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Researcher Choices for Infant Sleep Assessment: Parent Report, Actigraphy, and a Novel Video System

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ABSTRACT

Incorporating infant sleep, either as a predictor or as an outcome variable, into interdisciplinary work has become increasingly popular. Sleep researchers face many methodological choices that have implications for the reliability and validity of the data. Here, the authors directly investigated the impact of design and measurement choices in a small, longitudinal sample of infants. Three sleep measurement techniques—parent-reported sleep diaries, actigraphy (Micromini Sleep Watch), and a commercial videosomnography (Nanit)—were included, using actigraphy as the baseline. Nine infants' sleep (4 girls) was measured longitudinally using all three measurement techniques. Nanit provided summary statistics, using a proprietary algorithm, for nightly sleep parameters. The actigraphy data were analyzed with both the Sadeh Infant and Sadeh algorithms. The extent to which measurements converged on sleep start and end time, number of wake episodes, sleep efficiency, and sleep duration was assessed. Measures were positively correlated. Difference scores revealed similar patterns of greater sleep estimation in parent reports and Nanit compared with actigraphy. Bland-Altman plots revealed that much of the data were within the limits of agreement, tentatively suggesting that Nanit and actigraphy may be used interchangeably. Graphs display significant variability within and between individual infants as well as across measurement techniques. Potential confounding variables that may explain the discrepancies between parent report, Sadeh Infant, Sadeh, and Nanit are discussed. The findings are also used to speak to the advantages and disadvantages of design and measurement choices. Future directions focus on the unique contributions of each measurement technique and how to capitalize on them.

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Actigraphy; infant; parent report; sleep measurement; videosomnography

Infant sleep is a popular research topic. A quick search (in November 2020) of Google Scholar generated over 16,000 results with publication dates within the year. Infant sleep research focuses on two primary areas: (a) the developmental trajectory of sleep and (b) the relationship between sleep and other developmental outcomes such as self-regulation (Schumacher et al., 2017), executive function (Bernier, Carlson, Bordeleau, & Carrier, 2010), and learning (Seehagen, Konrad, Herbert, & Schneider, 2015). The developmental trajectory of sleep is marked by change—less daytime sleep, fewer wakings during the night, and longer durations of continuous sleep—and characterized by both inter- and intraindividual variability (Mindell et al., 2016). For example, it

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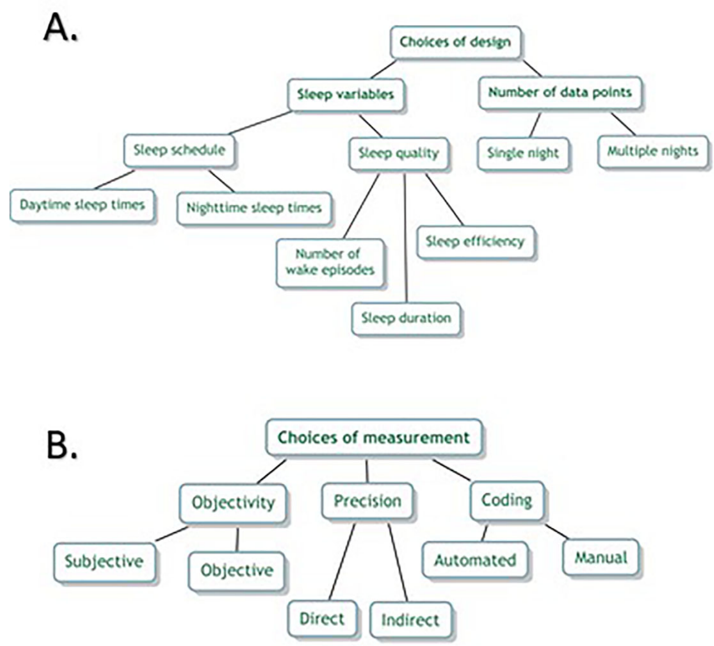


Figure 1. Decision tree for choices of (A) design and (B) measurement.

is common for one baby to fall asleep sometime between 7 and 8 p.m. each night while another does so between 8 p.m. and 10 p.m.

Such variability, paired with age-appropriate outcome measures, makes it possible to investigate the functional role of sleep. Within the domain of learning and memory, for example, conclusions regarding sleep's role range from integral to the process of memory consolidation (Horváth, Hannon, Ujma, Gombos, & Plunkett, 2018; Seehagen et al., 2015; Simon et al., 2017) to relatively inconsequential (Lukowski & Milojevich, 2013; Tham, Schneider, & Broekman, 2017). Other researchers report only an indirect benefit to memory and instead proffer sleep as a mechanism for forgetting and weeding out irrelevant details (Konrad et al., 2019).

The diversity of findings may partially stem from the multitude of choices available to measure sleep (Dutil et al., 2018). These choices are informed by many factors, from budget to ease of use, but they have implications for the reliability and validity of the data collected, as well as for the conclusions that can be drawn (Galland, Kennedy, Mitchell, & Taylor, 2012; Meltzer, Montgomery-Downs, Insana, & Walsh, 2012). Generally, there are two types of choices to be made, of design and of measurement. Figure 1 displays a decision tree for each. The implications for reliability and validity should be weighed at each step. Inaccurate measurement can lead to false conclusions or a misrepresentation of the "normal" trajectory of sleep.

