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Early identification of sleep phenotypes in infants by videosomnography: a cross-sectional study

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ABSTRACT

Study Objectives: We propose to identify different sleep phenotypes in infancy, relying on auto-videosomnography metrics.
Methods: In this cross-sectional study, objective infant sleep metrics of six hundred twenty-three infants aged 9 to 13 months, recruited among users of Nanit baby-monitor in the United States, were obtained from Nanit auto-videosomnography (1 week of data averaged) in the child's natural sleep environment. A cluster analysis was conducted to group infants based on sleep metrics.
Results: Three reproducible and stable sleep phenotypes were identified: Long Sleepers (n.338), Interrupted Sleepers (n.130) and Short Sleepers (n.155). All sleep metrics were statistically significant different in the three groups. Long Sleepers had longer nighttime sleep duration than Interrupted and Short Sleepers. Interrupted Sleepers presented more awakenings than Short and Long Sleepers, and similarly more parental interventions. Short Sleepers presented later bedtimes and earlier wake up times when compared with Long and Interrupted Sleepers. Nighttime sleep efficiency was better in Long Sleepers than in Interrupted and Short Sleepers, but Short Sleepers presented better sleep efficiency than Interrupted Sleepers.
Conclusions: Cluster analysis based on objective sleep metrics offers a novel multidimensional approach for the early identification of infants' sleep patterns. Phenotyping sleep patterns is extremely important in identifying the risk for developing neurobehavioral disorders since night wakings and reduced sleep duration in infancy might be predictive of the development of emotional and behavioral problems later in childhood.

Keywords: videosomnography; infant sleep; sleep patterns

BRIEF SUMMARY

Current Knowledge/Study Rationale: During the first year of life, infants go through significant changes in their sleep patterns. From the irregular sleep-wake cycles of newborns, sleep gradually evolves to more predictable patterns.
Study Impact: This cross-sectional study, based on objective metrics of a large sample of infants aged 9 to 13 months, offers a panorama of different sleep phenotypes in infancy. The early identification of sleep phenotypes, that account for the multidimensionality of sleep, might be critical since night wakings and reduced sleep duration in infancy might predict neurobehavioral disorders at later ages.

INTRODUCTION

During the first year of life sleep and wake patterns show rapid development in humans, reflecting the maturation of central nervous system structures, like the hypothalamus or the neurotransmitter system [1]. During the first 12 months, there is an overall decline in total sleep duration and a gradual consolidation of more sleep time and longer bouts during the night. Despite general trends in reaching "sleep milestones", there is still a high degree of heterogeneity and variability in infant sleep duration and frequency of night awakenings.

For a long time, the characterization of sleep has been performed by looking at several dimensions of sleep separately, but lately, there has been a shift to focus on the multidimensional construct of sleep health [2]. A few recent studies have developed multidimensional sleep characterization in adults and school-age children [3–5], assessing what sleep characteristics are present in the same people and what subgroups exist in the population. Nonetheless, this type of work has been scarce in early childhood.

One study by Hughes et al. [6] found four sleep clusters in 9-month-old infants, one identified as optimal sleep with long duration and no awakenings, one with similar sleep duration but more awakenings, and two with shorter duration and more awakenings but different parental perception of sleep problems. This study had several strengths including a large sample size, but one limitation was the reliance on parental reports of sleep, which is known to be affected by potential biases [7].

More recent research identified five distinct sleep multi-trajectory groups in children from age 1 to 5.5 years for nighttime sleep duration (NSD) and daytime sleep duration (DSD), night waking (NW), and sleep-onset difficulties (SOD), by parental phone interviews in 9273 children [8]. The "Good sleepers" (31.6%) and "Long sleepers" (31.0%) groups had low NW and SOD prevalence and shorter NSD but longer DSD in "Good sleepers" than in "Long sleepers."

