This lack of uniformity and clear scoring rules are discussed in a review by Meltzer et al. [6], and Galland et al. [10], with a call for research that clearly describes actigraphy scoring rules and definitions. Therefore, in an effort to advance the evidence base for scoring actigraphy data and improve the rigor and reproducibility of research using these devices for infants, we describe in detail our data scoring rules in our methods.

With the increasing use of actigraphy in pediatric populations [6], it is important to know how sleep values differ when quantified using actigraphy versus mother-reported measures. A few studies have found that mothers report infant sleep schedules (eg, sleep onset/offset) fairly accurately when compared to actigraphy; yet, mothers' perception of infant nighttime sleep duration is less accurate, due to their underestimation of nighttime wakings [11–14]. One limitation of these studies is that they focus on infants' nighttime sleep behaviors, with little-to-no research that has included infants' daytime sleep behaviors. To explore these relationships, more research is needed that compares actigraphy vs. mother-reported values for both daytime and nighttime sleep durations throughout infancy. Furthermore, the day-to-night and night-to-day temporal patterns of infant sleep have not been studied. On nights when infants sleep longer or more efficient than usual, their next-day nap sleep duration may be affected, and on days when infants' nap sleep duration is longer than usual, that nights' sleep onset, interval duration, and/or maintenance efficiency (ie, quality) may be affected. These empirical questions remain unanswered and warrant further investigation.

The primary aim of this study is to describe infants' sleep-wake patterns across the first six months of life. To do so, we describe the developmental patterns from 6 to 24 weeks of age and the daily temporal patterns between subsequent night-to-day and day-to-night sleep onset, interval duration, and maintenance efficiency using actigraphy. As a secondary aim, we compare actigraphy and mother-reported values for infants' daytime nap and nighttime sleep patterns and describe our infant-specific actigraphy scoring process in the methods.

2. Materials and methods

2.1. Study design and participants

This observational, pilot study was a micro-longitudinal burst design. There were three, one-week bursts of data collection when infants were 6, 15, and 24 weeks of age. This design allowed us to quantify the developmental patterns (across bursts) and the day-to-day patterns (within bursts) of infant sleep characteristics.

Mothers were recruited during pregnancy from Obstetrics and Gynecology clinics and from Labor and Delivery at a local hospital in Central Pennsylvania. Nurses at these sites distributed study flyers, and interested mothers were screened for eligibility using an electronic questionnaire. All self-reported measures were collected electronically using REDCap [15]. Inclusion criteria consisted of mothers 18–35 years of age who recently delivered a singleton newborn. Infants had to be full-term at delivery (≥37 weeks' gestation), with a birth weight ≥2500 g, and <6 weeks of age at recruitment. Mothers and infants were excluded if one had a major pre-existing health condition (eg, congenital heart disease, cancer) or planned to move far from the study area within the following six months.

Mother-infant dyads who met this inclusion criteria were scheduled for a lab visit when their infant was six weeks of age. At this visit, mothers signed an informed consent approved by the university's Institutional Review Board. N = 24 mother-infant dyads were enrolled. From this, one infant had missing data at the six-week burst (actigraphy device error), and one infant had missing data at the 24-week burst (non-compliance).

2.2. Measures

2.2.1. Actigraphy sleep device

Objective measures of infant sleep were collected using a sleep monitoring device (Actiwatch Spectrum; Philips-Respironics, Murrysville, PA). At the start of each burst, mother-infant dyads came in for a lab visit where infants were fitted with this device. The device was placed on the infant's right ankle, which is the recommended placement site for infants and toddlers [16]. This device was also placed over top of a thin fitted cotton/polyester sock (Garanimals, Garan, Inc.; New York, New York) to prevent skin irritation while still enabling the impedance-based function in the device to register “on-ankle” time verifying compliance. Data were collected continuously for a period of seven days, as recommended for reliable measures in children [17]. Mothers were instructed to leave the sleep device on their infant for these seven days, and only remove the device when cleaning/bathing the infant's skin underneath. After seven days of wear-time, the device was removed.

2.2.2. Mother-reported infant sleep

Mother-reported measures of infant sleep were collected using the validated Brief Infant Sleep Questionnaire (BISQ) [18]. The BISQ assessed variables such as daytime nap, nighttime, and total 24-h (daytime + nighttime) sleep duration, average nap duration, and number of naps per day. Nighttime sleep duration was defined as sleep between 7:00PM–7:00AM, and total daytime nap duration was defined as sleep between 7:00AM–7:00PM. Of the original 34-item BISQ, we administered 24 items; 10 items that were not of interest to our objectives or were redundant to other questionnaires administered during this study were excluded. Mothers completed the BISQ one time during each of the three data collection bursts.