Choices of design

The first design choice involves deciding what aspects of sleep are of interest. The most commonly investigated sleep variables are schedule and quality (e.g., Konrad et al., 2019). Sleep schedule variables include sleep start time, midpoint of sleep, morning wake time, and nap time(s). Sleep quality variables assess the extent to which sleep is disrupted, such as the number of wake episodes and sleep efficiency (percent of time spent asleep out of the total time in bed) (Camerota, Tully, Grimes, Gueron-Sela, & Propper, 2018). The theoretical framework of the research is essential in guiding these choices and situating infant sleep as a predictor or an outcome.

To illustrate this process, consider two lines of work: that of Kurdziel, Duclos, and Spencer (2013) and McNamara, Belsky, and Fearon (2003). The former's research was motivated by the active systems consolidation theory, which posits a direct role for sleep in memory consolidation. The latter framed their research from an attachment theory perspective, which asserts that attachment styles impact the developmental trajectory of sleep. Both included measures of sleep schedule and quality because they had hypotheses related to each. Both found significant results in sleep quality which was related to learning (Kurdziel et al., 2013) and insecure-resistant attachment styles (McNamara et al., 2003).

The second design decision regards frequency of data collection. Are researchers interested in how average sleep patterns relate to outcomes such as learning and cognition (Lukowski & Milojevich, 2013)? Or are they interested in the effect of a single daytime nap (e.g., Berger & Scher, 2017; Horváth et al., 2018; Simon et al., 2017) or night of sleep (Seehagen et al., 2015)? Measurement techniques, which are more fully discussed in the following section, can disrupt "typical" sleep patterns because they require participants to sleep in an unfamiliar environment or wear equipment on their body. As such, researchers may incorporate a period of adjustment, remove initial data points, or average data across time, all of which require more data collections to produce a useable dataset (Akacem et al., 2015).

Other research questions may depend on night-to-night variability to link specific sleep characteristics to next-day functioning. For example, parent reports averaged over hundreds of infants clearly show the expected developmental trends of fewer wake episodes with time (Mindell et al., 2016). However, increasing the sampling density to capture individual trajectories shows a much more nuanced and nonlinear developmental process. It also allows sleep patterns to be linked with other psychological domains, such as the onset of new motor skills (Berger & Moore, 2018).

Choice of measurement

The choices that researchers make about how to measure sleep impact our understanding of its development in context. Design decisions can fall into three subcategories: choices of objectivity, precision, and coding. Objective measurement techniques record behavioral, physiological, or neural signals during sleep (Ednick et al., 2009). At the other end of the spectrum, subjective measures involve a self or parent report of sleep. These are most accurate for documenting sleep schedules because the behavioral indicators of sleep versus wake, such as limited movement and closed eyes, are easily observable (Bernardi & Siclari, 2019). Objective measures are necessary for recording the physiological aspects of sleep that are invisible to the naked eye. Additionally, objective measurement removes the burden of data collection from the participant.

Researchers' second consideration regards precision. Here, precision refers to the spectrum of direct and indirect measurement techniques. Direct measurement utilizes observation, for behavioral aspects of sleep, or sensors that record physiological aspects, like muscle contractions (electromyography) or heart rate (electrocardiography) (Werth et al., 2017). Indirect measurements use a proxy to infer information about the variable of interest. For example, researchers could record an individual's physical movements for 24 hr with an actigraph and use motility patterns to delineate sleep and wake periods (Sadeh, 2011).

The third choice is the way resulting data are coded—manually or with an automated system. When the measurement technique (e.g., actigraphy) is sensitive enough to collect data on a minute-by-minute (or even more frequent) basis, an automated coding system is typically used to score sleep and wake (Galland et al., 2012; Meltzer et al., 2012). However, there is a lack of consistency in that researchers using the same measurement technique may not use the same algorithm to code the resulting data (Grigg-Damberger et al., 2007). The gold standard of sleep measurement, polysomnography (PSG), continues to utilize manual coding. Sleep technicians are trained to mark not only sleep versus wake, but also the state (rapid eye movement [REM] and non-REM), for each 30-s epoch (Grigg-Damberger et al., 2007). PSG is the most rigorous and encompassing form of sleep measurement, utilizing a combination of objective, direct measurements such as electroencephalography (EEG), electrooculography, electromyography, and electrocardiography (Scott, Lack, & Lovato, 2020).

Debate around choices of measurement is more common in pediatric sleep medicine because diagnosis and treatment require a high level of specificity (Scott et al., 2020). As the value of interdisciplinary work is increasingly recognized, basic researchers should consider, more critically, their methods. Working within typical populations restricts the range of variability and small but meaningful differences may be lost to estimation. As research questions evolve from, for example, demonstrations that sleep facilitates learning in infancy (Berger & Scher, 2017) to disentangling the process through which sleep does so, our methodologies must evolve as well (Horváth et al., 2018). Measurement techniques must innovate to address more in-depth and nuanced questions, without sacrificing accuracy or ease of use. In turn, these advances have the potential to unlock previously unexplored aspects of the developmental trajectory of sleep.

Present study

The aim of the present study was to compare sleep measurement methodologies in a small, longitudinal sample of infants. Consistent with the most commonly used measures in the literature, our sleep variables of interest included sleep start time, morning wake time, number of wake episodes, sleep efficiency, and sleep duration (Dutil et al., 2018). Measurement techniques comprised two established methods—parent-reported sleep diaries and actigraphy—and an innovative form of videosomnography, the commercially available video baby monitor system, Nanit (Nanit, New York, NY). We hypothesized that the methods would show most agreement on measures of sleep schedule. Additionally, we hypothesized that Nanit would produce sleep quality estimates closer to actigraphy than would parent report.