A recent systematic review showed distinct trajectories for sleep duration, sleep problems, and bed-sharing. Sleep duration trajectories are most pronounced at younger ages and diminish as children age. Research on specific sleep issues like insomnia identified two subgroups: one with consistent, low-level problems and the other with chronic, variable issues. Shorter sleep duration and sleep problems are associated with sociodemographic, emotional, and behavioral factors. Predictors include lower socioeconomic status, maternal depression, and night-feeding behaviors. These findings can inform interventions to improve sleep health [9].

Therefore, gaining a better understanding of various sleep patterns and phenotypes in infancy can offer valuable insights into infant development and help in understanding their potential long-term impact on health and neurodevelopment [10–12].

New technological advancements in signal/video-processing techniques and the rise of tele-medicine approaches have made possible large population-level studies with objective sleep measures derived by auto-videosomnography (auto-VSG) [13–15].

Given this background, this study aims to fill the current gap in the literature by using objective sleep metrics obtained via auto-VSG to identify distinct clusters of sleep patterns in US infants aged 9-12 months.

METHODS

Participants

US-based caregiver users of Nanit baby monitors with a child 9-13 months old (N = 76,700) were invited via email to take part in this study on April 18, 2023. Nanit is a commercially available video baby monitor system. This system analyzes infant motility patterns that are translated into sleep-wake patterns, using computer vision technology, with high level of accuracy comparing Nanit to video observation and actigraphy[16]. Electronic informed consent was obtained and explicitly stated that automated sleep data from the preceding week (April 10th to 17th, 2023) would be utilized for the study. Parents were asked to fill out an online survey for demographic information. Participants who agreed to take part were given the opportunity to enter a draw to win a $300 gift card on an on-line merchant. The study adhered to the principles outlined in the Declaration of Helsinki. Data collection utilized participant alphanumeric codes to ensure anonymity.

Parents of 1335 infants agreed to participate in the study. The final sample was determined based on specific inclusion criteria. Firstly, participants had to have at least five nights of valid auto-VSG data available within a 1-week assessment period, resulting in the exclusion of 482 entries. Secondly, participants had to identify as parents of infants aged 9–13 months, leading to the exclusion of 4 entries. To ensure the quality of auto-VSG registration, certain cutoff criteria were applied to each assessed night. Infant sleep-onset times were required to fall within the 4 pm–12 am range, sleep-offset times within the 4 am–11 am range, and sleep duration to be greater than 5 hours. These cutoffs, informed by previous studies [14,15], aimed to ensure that only nighttime sleep episodes were considered and that a sufficient amount of infant recording occurred while the infant was in the cradle. In total, 623 infants met these criteria and constituted the final sample, with 4224 nights assessed (mean number of nights per participant = 6.8). Average sleep metrics were calculated for each infant across the assessment period.

Measures

Demographic characteristics

Through an online survey parents were asked to report their infant's age and gender, in addition to their demographic characteristics, which included items regarding gender, age, ethnicity, education, residence, employment status, annual household income.

Auto-videosomnography (auto-VSG)

Objective sleep data were collected in the natural home environment of infants using Nanit camera monitors (Nanit, dba Udisense Inc., NY, USA). These monitors, positioned above the infant's crib, continuously record the crib setting during nighttime hours. Using computer vision algorithms able to detect motion and immobility patterns, these videos are automatically analyzed and converted into metrics related to infant sleep-wake patterns and parental visits. Nanit algorithms have been validated against both actigraphy and polysomnography [16,17]. Unlike actigraphy, which typically monitors movement at the wrist or ankle, the auto-VSG system captures movement from the entire body [18], furthermore, it detects movement into the crib setting of the caregiver/s, giving additional information about caregiver crib visits during the night.

The auto-VSG metrics utilized in this research encompass several parameters: (a) Nighttime infant sleep duration: total minutes scored as sleep during the nocturnal sleep period; (b) Number of nighttime infant awakenings: instances of awakenings lasting three or more minutes within the sleep period; (c) Number of parental nighttime visits: frequency of parental presence detected within the crib area throughout the night; (d) Nighttime sleep efficiency: percentage of the sleep period spent asleep (calculated as minutes scored as sleep divided by the duration of the nocturnal sleep period, multiplied by 100); (e) Sleep onset time: time at which the infant initially falls asleep; (f) Wake-up time: time at which the infant definitively wakes up in the morning. Since in some cases it is possible that the child fell asleep outside the crib (and therefore outside the area recorded by the camera), the sleep latency derived from the auto-VSG was not considered.