2.3. Actigraphy sleep scoring process

The sleep device collected activity counts in 30-s epochs. The sensitivity was set to Medium (wake threshold value = 40 activity counts for 1-min epochs) to be consistent with the majority of research using actigraphy in pediatric populations [6]. Once all sleep actigraphy data were collected, a replicable scoring process was completed.

First, the downloaded actigraphy data were exported from Actiware software (Version 5.71, Philips-Respironics, 2012). Next, a SAS-based hierarchical, algorithmic methodology was applied to the raw data to identify initial sleep/wake periods [19,20]. If a day had <20 h of wear time or ≥4 h of off-wrist time, that day was made invalid and not used in these analyses [21]. The only exception was the first and last day within a one-week recording, when participants were given the device or returned the device before the 24-h day was complete. If the first and/or last day captured the main nighttime sleep interval, even with <20 h of total wear time, these days were kept for analyses. If the main nighttime sleep interval was not captured, the first and/or last day was not kept for analyses. For any one-week recording with <3 valid days, that weeks' recording was made invalid. In our data, all participants had ≥3 valid days for each recording week at all timepoints; therefore, no weeks were made invalid.

Second, visual assessments of the algorithm-identified sleep/wake intervals were done in a graphical user interface to improve the scoring accuracy (Fig. 1). Two trained scorers (ELA, LM) independently evaluated each participants' actigraphy recordings. Scorers manually adjusted, inserted, or removed any sleep intervals that needed to be corrected, based on the rules listed in Table 1. These decision rules were derived from a validated scoring procedure detailed by Marino et al. [21], and were modified based on multiple expert opinions in order to be applicable to infants. For example, previous scoring rules for adults consider naps ≥30 min in duration [22]. This rule was modified to be ≥15 min for infants, given previous research that showed naps of infants and nursing mothers can be shorter in duration [23–26]. When adjusting the algorithmically-set intervals, both scorers identified "sleep" as areas of lower activity within the context of the overall activity profile for each subject. Sudden decreases in light levels were used for confirmatory purposes but were not required in scoring sleep intervals. Third, after each scorer independently adjusted the computer-identified sleep/wake intervals, a comparison was done on an interval-by-interval basis to test for interrater agreement. The scorers then met to resolve any discrepancies, which resulted in the final scored data set (approved by OMB).

We calculated five main outcome variables of interest: nighttime sleep interval duration, total daytime nap sleep duration, total 24-h sleep duration, sleep maintenance efficiency, average nap duration, and the number of naps per day. Nighttime sleep interval was calculated as the number of hours from sleep onset to sleep offset, including nighttime wakefulness. Additional information on determining sleep onset and sleep offset is listed in Table 1. Total daytime nap sleep was calculated as the sum of all nap durations within a given day. Total 24-h sleep was calculated as the sum of the nighttime sleep interval and total daytime nap sleep within a given day. We report nighttime, total daytime, and total 24-h sleep durations as hours/day and average nap duration as minutes/nap. Sleep maintenance efficiency was calculated as the percentage of the nighttime sleep interval that was spent asleep, after accounting for wake after sleep onset (WASO) [21] (see Table 1).

Additional outcome variables were calculated for the analyses that compared actigraphy to mother-reported values of infant sleep. The first was nighttime total sleep time (see Table 1 for definition and equation), daytime total sleep time (total daytime nap sleep duration − WASO during these intervals), and 24-h total sleep time (nighttime total sleep time + daytime total sleep time). Total sleep time variables quantified the time spent in a sleep state during sleep intervals. These variables were included in order to examine nighttime, daytime, and total 24-h values for mother-report vs. actigraphy sleep intervals and mother-report vs. actigraphy total sleep time.

2.4. Statistical analysis

The first aim was to describe the developmental patterns of infant sleep across bursts, from 6 to 24 weeks of age. We used a mixed model method for testing the main effect of time on our five outcome variables stated above. These models accounted for the lack of independence between observations that were made repeatedly on the same individual. For these analyses, a "day" was based on a 24-h cutpoint day. To quantify the daily variation in nighttime, total daytime, and total 24-h sleep duration, we created an average score across the seven days within each burst. The daily variation was quantified as the standard deviation of this average score. For each outcome variable, an average standard deviation is reported for each burst.

Next, we describe the daily temporal patterns between nighttime sleep interval and sleep maintenance efficiency on next-day, daytime nap sleep, and in reverse, daytime nap sleep on that nights' sleep onset, interval duration, and maintenance efficiency. We used multilevel models to examine these within-subject effects at each burst. The first set of models tested if nighttime sleep intervals that were longer than usual and/or included greater sleep maintenance efficiency, compared to each infants' personal average, were associated with next-day total daytime nap sleep duration. The second set of models tested if total daytime nap sleep duration that was longer than usual, compared to each infants' personal average, was associated with that nights' sleep onset, interval duration, and/or maintenance efficiency. When significant, we characterized total daytime nap sleep as average nap duration and number of naps, tested as independent predictors in separate models. For these models, a "day" was calculated as sleep onset to sleep onset. Further, we controlled for the between-subject effects of these associations, which compared infants' mean across days at each burst to the sample mean at that burst.