Parent-reported sleep diaries

A significant portion of infant sleep research is based on parent report. Diaries typically require parents to indicate, in a 24-hr time frame, when infants fell asleep and woke up (Anders, Sadeh, & Appareddy, 1995). Diaries have both benefits and drawbacks. They are easy to use and by far the most affordable option. Technological advances have even eliminated the need for physical copies of forms and manual data entry (Mindell et al., 2016). Big datasets can be collected in relatively short periods of time and questionnaires can reach more diverse and underrepresented populations. Research using both parent report and an objective measure of sleep reported a strong correlation between the two, specifically regarding sleep schedule variables. Parents were least accurate in reporting on the quality of sleep between bedtime and wake because infants may not cry or otherwise indicate whether they are awake (Sadeh, 2004, 2011). Additionally, subjective reports run the risk of becoming burdensome, missing data, and human error.

Actigraphy

Actigraphy is the most common objective measure of sleep (Schoch, Jenni, Kohler, & Kurth, 2019). It is an accelerometer housed in a small case that resembles a wristwatch (placed around an infant's ankle) that continuously records motility. The amplitude of movement is processed through age-specific algorithms to classify sleep-wake cycles and measure quality of sleep (Sadeh, Raviv, & Gruber, 2000). Actigraphy correlates highly with PSG, with 85% agreement on sleep onset and offset as well as general quality (Sadeh, 2011; Sadeh, Lavie, Scher, Tirosh, & Epstein, 1991). It is minimally intrusive as well as cost-effective and can collect data for long periods of time without researcher assistance. Because of its popularity, many companies have designed their own actigraphs, but they are not equally reliable and valid (Insana, Gozal, & Montgomery-Downs, 2010). As researchers make choices about coding (actigraphy data, specifically), they should be mindful of the sampling rates, scoring parameters, and frequency of use in the literature when choosing a brand. A reliable and valid method should also be compared with the gold standard of polysomnography.

Actigraphy is an indirect measure, relying on movement to infer sleep parameters, which sacrifices some precision. The most common resulting errors include the misidentification of quiet wakefulness as sleep or incorrectly labeling active sleep as wake (Meltzer et al., 2012). Additionally, artifacts caused by external movement like that of a stroller can lead to inaccurate data. Sleep diaries are frequently used in conjunction with actigraphy to account for these anomalies; movement artifacts can be manually removed to make the sleep parameters more accurate (Sadeh, 2011).

There are three population-specific, automated algorithms used to analyze actigraphy data from Ambulatory Monitoring (Ardsley, NY): Sadeh, Sadeh (<1 year), and Cole (Galland et al., 2012). Only the first two will be discussed. Their primary difference is the Sadeh (<1 year), henceforth referred to as Sadeh Infant, has a higher tolerance for movement (Sadeh et al., 1991). Nervous system development leads to less physical movement during sleep around the end of infancy (Anders et al., 1995), but the justification for switching from the Sadeh Infant to Sadeh at exactly 12 months is less clear.

A final challenge associated with actigraphy is the possibility of asymmetric motility during sleep. In a recent investigation, two actigraphs were used simultaneously, each worn around an infant's ankle, and the resulting sleep-wake patterns compared. The greatest discrepancies were in the identification of wake episodes. In one third of the evenings, the two actigraphs reported different total numbers of wake episodes and wake episode durations. However, they did not differ in the amount of activity recorded hour by hour (Atun-Einy, Tonetti, Boreggiani, Natale, & Scher, 2018).

Videosomnography

Another option for objective sleep measurement is videosomnography. Video monitoring has been popular since the 1970s, both used in isolation and with other methods such as polysomnography (Anders & Keener, 1985; Anders et al., 1995; Silvestri et al., 2009; Wang, Chen, & Chen, 2019). Videosomnography has evolved with time, now using a sophisticated system of hardware and software (Bit-Rate, Compression) including an infrared camera (Ipsiroglu et al., 2015); images and video are captured in real time, along with movement, position, sound, sleep-wake states, and environmental factors (Ipsiroglu et al., 2015; Wang et al., 2019).

There are also commercially available videosomnography systems, particularly for infant populations, such as BabbyCam and Nanit. Nanit uses a camera with an infrared light mounted over the crib. When installed, the user manually defines the area of the crib as well as the space where parents typically attend to their infants. The videos are time lapsed and an app permits the user access to past dates and times. Nanit has developed a system for analyzing infant sleep using computer vision technology, which has previously been demonstrated to be accurate in determining sleep and wake states when compared with actigraphy and polysomnography (Barnett, Glazer, Ivry, Ankri, & Veler, 2019; Glazer et al., 2017). Highly specific algorithms can generate sleep summary statistics, including sleep start time, morning wake, and number and duration of wake episodes, as well as distinguish between parental interactions.

Table 1. Participant information.

Infant	Sex	Race/Ethnicity	Age (Months) At Start	Age (Months) At End	Span of Participation (Days)	Nights With Parent Report	Nights With Actigraphy Data	Nights With Nanit Data	Total Nights Scheduled
1	M	White	6.48	9.5	93	3	5	6	6
2	M	Black, Asian/Pacific Islander, White	7.4	11.47	125	11	11	12	12
3	M	White	8.19	13.08	150	13	14	14	14
4	F	White	2.93	12.0	248	27	27	27	28
5	F	Jewish	6.67	9.89	91	7	8	7	8
6	F	White	6.05	10.06	122	9	15	18	20
7	F	Black, Asian/Pacific Islander, White	2.39	10.72	253	3	15	15	15
8	M	White	4.31	10.98	90	3	3	2	3
9	M	Jewish	0.89	10.32	289	9	9	8	9

In-home videosomnography has the potential to remove the burden of reporting from parents and alleviate some of the methodological problems associated with actigraphy, including being less physically intrusive. It also accounts for information from the entire infant, as opposed to a single limb as in actigraphy. However, most commercially available devices have rarely been used in research and it remains to be determined how they compare to existing reliable and validated methods.