Data analysis plan

All statistical analyses were performed using SPSS version 23 (SPSS, Inc., Chicago, IL) and R Studio software (version 2023.06.1). First, a descriptive analysis of the variables of interest was conducted to obtain means, standard deviations (SD), frequencies, and percentages. T-tests were performed to rule out gender differences in sleep metrics.

To group infants according to their sleeping patterns, a cluster analysis based on auto-VSG was conducted using a series of hierarchical (Ward's method) and non-hierarchical (k-means) cluster analyses to determine the best representative model for this set of data and to test stability and replicability of the clusters [19]. The hierarchical cluster analysis using Ward's method generated a dendrogram, the points of large change between successive fusion levels were used to define the number of clusters within the studied population. This estimated number of clusters was prespecified in the k-means cluster analysis that was used as the principal clustering technique. To ensure repeatability and stability, the k-means algorithm was repeated several times at random starting points using an alternative statistical software package (STATISTICA) and repeated within randomly selected subsets of the studied sample. Sleep variables chosen for cluster modelling were selected based on their contribution to characterize sleep quality and efficacy. All sleep continuous measurements were standardized using z scores and were log-transformed to approximate a normal distribution where this was indicated.

The between-cluster comparison of sleep variables was performed using one-way analysis of variance (ANOVA) for continuous variables and the $\chi 2$ test for categorical variables. Post hoc tests were performed, Tukey HSD test for equal variances and Games-Howell test for not equal variances.

RESULTS

Based on the selection criteria, 623 infants (52% girls) aged 9 to 13 months were involved in this study. 65 infants (10.4%) were premature. **Table 1** presents the demographic characteristics of both parents and infants.

Sleep characteristics: gender differences and age-related changes

In the sample mean nighttime sleep duration was 621.23 min (± 61.31 min), mean sleep-onset time was at 19:42 (± 00:48), and mean sleep-offset time at 06:45 (± 00:41) (**Table 1**). Subjects had an average of 2.5 (± 1.2) nighttime awakenings per night, with 373 (59.9%) infants having more than 2 awakenings/night. The study provides some evidence about gender differences in sleep metrics, indicating female infants waking up later ($t(621) = 3.1$, $p = 0.002$) and sleeping more during the night ($t(621) = 3.5$, $p < 0.001$) compared to their male counterparts. There was an age effect in sleep patterns with older infants having higher sleep efficiency ($r=0.09$, $p<0.05$) and fewer night awakenings ($r= -0.14$, $p<0.001$), demonstrating a consolidation of nocturnal sleep.

Premature infants did not show significant differences in sleep metrics from the rest of the sample. African Americans infants presented later sleep onset times when compared with non-Hispanic white infants (00:45 ± 00:14, $p=0.016$). No differences in sleep metrics were found with the increase of number of children in the family.

Sleep clusters

Sleep variables chosen for cluster modelling were selected based on their contribution to characterize sleep quality and efficacy, final clusters were defined based on nighttime sleep duration, number of awakenings and sleep-onset time.

Cluster analysis identified three auto-VSG-derived reproducible and stable sleep clusters (**Table 2**). Each cluster was labelled according to main sleep characteristics: Long Sleepers (n=338; 54.2%), Interrupted Sleepers (n=130; 20.9%), and Short Sleepers (n=155; 24.9%). All sleep metrics were statistically significantly different among the groups and are portrayed in **Figure 1**. The scatterplots, the histograms and the density plots showed the distribution of the three groups. For example, in the first line, the histogram clearly shows that the Interrupted Sleepers have lower sleep quality vs. Long and Short Sleepers. The intersection with other variables shows how each cluster differs from the others. **Table 2** reports the statistical differences in sleep metrics between the three groups analyzed with Welch test and post-hoc analysis.