Last, we compared actigraphy and mother-reported values of daytime and nighttime infant sleep patterns. Cross sectional analyses used dependent t-tests to examine mean differences across these two measures, at each time point, for our five main outcome variables of interest. In regards to nighttime, daytime, and total 24-h sleep, we also compared mother-reported values to nighttime total sleep time, daytime total sleep time, nap duration, and 24-h total sleep time. Longitudinal analyses used mixed models that accounted for repeated observations on the same individual, to test changes over time in mother-reported measures of infant sleep.

All statistical analyses were performed in SAS Version 9.4 with significance defined a priori as $p \leq 0.05$. Data are reported as mean ± standard deviation.

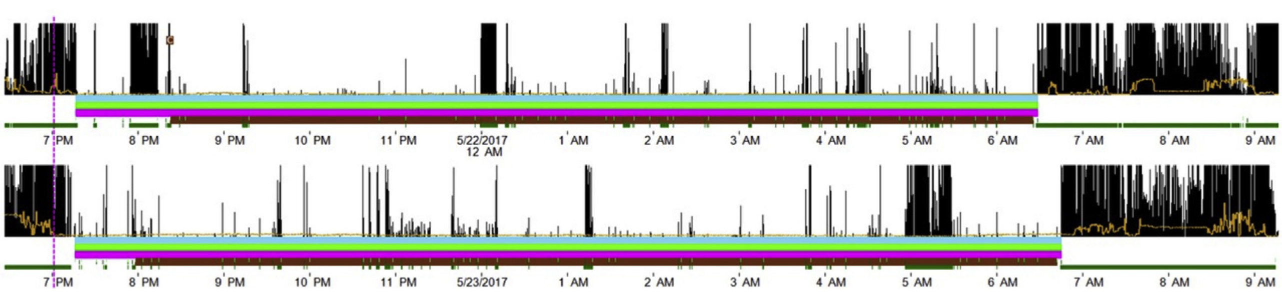

Fig. 1. Example of the graphical user interface used to improve scoring accuracy. Brown = initial algorithm-suggested sleep interval. Pink = Scorer #1 corrected sleep interval. Green = Scorer #2 corrected sleep interval. Blue = Final sleep interval after a comparison of both scorers.

Table 1
Included are definitions for key variables and proposed decision rules when scoring actigraphy data in infants to guide future research.

Variable	Definition	Decision rule
Nighttime sleep onset	The clock time in which the infants' nighttime sleep interval began (ie, fell asleep for the night)	Mothers reported on the BISQ when their infant typically fell asleep for the night. The longest sleep interval starting closest to this reported time was used as the start of main sleep.
Nighttime sleep offset	The clock time in which the infants' main sleep interval ended (ie, woke-up for the day)	Mothers reported on the BISQ when their infant typically woke up for the day. The longest sleep interval ending closest to this reported time was used as the end of main sleep.
Nighttime sleep interval duration	The duration of time between nighttime sleep onset to offset	The nighttime sleep interval duration was the longest sleep interval (from sleep onset to sleep offset) that at least partially overlapped the hours of 10PM and 8AM in a 24-h cutpoint day.
Nighttime total sleep time	Time spent asleep during the nighttime sleep interval	Calculated as (nighttime sleep interval duration − WASO during this nighttime sleep interval)
Wake after sleep onset (WASO)	The number of minutes scored as wake during the nighttime sleep interval	Wake threshold selection corresponds to "medium" (activity counts ≥40 for 1-min epochs) if using Actiware software, Version 5.71
Sleep maintenance efficiency	The percentage of time spent asleep during the nighttime sleep interval	Calculated as: [(Nighttime sleep interval duration − WASO during nighttime sleep)/nighttime sleep interval duration] x 100. Values closer to 100% indicate greater sleep maintenance efficiency.
Nap	All sleep intervals that were *not* the nighttime sleep interval (ie, shorter than the nighttime sleep interval)	Sleep intervals had to be ≥ 15 min in duration to be considered a nap. If there was ≥15 min of wake time in the middle of a nap, this was split into two separate naps.
Nap vs. nighttime sleep interval	A short sleep duration close to the start or end of the nighttime sleep interval could be scored as a nap or included as part of the nighttime sleep interval	To be considered a nap, there had to be > 60 min of wake between the nap and start or end of the nighttime sleep interval. If there was <60 min of wake, the shorter sleep interval was considered to be part of the nighttime sleep interval.
Invalid day	A single 24-h day that was determined to be "invalid" and not used for data analyses	If ≥ 1 of the following occurred: 1. ≥4 h of off-wrist time (eg, did not wear device) 2. ≥4 h of constant false activity (eg, battery failure)
Invalid recording	The full one-week actigraphy recording was determined to be "invalid" and not used for data analyses	If ≥ 1 of the following occurred: 1. Data not able to be retrieved (eg, unable to download) 2. <3 "valid" days within a one-week recording
Invalid nighttime sleep period	The nighttime sleep interval was not scored within a single 24-h day	The nighttime sleep interval was not scored if: 1. The device was removed before the start of the nighttime sleep interval 2. The device was put on >1 h after the typical start of the nighttime sleep interval. Other days within that one-week recording for that participant were used to determine the typical start time. 3. The device was removed >1 h before the typical end time of the nighttime sleep interval, for that one-week recording. Other days within that one-week recording were used to determine the typical end time.
Cutpoint	The start and end time of each 24-h day during scoring. The cutpoint time is recording-specific. It can vary across participants and recordings, but not within a recording. This cutpoint time intersected the least number of sleep intervals within a recording.	A time of 7PM was tested first. If 7PM intersected a sleep interval on ≥1 day, 6PM and 8PM were tested next. If these intersected a sleep interval on ≥1 day, 5PM and 9PM were tested next. This pattern continued until a cutpoint time that intersected the least number of sleep and off-wrist intervals, and was as close to 7PM as possible, was achieved.