Method

Participants

Nine healthy, full-term infants (5 boys) with no reported developmental delays participated. They had no health problems during the study. Seven infants were from the New York metropolitan area and two were from Israel. All families were middle to upper middle class. Five infants slept in a crib in their own room, one shared a room with an older sibling, and three slept in a crib in their parents' room. No families regularly co-slept in the same bed. Infants' ages at the start and end of the study, the number of nights of data collection and total participation interval are summarized in Table 1. All participants were part of a larger study for which data collection is still ongoing about the relation between sleep and the onset of motor milestones. The research was approved by the Institutional Review Boards of the College of Staten Island and University of Haifa and parents provided written informed consent for participation at the beginning of the study (IRB#2018-1039).

Sleep measurement

Data collection from the three sleep measurements were scheduled for three evenings each month. Aside from sleep measurement, those evenings were typical ones in which infants slept in their own cribs and maintained their usual routine.

Parent report

For each of three nights per month, parents recorded the time their infant fell asleep, the time they woke up, the number of night wakings, and the total amount of daytime sleep. Five parents completed the diary via paper and pencil; four did so in an Excel file. The sleep diary has been successfully used with a sample of infants with similar demographics (Berger & Moore, 2018).

Actigraphy

On the same nights that parents kept the sleep diary, infants wore a MicroMini Sleep Watch actigraph (Ambulatory Monitoring) around their left ankle. These actigraphs utilize a triaxial accelerometer with a sampling frequency of 32 Hz. Actigraphs were initialized for zero crossing mode and collected data in 1-min epochs (Atun-Einy et al., 2018). Activity data were processed for the primary analysis using the Sadeh Infant algorithm. They were scored a second time using the Sadeh algorithm. Each algorithm used awakening rules of 5 contiguous wake blocks to start and 15 contiguous sleep blocks to end.

Nanit

Families were lent a Nanit video monitoring system for the duration of the study. The system comprises a camera on an arched tripod, installed behind the crib so that the camera is suspended over the center of the crib like a mobile. A slight curve to the lens permits a full, unobstructed view of the sleep environment. Parents had access to the Nanit app, which provided nightly videos of their infant when in the crib and sent customizable alerts based on movement or noise. Videos were automatically recorded every night and were processed via the computer vision algorithm. The proprietary algorithm is based on a combination of the guidelines used in scoring videosomnography (Anders & Keener, 1985) and actigraphy (Sadeh, Acebo, Seifer, Aytur, & Carskadon, 1995). At our request, Nanit provided sleep summary statistics for the same three evenings that we collected diary and actigraphy data.

Data analysis

We had five sleep variables of interest: time of sleep onset, morning wake time, number of nightly wake episodes, sleep efficiency, and sleep duration. Sleep efficiency represents the percent of time the infant was asleep during the total sleep period. For example, if an infant was put to bed at 7 p.m. and woke up at 6 a.m. and they slept, uninterrupted for the entire 11 hr, they would have a sleep efficiency of 100%. If they only slept for 10 of the 11 hr, their sleep efficiency would be 90% and so on. Graphical displays of data per participant were examined for outliers.

Preliminary analysis compared the first three sleep variables across all methods (parent report, actigraphy, and Nanit). All were non-normally distributed. We ran bivariate Pearson correlations on the average of nightly measures to capture the general association between methods, with an increased threshold of $p < .01$ (Bland & Altman, 1999; Shan, Zhang, & Jiang, 2020). Then, difference scores for individual evenings were calculated to capture the extent to which the measures converged. Actigraphy (Sadeh Infant) was used as a baseline and the other methods subtracted because actigraphy is the most common of the three in the literature (Ednick et al., 2009).

Other measures of sleep quality—sleep efficiency and duration—were compared only between actigraphy (Sadeh Infant algorithm) and Nanit because prior research has documented the discrepancies between parent report and actigraphy (e.g., Schoch et al., 2019). The Bland-Altman technique, with modifications for repeated measures, was used to assess the level of agreement between Sadeh Infant and Nanit on sleep efficiency, number of wake episodes, and sleep duration. As in other work, the limits of agreement were set to 95% (2 *SD*s) (Bland & Altman, 1999; Myles & Cui, 2007). Finally, to better understand the role of sleep measurement methods in a developmental context, a case study of the infant with the most intensive data collection—a participation interval of over 8 months with 27 nights of data collection—was analyzed separately. Age was entered as a predictor for number of wake episodes and sleep duration (the only two outcome measures comprised of ratio data that has not been transformed) in nonlinear regressions to estimate the shape of an individual trajectory.

Results

Outliers and excluded data

Of 115 potential nights of data contributed by the 9 infants, Nanit data was excluded for 11 because the infants were removed from their cribs during the night or early morning hours. Measures of sleep quality, wake episodes, and morning wake time were dropped, but sleep onset was retained. The 107 nights of actigraphy data were inspected for anomalies based on device issues such as falling off during the night. Three nights were excluded.

Correlations and difference scores across methods

The correlation matrix for sleep schedule variables by measurement technique is presented in Table 2. Overall, parent report, actigraphy, and Nanit were significantly, positively correlated.