Nighttime sleep duration

Long Sleepers had longer nighttime sleep duration than Interrupted (47.46 ± 4.68 min, $p<.001$) and Short Sleepers (103.26 ± 4.74 min, $p<.001$).

Night awakenings

Interrupted Sleepers presented more awakenings than Short (2.37 ± 0.12, $p<.001$) and Long Sleepers (2.23 ± 0.11 h, $p<.001$), and similarly more parental intervention (respectively 1.45 ± 0.29, $p<.001$ and 2.00 ± 0.28, $p<.001$). Long and Short Sleepers did not differ in awakenings, but only in parental intervention, being more frequent in Short Sleepers (0.55 ± 0.10, $p<.001$).

Sleep onset time and wake up time

Short Sleepers presented later sleep onset times and earlier wake up times when compared with Long (01:16 ± 00:04, $p<.001$ and -00:19 ± 00:04 h, $p<.001$) and Interrupted Sleepers (01:03 ± 00:05, $p<.001$ and -00:22 ± 00:05, $p<.001$)

Nighttime sleep variability

Long Sleepers had less variability in nighttime sleep than Interrupted (-15.00 ± 2.88, $p<.001$) and Short Sleepers (-11.94 ± 2.22, $p<.001$).

Nighttime sleep efficiency

Nighttime sleep efficiency was better in Long Sleepers than in Interrupted (0.05 ± 0.01, $p<.001$) and Short Sleepers (0.01 ± 0.01, $p<.001$), Short Sleepers presented better sleep efficiency than Interrupted Sleepers (0.04 ± 0.01, $p<.001$).

No age or gender difference was found between clusters and the three clusters did not differ significantly in the presence of prematurity.

DISCUSSION

The study explored infants' sleep objectively in their ecological environment, providing sleep values and identifying three different clusters of sleep.

Sleep values

Sleep metrics from this study are particularly informative since auto-VSG has the ability to objectively assess infant sleep in a non-invasive way and in the child's natural sleep environment, including information on the child's nighttime behaviors and parental interventions [20].

When comparing our data to sleep metrics derived from parent report studies for the same age group, night sleep duration found in the present study falls in line with previous research on normative sleep patterns in a large US–Canada sample of 5006 infants [21], while differing from two Italian studies on 704 [22] and 2889 infants [23], and from one Chinese study on 14883 infants [24] reporting shorter nighttime sleep; whereas a Swiss study on 493 infants reported 1h longer night sleep duration [25]. When comparing sleeping times, sleep onset times from our sample were similar to those from Switzerland [25] and earlier than those of Italy [22,23,26] and Taiwan [27]; whereas wake up times in the present study were earlier than those found in Switzerland [25] and in Italy [22,26].

When comparing our data to sleep metrics derived from actigraphy for the same age group, we find that one Australian study [28] and one USA study [29] reported shorter nighttime sleep duration. Also, a precedent study on US infants conducted with auto-VSG reported shorter nighttime sleep [15].

As expected, we found more stable sleep, expressed by a reduction of night awakenings and a prolongation of nocturnal sleep, in older children. In our sample, night awakenings were very frequent, 59.9% of infants had on average more than 2 awakenings/night. Precedent studies based on parent-reported sleep metrics [21,22,26,30–32] and a systematic review [30], reported lower frequencies, this could be explained by the non-detection of short awakenings by parents and by the high sensitivity of auto-VSG.

Parents probably detect and report only major awakenings, as reflected by a lower number of parental visits, compared to awakenings in our sample.

Contrary to previous studies showing no gender differences in sleep patterns at 1 year old [23,33,34], our findings suggest different sleep patterns in female infants, having longer nighttime sleep and later wake-ups than their male peers.

Sleep clusters

Clinical practice teaches that, even though there are normative values, sleep patterns in infancy can vary greatly from one child to another.