3. Results

Infants were mostly White, while mothers were mostly married, and college educated (Table 2). The majority (75%) of families earned a household income ≥ $50,000/year (Table 2). There was high compliance with infants' wearing the actigraphy device. The average percentage of off-ankle time (eg, when infants did not wear the device, per device impedance signal) was minimal at 1 ± 2.5% (range: 0–18.3%) of time on valid recording days. The average number of valid days within a requested one-week recording was 6.8 ± 1.1 (range: 3–10) days. These values did not differ by burst ($p > 0.05$) and are therefore reported as one average across all bursts.

3.1. *Developmental patterns from 6 to 24 weeks of age*

3.1.1. *Average values across time*

Longitudinal patterns of infants' nighttime sleep interval duration were marginally significant for increasing from 6 to 24 weeks of age ($p = 0.09$; Fig. 2). Total daytime nap duration decreased across bursts, with a greater duration at 6 than at 24 weeks of age ($p = 0.02$; Fig. 2). Total 24-h sleep duration and sleep maintenance efficiency during nighttime sleep did not change across bursts ($p > 0.05$). Sleep maintenance efficiency during nighttime sleep was 82.9 ± 6.8%, 81.9 ± 4.5%, and 83.0 ± 4.9% at infant ages 6, 15, and 24 weeks, respectively. The number of infant naps decreased from 6 to 24 weeks of age ($p < 0.01$), while the average nap duration did not change across bursts ($p = 0.11$). The average nighttime, total daytime, and total 24-h sleep durations, nap duration, and number of naps per day at each infant age are listed in Table 3.

3.1.2. *Daily variation across time*

The average standard deviation among days within each burst represents within-burst, day-to-day variation. This day-to-day variability for infants' nighttime sleep interval duration decreased across bursts, with an average standard deviation of 1.1, 1.1, and 0.9, hours/day at 6, 15, and 24 weeks, respectively ($p = 0.03$). Similarly, the day-to-day variability of infants' total daytime nap duration were marginally significant in decreasing across bursts, with an average standard deviation of 1.1, 1.1, and 0.9 h/day at 6, 15, and 24 weeks, respectively ($p = 0.05$). In contrast, the day-to-day variability for infants' total 24-h sleep duration did not vary across bursts, with an average standard deviation of 1.4, 1.5, and 1.2 h/day at 6, 15, and 24 weeks, respectively ($p = 0.16$).

3.2. *Daily temporal directionality between subsequent day and night sleep*

3.2.1. *Nighttime sleep interval and maintenance efficiency were unrelated to next-day total daytime sleep*

Nights in which infants' nighttime sleep interval was longer than usual was not associated with total daytime nap sleep duration on the subsequent day, when tested at each infant age

Table 2
Infant and maternal demographics (n = 24). Mothers were mostly married, college educated, and working full-time. Infants were mostly White and born full-term at a normal birth weight.