Differences between actigraphy (analyzed with the Sadeh Infant algorithm) and parent report, Nanit, and Sadeh for sleep start, morning wake time, and number of wake episodes are depicted in Figures 2–4. Descriptive statistics are in Table 3. Parents and Nanit reported overall more sleep than Sadeh Infant—earlier start times, later morning wake, and fewer night wakings. Sadeh displayed the most conservative scoring of sleep resulting in the later sleep start times and earlier morning wake but not consistently more wake episodes.

Bland-Altman plots

Figure 5A displays the Bland-Altman plot for the number of wake episodes detected by the two methods (Sadeh Infant and Nanit). All but four points (5.0%) fall within two standard deviations of the mean difference; however, there is a bias of slightly more than one wake episode, as Sadeh Infant consistently reports more.

Nanit-reported sleep efficiency differed from Sadeh Infant by an average of 3.9 percentage points ($SD = 11.15\%$). Figure 5B displays the Bland-Altman plot for sleep efficiency. All but seven data points (8.64%) fall within two standard deviations of the mean, and there is more variability in lower sleep efficiency scores.

Sadeh Infant consistently estimated longer sleep durations ($M = 49.8$ min, $SD = 75.68$ min). Figure 5C displays the Bland-Altman plot for sleep duration. All but 2 of the 79 points (3.7% of the data) fall within the limits of agreement.

Sleep measurement across development

To quantify the shape of Infant 4's individual trajectory, age was entered as a predictor in a non-linear regression for wake episodes and sleep duration as reported by each measurement technique. As expected, age was a significant predictor, across sleep variables and techniques. However, the shape of the best-fitting regression line varied by sleep variable and measurement technique, as displayed in Figures 6 and 7. Sadeh Infant and Nanit depicted a linear relationship between wake episodes and age, $F(1, 19) = 6.30$, $p < .05$, $R^2 = .25$, and $F(1, 19) = 12.95$, $p < .01$, $R^2 = .41$, respectively (see Figure 6). In contrast, parent report data were quadratic, $F(2, 18) = 6.81$, $p < .01$, $R^2 = .43$, and Sadeh cubic, $F(3, 17) = 4.54$, $p < .05$, $R^2 = .45$. The association between sleep duration and age was also linear within Nanit data, $F(1, 23) = 5.05$, $p < .05$, $R^2 = .18$, but quadratic as measured by Sadeh Infant, $F(2, 22) = 7.25$, $p < .01$, $R^2 = .39$, and Sadeh, $F(2, 22) = 8.28$, $p < .01$, $R^2 = .43$ (see Figure 7).

Table 2. Correlation matrix comparing sleep metrics across measurement techniques.

	Sleep Onset				Morning Wake				Wake Episodes				Sleep Efficiency				Sleep Duration			
	Actigraphy (Sadeh)	Actigraphy (Infant)	Nanit	Parent Report	Actigraphy (Sadeh)	Actigraphy (Infant)	Nanit	Parent Report	Actigraphy (Sadeh)	Actigraphy (Infant)	Nanit	Parent Report	Actigraphy (Sadeh)	Actigraphy (Infant)	Nanit	Parent Report	Actigraphy (Sadeh)	Actigraphy (Infant)	Nanit	Parent Report
Actigraphy (Sadeh algorithm) ($n = 9$)	1	—	—	—	1	—	—	—	1	—	—	—	1	—	—	N/A	1	—	—	N/A
Actigraphy (Sadeh Infant algorithm) ($n = 9$)	.946**	1	—	—	.947**	1	—	—	.354	1	—	—	.214	1	—	N/A	.779	1	—	N/A
Nanit ($n = 9$)	.856**	.937**	1	—	.547	.741	1	—	.271	.197	1	—	.506	.304	1	N/A	.115	.361	1	N/A
Parent report ($n = 9$)	.801**	.393**	.917*	1	.862**	.932**	.598	1	.014	−.521	−.2	1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note. Data were averaged per participant to account for repeated measures before correlations were run. N/A = ●●●.
**$p < .01$.

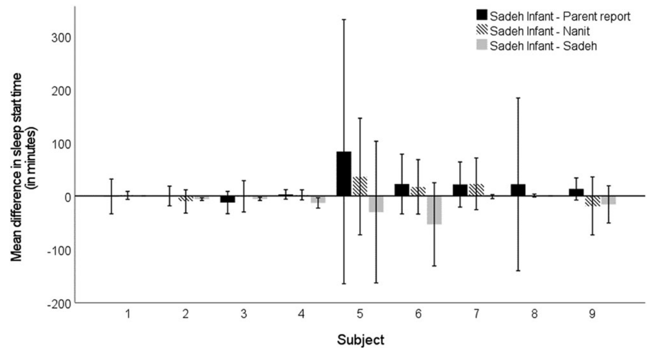


Figure 2. Bar graphs of sleep onset time difference scores across sleep measurement techniques. *Note.* Sadeh Infant was used as a baseline and other measurement techniques were subtracted including parent report, Nanit, and Sadeh. Error bars are 95% confidence intervals. Positive difference scores reflect instances in which the baseline (Sadeh Infant) estimated later sleep start times. Negative difference scores indicate the opposite.