Previous research has primarily classified infant and child sleep based on singular sleep metrics; for example, night awakenings were utilized by Weissbluth et al.[35], while sleep duration was analyzed by Magee et al.[36]. In instances where multiple sleep metrics were employed, the data were predominantly derived from parental reports or historical accounts [12,37–40]. Only one study utilized objective measures derived from a limited sample of adults[41], whereas Matricciani et al.[4] uniquely clustered children based on actigraphy metrics. In their investigation, the authors determined the number of clusters (four) by visually examining the hierarchical cluster results coupled with the interpretability of K-means cluster solutions. Similarly, our study employed the same methodology; however, owing to variations in initial metrics and differences in sample composition regarding county and age, the resulting classification yielded a slightly different outcome (three clusters versus four).

The main advantage of classification by cluster analysis is objectivity, since the use of a methodology for including multiple variables with the same weighting helps minimize a priori bias. In psychiatry, the techniques of cluster analysis have been used for the identification of symptom expression patterns helping to define diagnostic categories [42]. Since sleep is a multidimensional construct, recorded in multiple facets by the auto-VSG, clustering analysis was particularly helpful to categorize sleep phenotypes in our sample. The sleep clusters identified in this study consisted of: (1) one large group constituted by infants with long, efficient, and stable night sleep (Long Sleepers); (2) a group of infants characterized primarily by multiple nocturnal awakenings (Interrupted Sleepers); and (3) a third group represented by infants having a short, but rather continuous, night sleep (Short Sleepers). Long Sleepers may be infants with potentially healthier sleep, having better sleep efficiency and longer night sleep than the other two groups. They have similar sleep timing with Interrupted Sleepers, who, however, have more time awake during the night due to frequent awakenings. Finally, Short Sleepers were infants with later sleep onset times and earlier wake up times, characterized by higher sleep efficiency but a lower sleep duration than Interrupted Sleepers.

Phenotyping sleep patterns is extremely important to identify infants at risk for developing neurobehavioral disorders since night wakings and reduced sleep duration in infancy are predictive of the development of emotional and behavioral problems later in childhood. It has been demonstrated that night wakings at 3 months are prospectively related to internalizing and externalizing symptoms and are closely related to dysregulation in toddlers [43].

Strengths and limitations

One limitation of the study is that sleep variables were derived mixing data from weekday and weekend sleep, without differentiating them.

Another limitation is the sample's majority non-Hispanic white makeup and elevated socioeconomic status, with just 1.9% being African American. Consequently, the generalizability of the findings is limited. This bias is likely due to the cost of the Nanit device (~$300). In addition, only a small proportion of the users invited to participate in the study accepted the invitation, this results in a potential selection bias. The generalizability of the results is therefore limited. The other limitation is that it is based on video recording of motion and stillness within the crib, therefore sleep-wake patterns that occur outside of the crib cannot be captured.

A major strength of the study is the use of objective measurement of sleep with a commercially available camera providing cost-effective videosomnography monitoring of infant sleep-wake states in an ecological environment that allows us to achieve greater precision when examining sleep trajectories or when phenotyping sleep patterns.

CONCLUSIONS

Our study, using auto-VSG, allowed us to examine a large population of infants with objective sleep measures metrics in their ecological environment. These data allowed us to detect three distinct phenotypes of sleep in infants aged 9-13 months.

The early identification of sleep phenotypes might be extremely important for the prevention of later mental health disorders since different studies showed that infants with persistent severe sleep problems during the first postnatal year have an increased risk of anxiety problems and emotional disorders at age 10[44] and also that shorter sleep and poorer sleep quality in infancy were prospectively related to emotional and behavioural symptoms in toddlers, and these associations were strongest for internalizing and dysregulation symptoms [43].

Further investigations, using a longitudinal study design, could help understand the trajectory of these three specific sleep phenotypes that might be an early indicator of a genetic predisposition to develop healthy sleep, short sleep or insomnia at later ages [45].