Infant demographics	
Gestational age at birth (weeks), mean (SD)	39.6 (0.9)
Birth weight (g), mean (SD)	3679.5 (418.6)
Male sex, n (%)	14 (58.3%)
Not Hispanic/Latino, n (%)	23 (100%)
Race, n (%)	
White	19 (79.2%)
Asian	3 (12.5%)
Other (multi-racial)	2 (8.3%)
Maternal demographics	
Married, n (%)	22 (95.7%)
Education, n (%)	
Some college	1 (4.2%)
College graduate	15 (62.5%)
Graduate degree +	8 (33.3%)
Employment status	
Unemployed	6 (25.0%)
Student	2 (8.3%)
Work part-time	1 (4.2%)
Work full-time	15 (62.5%)
Annual household income, n (%)	
\$10,000–24,999	3 (12.5%)
\$25,000–49,999	3 (12.5%)
\$50,000–74,999	3 (12.5%)
\$75,000–99,999	8 (33.3%)
≥\$100,000	7 (29.2%)

($p > 0.05$). Similarly, there was no association between nights with greater sleep maintenance efficiency and next-day total daytime nap sleep duration, at each infant age ($p > 0.05$).

3.2.2. Effects of daytime sleep on that-nights' sleep interval duration and maintenance efficiency

At 6 and 15 weeks of age, total daytime nap sleep duration that was longer than usual was not associated with that nights' sleep onset, interval duration, or maintenance efficiency ($p > 0.05$). However, at 24 weeks of age, total daytime nap sleep duration was positively associated with that nights' sleep interval duration and negatively associated with that nights' sleep onset and maintenance efficiency. For every 1 h above infants' usual total daytime nap sleep duration, infants were put to bed 8.2 min earlier, where they slept 14.2 min longer and 1.0% less efficient that night ($p \leq 0.05$).

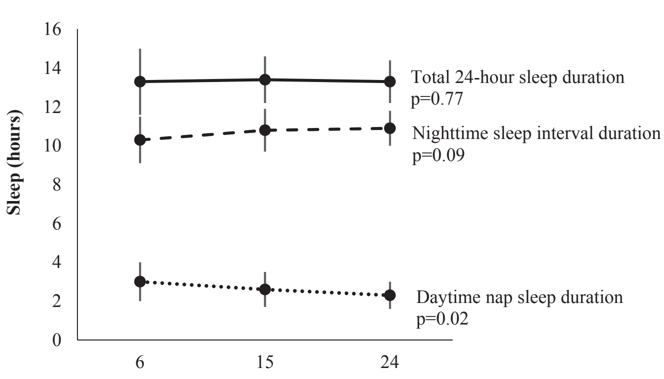

Fig. 2. Nighttime, daytime, and total 24-h sleep durations across the first 6 months of life, measured using actigraphy. Total 24-h and nighttime sleep interval duration did not differ across infant age, while daytime nap sleep duration decreased. Post hoc comparisons on daytime nap sleep duration indicated that six weeks differed from 24 weeks ($p = 0.02$). Values presented are mean ± standard deviation.

To further explore these relationships at 24 weeks of age, we characterized daytime sleep as average nap duration and number of naps. More naps, but not average nap duration, drove the association on that nights' sleep onset. For each additional nap above infants' usual, sleep onset was 7.2 min earlier that night ($p = 0.05$), while there was no association between average nap duration and sleep onset that night ($p = 0.25$). In contrast, longer nap duration, but not the number of naps, drove the associations on that nights' sleep interval duration. For every 1 h above infants' usual nap duration, that nights' sleep interval duration was 35.9 min longer. Average nap duration was marginally significant for a negative relationship on that nights' sleep efficiency, such that for every 1 h above infants' average nap duration, that nights' sleep was 1.6% less efficient ($p = 0.08$). There were no associations between the number of naps and that nights' sleep interval duration or maintenance efficiency ($p > 0.05$).

3.3. Actigraphy-obtained vs. mother-reported measures

A cross-sectional comparison between actigraphy-obtained and mother-reported values for infants' nighttime, total daytime, and total 24-h sleep durations, nap duration, and number of naps per day, at 6, 15, and 24 weeks of age, are listed in Table 3. When nighttime sleep was quantified as nighttime sleep interval duration, mothers tended to underestimate infants nighttime sleep duration by ~1–2 h/day (Table 3). When quantified as nighttime total sleep time, mothers tended to overestimate infants nighttime sleep by ~1 h/day at 24 weeks of age, with no difference in these measures at 6 and 15 weeks of age.

Mothers consistently overestimated infants' total daytime sleep by ~2–3 h/day, when compared to actigraphy-obtained values for both daytime nap sleep duration and daytime total sleep time ($p < 0.05$; Table 3). Infants' number of naps/day and average nap duration were also overestimated by mothers at each infant age ($p \leq 0.05$; Table 3). Mothers reported that infants took ~0.5–1.0 more naps/day that were ~27–40 min longer than the naps recorded using actigraphy. For total 24-h sleep, mothers overestimated infants' total 24-h sleep interval duration by ~0.5–1.5 h/day when compared to actigraphy. When quantifying 24-h total sleep time using actigraphy, mothers still overestimated and by a larger amount of ~3–3.5 h/day.