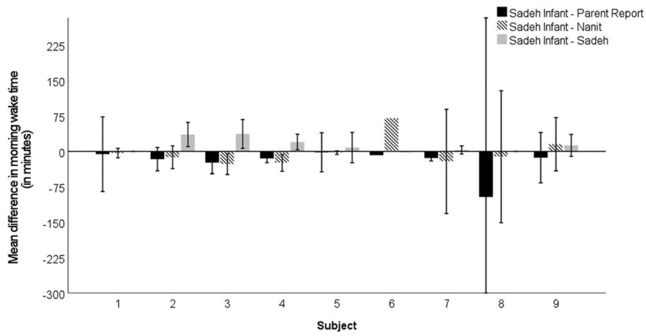


Figure 3. Bar graphs of morning wake time difference scores across sleep measurement techniques. *Note.* Sadeh Infant was used as a baseline and other measurement techniques were subtracted including parent report, Nanit, and Sadeh. Error bars are 95% confidence intervals. Positive difference scores reflect instances in which the baseline (Sadeh Infant) estimated later morning wake time. Negative difference scores indicate the opposite.

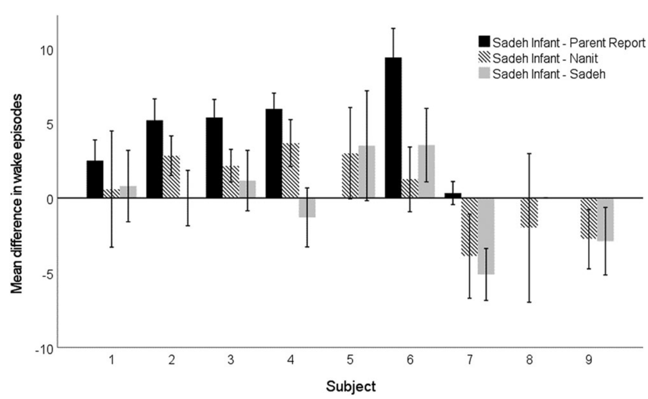
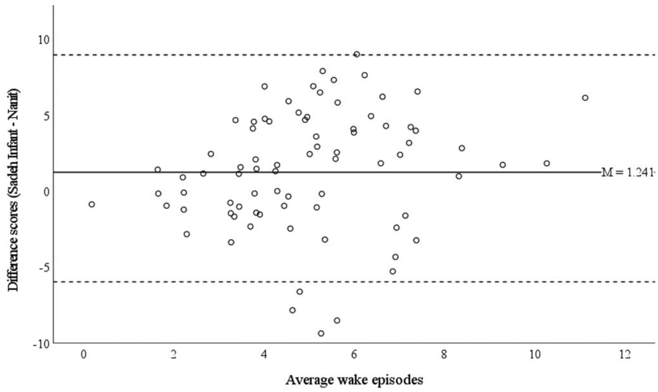


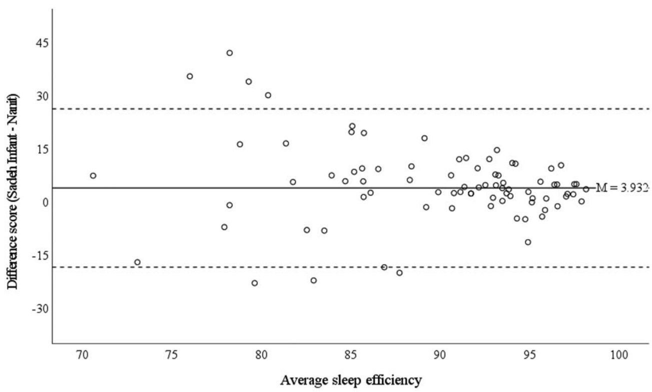
Figure 4. Bar graphs of wake episode difference scores across sleep measurement techniques. *Note.* Sadeh Infant was used as a baseline and other measurement techniques were subtracted including parent report, Nanit, and Sadeh. Error bars are 95% confidence intervals. Infants 5, 7, 8 and 9 had no parent report data on wake episodes. Positive difference scores reflect instances in which the baseline (Sadeh Infant) estimated more wake episodes. Negative difference scores indicate the opposite.

Table 3. Descriptive statistics of difference scores.

	Sleep Start Time (Minutes)				Morning Wake Time (Minutes)				Wake Episodes			
	n	*M*	*SD*	Range	*n*	*M*	*SD*	Range	*n*	*M*	*SD*	Range
Sadeh Infant–Parent report	76	8.3	35.4	−87 to 198	75	−13.4	37.3	−150 to 107	60	5.5	2.8	0 to 12
Sadeh Infant–Nanit	88	0.76	34.5	−138 to 87	81	−14.1	40.4	−163 to 74	79	1.2	3.9	−9 to 8
Sadeh Infant–Sadeh	96	−11.7	23.4	−119 to 2	96	20.1	33.5	−26 to 147	96	−0.3	4.4	−16 to 11



A.



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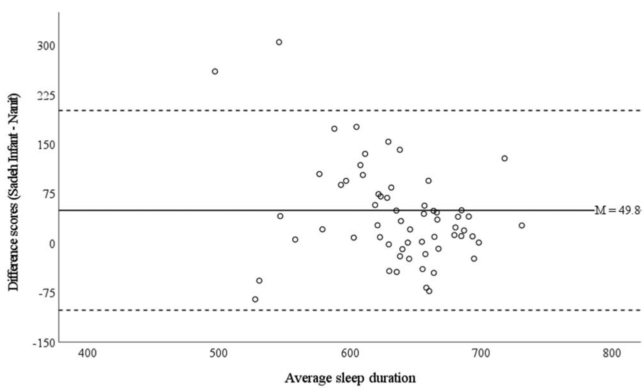

C.