ABBREVIATIONS

Auto-VSG: auto-videosomnography

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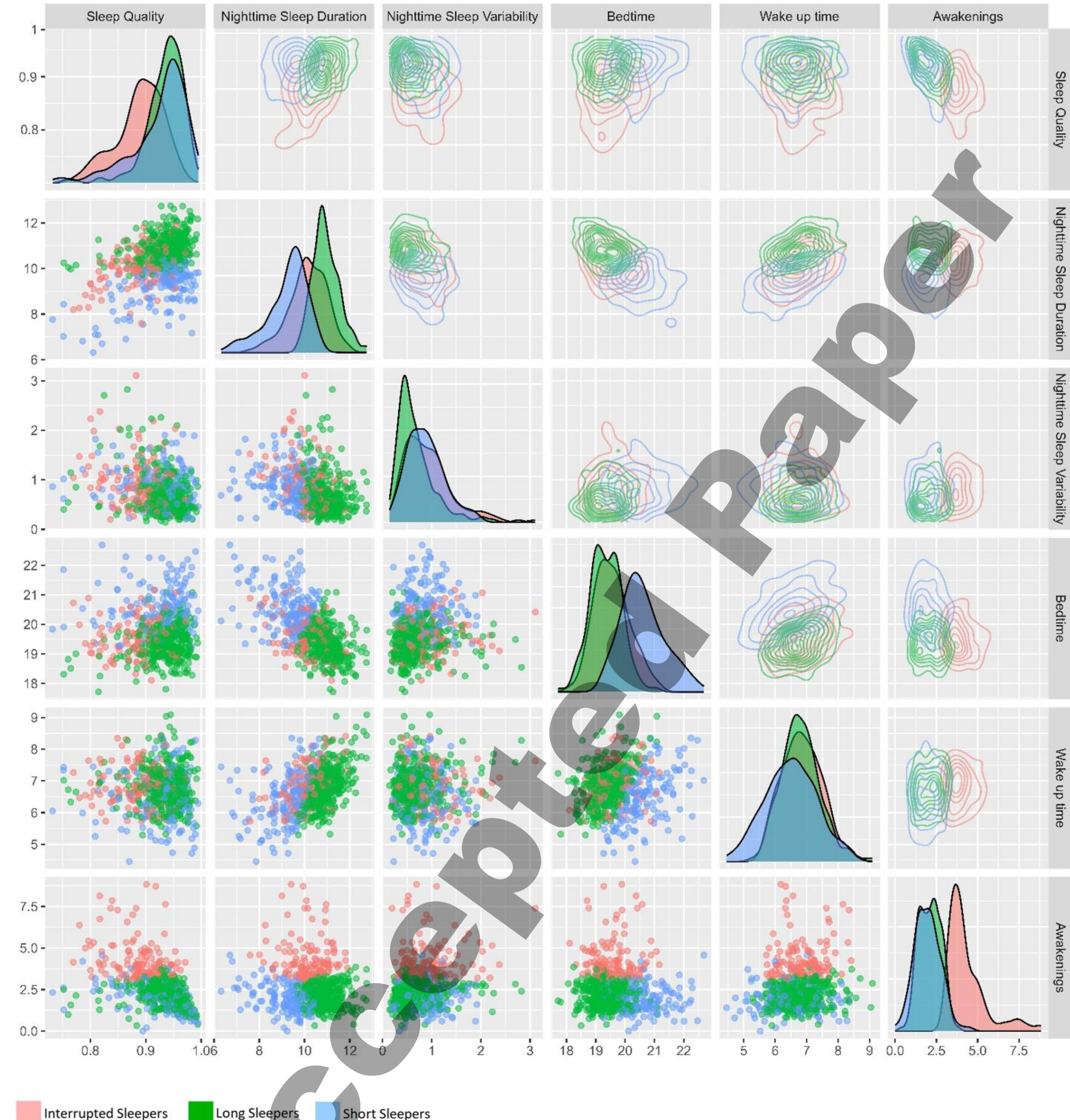
Figure 1—Pairwise scatter plot matrix (lower boxes), histograms depicting data distribution (diagonal boxes) and density plot (upper boxes) of sleep metrics for each cluster.