Previously above, we described longitudinal changes for infants' sleep characteristics when measured using actigraphy. Nighttime sleep interval duration was marginally significant for increasing from 6 to 24 weeks of age, while total daytime nap sleep duration and the number of infant naps decreased. Total 24-h sleep duration (including average daytime nap duration) did not change from 6 to 24 weeks of age. These longitudinal patterns were similar when using mother-reported measures. The only difference was that nighttime sleep duration significantly increased ($p < 0.01$), rather than marginal significance.

4. Discussion

Using actigraphy, we characterized patterns of infant sleep-wake states across the first six months of life. From 6 to 24 weeks of age, total daytime nap sleep duration decreased, with a marginal significance for nighttime sleep interval increasing. Total 24-h sleep duration was time invariant. Daily temporal patterns indicated that changes to infants' usual nighttime sleep interval did not influence next-day sleep; yet, at 24 weeks, changes to infants' usual daytime nap sleep duration influenced that nights' sleep onset, interval duration, and maintenance efficiency. When compared to actigraphy, mothers tended to underestimate infants' nighttime sleep and overestimate infants' daytime sleep. Collectively, this provides

Table 3
Actigraphy vs. mom-report measures of infant sleep indicated mothers tended to over-estimate infants' daytime and total 24-h sleep. Actigraphy vs. mother-report measures of infants' nighttime sleep depended on how nighttime sleep was calculated using actigraphy.

	Actigraphy		Mom-report	Mean differences	
	Sleep interval duration	Total sleep time		Sleep interval duration − Mom-report	Total sleep time − Mom-report
Nighttime sleep (hours)					
6 weeks	10.3 ± 1.2 (7.5–12.4)	8.6 ± 1.3 (5.5–11.0)	8.6 ± 1.7 (4.0–11.3)	1.7 ± 1.9* (0.8, 2.5)	−0.1 ± 1.7 (1.3, 2.5)
15 weeks	10.8 ± 1.1 (9.0–14.2)	8.8 ± 0.9 (6.9–10.9)	9.5 ± 2.0 (3.5–12.0)	1.3 ± 1.9* (0.5, 2.1)	−0.7 ± 2.0 (1.5, 2.8)
24 weeks	10.9 ± 0.9 (9.4–13.4)	9.0 ± 0.7 (7.6–10.5)	10.2 ± 1.3 (5.5–12.0)	0.8 ± 1.4* (0.1, 1.4)	−1.2 ± 1.3* (1.0, 1.9)
Daytime sleep (hours)					
6 weeks	3.0 ± 1.0 (1.0–4.7)	2.9 ± 1.0 (1.0–4.6)	6.2 ± 2.1 (4.0–11.0)	−3.1 ± 2.2* (−4.1, −2.2)	−3.2 ± 2.2* (−4.2, −2.3)
15 weeks	2.6 ± 0.9 (0.7–4.0)	2.5 ± 0.9 (0.7–3.9)	4.6 ± 1.7 (2.0–10.5)	−2.0 ± 1.8* (−2.7, −1.2)	−2.1 ± 1.7* (−2.8, −1.4)
24 weeks	2.3 ± 0.7 (1.1–3.6)	2.2 ± 0.7 (1.1–3.5)	4.3 ± 1.9 (1.5–11.0)	−1.9 ± 2.1* (−2.9, −1.0)	−2.0 ± 2.1* (−3.0, −1.1)
Total 24-h sleep (hours)					
6 weeks	13.3 ± 1.7 (10.9–16.5)	11.5 ± 1.9 (7.9–14.6)	14.8 ± 2.6 (10.5–19.5)	−1.5 ± 2.8* (−2.7, −0.2)	−3.3 ± 2.7* (−4.5, −2.2)
15 weeks	13.4 ± 1.2 (11.1–15.8)	11.3 ± 1.1 (9.5–14.2)	14.1 ± 2.7 (7.5–19.0)	−0.7 ± 2.3 (−1.7, 0.3)	−2.8 ± 2.3* (−3.7, −1.8)
24 weeks	13.3 ± 1.1 (11.1–15.8)	11.3 ± 0.9 (9.3–12.8)	14.5 ± 2.2 (11.5–21.5)	−1.2 ± 2.5* (−2.3, 0.0)	−3.2 ± 2.5* (−4.3, -2.1)
Nap duration (min/nap)					
6 weeks	53.2 ± 13.5 (34.0–72.1)	51.5 ± 13.0 (33.3–69.7)	90.6 ± 28.7 (50.0–140.0)	−37.4 ± 28.6* (−49.8, −25.1)	−39.1 ± 28.7* (−51.5, −26.7)
15 weeks	53.5 ± 16.3 (29.8–84.4)	51.3 ± 15.4 (29.4–81.8)	81.1 ± 26.2 (42.0–140.0)	−27.5 ± 22.7* (−37.1, −17.9)	−29.7 ± 22.4* (−39.2, −20.2)
24 weeks	59.7 ± 12.0 (41.2–90.5)	57.3 ± 10.8 (39.6–83.3)	87.5 ± 43.9 (30.0–220.0)	−27.3 ± 41.6* (−45.8, −8.9)	−29.8 ± 41.8* (−48.3, −11.3)
Naps per day (n)					
6 weeks	3.4 ± 0.8 (1.7–4.7)		4.5 ± 2.3 (2.0–12.0)	−1.1 ± 2.6 (−2.2, 0.0)	
15 weeks	2.9 ± 0.6 (1.3–3.9)		3.5 ± 1.3 (2.0–8.0)	−0.6 ± 1.3* (−1.2, −0.1)	
24 weeks	2.4 ± 0.6 (0.8–3.6)		3.1 ± 0.8 (2.0–5.0)	−0.7 ± 0.8* (−1.0, −0.4)	