Figure 5. Bland-Altman plots of (A) the number of wake episodes, (B) sleep efficiency, and (C) sleep duration. *Note.* The y-axis displays difference scores and the x-axis displays the average between Nanit and actigraphy. The solid line indicates the mean and the dotted lines indicated the 95% limits of agreement at two standard deviations around the mean (Myles & Cui, 2007).

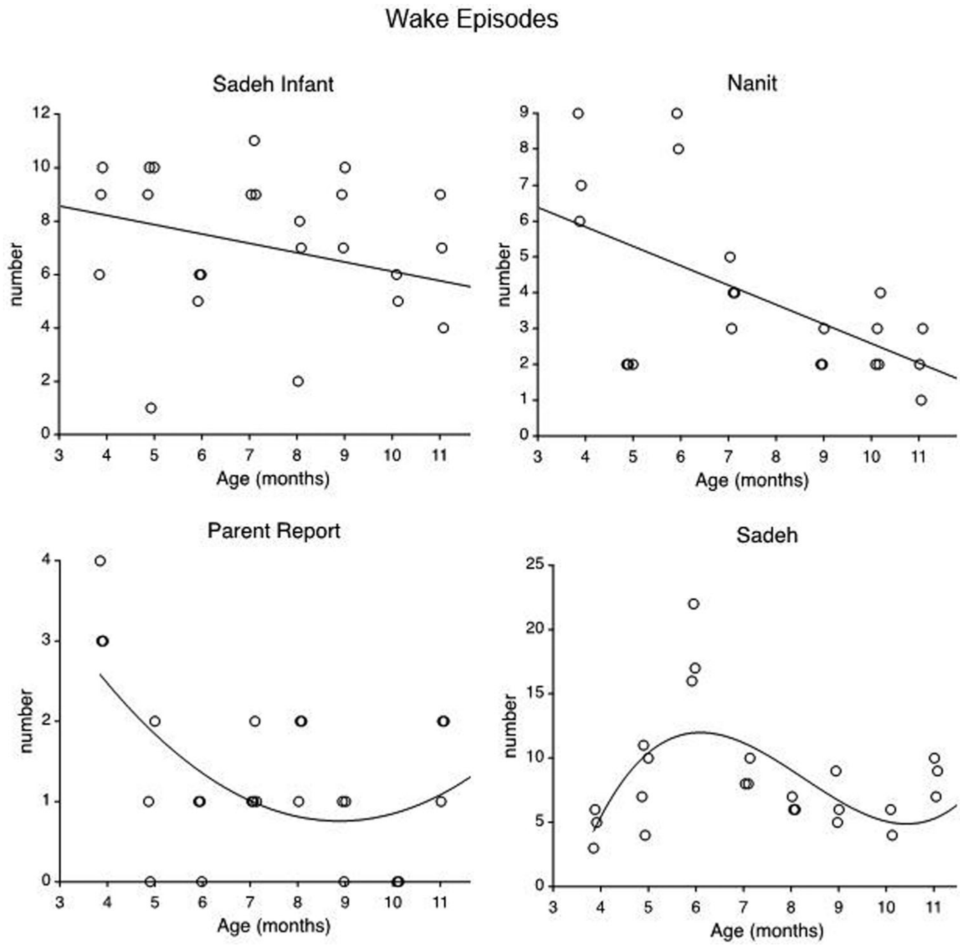

Figure 6. Scatter plot and regression of Infant 4's wake episodes by age per technique. *Note.* Regressions were conducted on multiple datasets, corresponding to each measurement technique and testing the fit of a linear, quadratic, and cubic curve.

Discussion

The aim of this study was to weigh the impact of researcher choices on studying infant sleep, including the extent to which three sleep measurement techniques—parent report, actigraphy, and an automated videosomnography system, Nanit—converged across five outcome measures. To do this, we studied sleep in nine infants using all three measures longitudinally and simultaneously. We also incorporated multiple coding procedures by analyzing actigraphy with both the Sadeh Infant and Sadeh algorithms. Overall, the measures described similar patterns of infant sleep and were significantly correlated.

Parents generally reported earlier sleep start times and later morning wake times, as well as many fewer wake episodes. The latter result supports other researching findings that as infants get older, they require less parental intervention at night (Sadeh et al., 2015). Additionally, some parents appeared to be more accurate than others. As displayed in Figures 2–4, difference scores were lower for Infant 2 and Infant 4, possibly demonstrating the confounding impact of parental characteristics on data collection, such as level of education, number of other children to care for, light versus deep sleepers, etc. Alternatively, discrepancies may reflect a problem with construct validity; subjective measures capture parents' perception of infant sleep, which may differ from their actual sleep patterns. For example, in one study, while infants' sleep behavior explained