The scatterplots, the histograms and the density plots showed the distribution of the three groups. For example, in the first line the histogram clearly shows that the interrupted sleepers have lower sleep quality vs. long and short sleepers. The intersection with other variables shows how each cluster differs from the others.

Table 1—Sample characteristics.

Age (months)	10.3 (1.1)
Gender (% girls)	324 (52%)
Number of children in family	1.3 (0.5)
Auto-videosomnography	
Nighttime sleep duration (min)	621.2 (61.3)
Nighttime sleep variation (min)	47.0 (26.0)
Sleep quality	0.9 (0.0)
Total time awake during night (min)	55.9 (29.5)
Sleep onset time (hh:mm)	19:42 (00:48)
Wake up time (hh:mm)	06:45 (00:41)
Infant nighttime awakenings	2.5 (1.2)
Parent nighttime crib visits	1.1 (1.8)
Number of nights available per infant	6.8 (1.0)
Parents	
Gender (% mothers)	524 (84.1%)
Age (years)	
≤24	6 (1.0%)
25–29	77 (12.4%)
30–34	282 (45.3%)
35–39	205 (32.9%)
40–44	41 (6.6%)
≥45	7 (1.1%)
Ethnicity	
Non-Hispanic white	485 (77.80%)
Asian	43 (6.9%)
Hispanic	41 (6.6%)
Multiracial	15 (2.4%)
African American	12 (1.9%)
Other/Prefer not to answer	26 (4.1%)
Place of residence	
Suburban	406 (65.2%)
Urban/City	151 (24.2%)
Rural	65 (10.4%)
Prefer not to answer	1 (0.2%)
Annual household income (USD)	
< \$50,000	12 (2.0%)
\$50,000–\$100,000	82 (13.2%)
\$100,000–\$150,000	134 (21.5%)
\$150,000–\$200,000	122 (19.6%)
> \$200,000	235 (37.7%)
Prefer not to answer	38 (6.1%)
Employment status	
Full-time	438 (70.3%)
Part-time	64 (10.3%)
At home parent	96 (15.4%)
On parental leave	6 (1.0%)
Unemployed/Furloughed	9 (1.4%)
Student	3 (0.5%)
Other/Prefer not to answer	7 (1.1%)

Data are provided as mean (standard deviation) for continuous variables, and n (valid %) for categorical variables.

Table 2—Statistical differences in sleeping metrics among groups.

	Long Sleepers (LS)		Interrupted Sleepers (IS)		Short Sleepers (SS)		W[a]	*P*	Post hoc test[b]
	M	SD	M	SD	M	SD			
Nighttime sleep duration (min)	656.82	35.10	609.38	49.28	553.55	54.27	256.61	<0.001	LS > IS > SS
Nighttime sleep variability (min)	40.86	24.38	55.88	29.51	52.77	22.61	21.53	<0.001	IS, SS > LS
Sleep quality	0.93	0.04	0.89	0.04	0.93	0.05	58.01	<0.001	LS > SS > IS
Total time awake during night (min)	50.43	33.35	81.80	32.86	53.84	41.26	43.43	<0.001	IS > LS, SS
Sleep onset time (hh:mm)	19:20	00:32	19:34	00:36	20:36	00:44	181.22	<0.001	SS > LS, IS
Wake up time (hh:mm)	06:49	00:38	06:52	00:37	06:30	00:49	10.96	<0.001	LS, IS > SS
Infant nighttime awakenings (n)	2.11	0.65	4.34	1.22	1.96	0.78	209.42	<0.001	IS > LS, SS
Parent nighttime crib visits (n)	0.56	0.69	2.56	3.13	1.11	1.12	40.07	<0.001	IS > SS > LS

[a]W for Welch test. [b]Post-hoc test: Games-Howell.