Values for actigraphy and mom-report are presented are mean ± standard deviation (minimum–maximum). Values for mean differences are presented are mean ± standard deviation (95% confidence interval). Positive values indicate greater actigraphy values. Negative values indicate greater mom-report values. *$p < 0.05$.

novel evidence on objective estimates for infants' developmental and daily sleep patterns, which differed from mothers' perceptions of infant sleep.

This was the first study to examine within-person changes of day-to-night and night-to-day sleep patterns during early infancy. We found that changes to infants' usual daytime sleep, rather than changes to their usual nighttime sleep, were associated with subsequent sleep bouts. Infants may have slept longer than usual in a given day due to reasons such as greater daytime stimulation or a growth spurt [27]. In contrast, infants may have slept less than usual in a given day due to reasons that include teething [28], exposure to warmer/colder temperatures [29], or parents keeping them up in hopes of them sleeping longer at night. After days in which infants got less daytime sleep than usual, they also spent less time in bed that night with more efficient sleep (eg, less wake time). These patterns may be explained by differences in parenting practices versus infants' physiological needs. Parents may have kept their infants up during the day or put them to bed later at night with the intention of having them sleep in later that next morning. Physiologically on these nights, infants may have slept more efficiently to make up for the sleep they did not get during the day. Testing the association between changes to infants' typical daytime sleep and that nights' longest continuous sleep bout would provide insight as to whether infants' nighttime sleep efficiency was impacted by short, sporadic, and independent night wakings, or long, concentrated night wakings that required parent involvement. Given the novelty of these associations in our data, future is needed to better understand the extent to which shorter and longer daytime/nighttime sleep durations are behaviorally-driven (eg, parenting practices) versus physiologically-driven to better understand these relationships.

A comparison of measures showed the longitudinal patterns of infant sleep from 6 to 24 weeks of age were similar between actigraphy and mother-report values. While mother-report appeared adequate for estimating general patterns of sleep over time, mothers' estimation of infant sleep at one specific time differed from actigraphy. It is unclear if mothers' perception of infants' nighttime sleep is their estimation of actual sleep time (eg, mentally subtracting out night wakings), or if mothers perceive infants' nighttime sleep as the full duration from falling asleep at night to waking in the morning. Therefore, we compared actigraphy nighttime total sleep time (eg, actual sleep) and nighttime sleep interval duration (eg, sleep onset to sleep offset) to mother-reported values. Mothers' perception of infant nighttime sleep was more than actigraphy-identified nighttime total sleep time, yet less than actigraphy-identified nighttime sleep interval duration. A number of studies have compared mother-report and actigraphy measures, finding that mothers typically overestimate infants' nighttime sleep [11–14], which is similar to our patterns at 24 weeks of age when using nighttime total sleep time. We found opposite patterns compared to previous literature when comparing mother-report to nighttime sleep interval duration, which may be for a couple of reasons. First, mothers may have perceived their infants' nighttime sleep duration to be their longest continuous sleep bout, rather than the sum of all sleep during the nighttime sleep period. If so, the longest continuous sleep bout is likely an underestimation of infants' total nighttime sleep. Second, mothers may have unknowingly been inclined to provide estimations of infants' nighttime sleep that were more reflective of their own personal nighttime sleep duration, rather than their infants.

Much of the literature on mother-report vs. actigraphy measures have not included infants' daytime sleep [11–14]. One other study did include naps and found that parent-reported sleep diaries recorded longer infant nap durations at six months of age, when compared to actigraphy [23]. Similarly in our sample, mothers greatly overestimated infants' daytime nap sleep duration, number of naps, and nap duration. Daytime nap sleep duration was ~2–3 h/day greater when collected via actigraphy, compared to mother-report. It appears this large discrepancy was due to an overestimation of infants' average nap duration; the number of naps per day was also overestimated, but to a lesser extent. There are a number of possible reasons as to why mothers may have overestimated infants nap duration. When infants nap, mothers may use this time to also nap, work, or take care of older children [30]. In any case, mothers' attention may be focused elsewhere during infant naps. This makes it possible for mothers to perceive their infant as having napped longer, when in reality, infants may be awake, but quiet, for a portion of their nap. In this event, if infants were awake for ≥15 min during the middle of a nap, our actigraphy scoring rules separated this sleep interval into two shorter naps with wake time in-between, whereas mothers would have likely considered this to be one longer nap. Further, the BISQ defines infants' daytime sleep as being between the hours of 7:00AM–7:00PM. When infant's wakeup after 7:00AM, mothers may consider sleep after 7:00AM as “daytime sleep,” even if some of this sleep was part of infants' nighttime sleep interval. Last, during postpartum, mothers are sleep deprived, which can result in a greater reporting bias; yet, this is not specific to just daytime nap sleep [31]. Given the frequency and importance of daytime sleep during early infancy, our results provide valuable evidence on methodological comparisons for an understudied area within infant sleep research. Yet, as actigraphy becomes more common in infants and scoring becomes more consistent, then we suggest different samples examine these same patterns to confirm or refute our findings.

Given the lack of established guidelines for scoring actigraphy data in infants, coupled with the increasing use of actigraphy in this population, there is a pressing need for more research that clearly identifies the methodological process for scoring these data [6,10]. We provided definitions and scoring rules that can serve as a starting place for future work to build upon (Table 1). When determining these scoring rules, one of the greatest challenges was the identification of infant naps. Currently, there are no guidelines for what constitutes a daytime nap in infants [6]. For adults, a rule of ≥30 min of sleep is often used to define a nap [18]; yet, infants can nap in periods less than 30 min [22–26]. This criterion value was too large to identify naps of a shorter duration that are entirely plausible for infants. Instead, we defined a nap as a sleep interval ≥15 min in duration. While this threshold of 15 min warrants future validation, we based this decision off the work from Samson et al. [24], and Sharkey et al., [26]. In comparison, other researchers have used cut-off values of ≥3 min [21] or ≥20 min [23]. A nap duration as short as 3 min may result in false positives, or an overestimation of naps, given the limitation that actigraphy-identified naps (using current and clearly limited algorithm/device combinations) have high sensitivity (ie, identification of true positives), yet low specificity (ie, identification of true negatives), when compared to PSG [32]. A more conservative nap definition of ≥20 min was found to have ‘slight’ agreement with parent-reported sleep diaries when infants were six months of age [22]; yet, nap durations <20 min or infants younger than six months of age were not tested. To further this work, we suggest that future studies use objective measures of PSG and videosomography to identify the minimum duration in which actigraphy devices can identify naps among infants less than six months of age, with ≥15 min as a starting point.

One limitation of this study was the small, homogenous sample that did not allow for the testing of possible moderators that could impact infant sleep patterns. Future studies with larger, more diverse samples should explore the moderating role of infant feeding mode, parity, and temperament, as well as family-level characteristics such as SES, chaos in the household, and coparenting quality. Another limitation is that the information collected on the BISQ differs slightly from the information collected using actigraphy. For example, with actigraphy, nighttime sleep interval was defined as sleep onset to sleep offset, while on the BISQ, nighttime sleep duration was the typical amount of time infants sleep between 7:00PM–7:00AM. Our results should be interpreted as the comparison of actigraphy-obtained sleep intervals durations to mothers' perceptions of infant sleep, rather than a validation or comparison of two exact measures.

This longitudinal burst design allowed us to quantify both the developmental and day-to-day patterns of infant sleep during the first six months of life. Thus, we provide a method for coding infant actigraphy data and new evidence on sleep-wake patterns during a critical period for developing healthy sleep habits. Our findings on infants' daytime nap sleep have particular importance and novelty, which is an area of research that warrants additional investigation. Moving forward, we encourage researchers to use actigraphy and further explore these sleep-wake patterns during infancy.

Disclosure

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Conflict of interest

The ICMJE Uniform Disclosure Form for Potential Conflicts of Interest associated with this article can be viewed by clicking on the following link: https://doi.org/10.1016/j.sleep.2019.05.017.

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