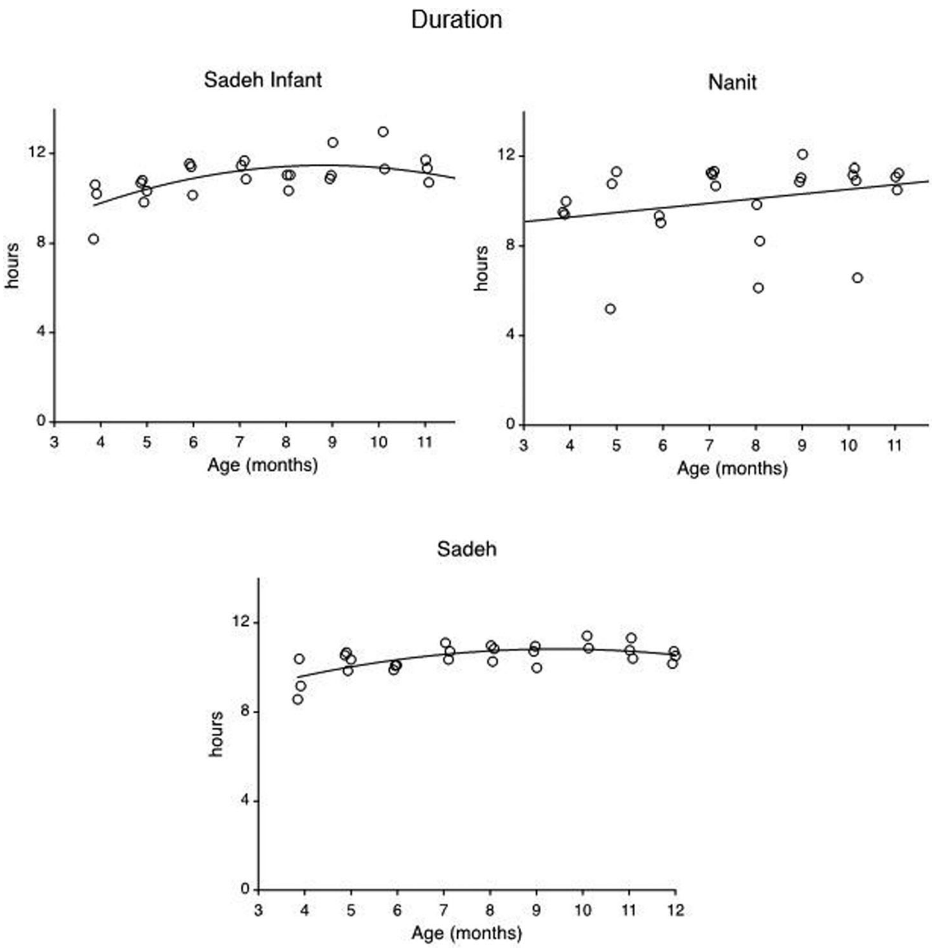

Figure 7. Scatter plot and regression of Infant 4's sleep duration by age per technique. *Note.* Regressions were conducted on multiple datasets, corresponding to each measurement technique and testing the fit of a linear, quadratic, and cubic curve.

about a quarter of the variance in maternal perception of their sleep, the addition of other factors such as infant temperament, maternal daytime functioning, and maternal sleep quality almost doubled the explained variance (Loutzenhiser, Ahlquist, & Hoffman, 2011). Both aspects are important, but they should be clarified based on the design.

Nanit data displayed a similar skew, with earlier sleep start times and later morning wake. Nanit consistently estimated more wake episodes than parents, but not as many as actigraphy. In the Bland-Altman plots, difference scores were centered around 2 instead of 0. Nevertheless, 95% of the differences fell within the limits of agreement, supporting the use of either method. Sleep efficiency scores differed by a small margin in the higher scores, with greater variability in lower scores. This may be due to a ceiling effect—the maximum score was 100% and the majority scored between 90% and 95%. Regardless, because more than 5% of the data fell outside the limits of agreement, the methods cannot be confirmed as equivalent in the way they measure sleep efficiency. Actigraphy reported higher sleep efficiency and longer sleep durations. Most of the sleep duration difference scores, 66 of 69 cases, were contained within the limits of agreement, supporting consistency between measures on this construct.

Greater variability in Nanit parameters were driven by a handful of distinct evenings, despite the removal of obvious outliers. Noisy data present an added layer of potential measurement error. Sleep trajectories typically fluctuate as a result of the interaction between sleep and other developmental domains, as opposed to outliers or measurement error. It is important not to conflate the two particularly when studying infant sleep. Figures 6 and 7 display the different developmental trajectories displayed by each measurement technique. Nanit may better capture subtle but real changes in sleep parameters.

Researcher choices

Our findings can also speak to the advantages and disadvantages of design and measurement choices. For the first design choice, sleep variables of interest, the inclusion of both sleep schedule and quality are recommended for a more encompassing (and accurate) depiction of infant sleep. When planning to incorporate sleep parameters into the analyses (as a predictor or outcome), an additional consideration is raised: the impact of variable type on the data analysis. This issue arose in our final set of analyses with only wake episodes and sleep duration. Time variables are difficult to incorporate and interpret because of the unit conversions (HH:MM:SS to minutes or seconds). Sleep efficiency is an already transformed variable (as a percentage).

The effect of the second design choice, frequency of sleep measurement, was demonstrated as we prepared the data for analysis. Several outliers had to be removed for a variety of reasons, but we retained a good sample of nightly data. If removing outliers is not an option, researchers may average the data instead, but central tendency manipulations have their own ripple effects. These effects are particularly salient for researchers who rely on night-to-night variability within the range of normal development. Faced with limited resources, researchers need to make informed decisions about how to allocate efforts or cut costly measures that do not add value. While multiple nights are recommended to control for outliers, each research question will have a unique perspective for weighing the benefit of improved accuracy with the cost of time, effort, and funds.

Our results provide several insights regarding choices of measurement as well. First, and consistent with previous research, objective measures were more sensitive in discriminating sleep from wake. For the second, direct versus indirect techniques, we can compare our results with those of Camerota et al. (2018), who assessed infant sleep using parent report, actigraphy, and most importantly, manually coded videosomnography. They found actigraphy, as compared with the videosomnography, estimated significantly earlier sleep start times, more night wakings, and more time spent awake. While it is important to note that their actigraphy data were not analyzed with either Sadeh algorithm, the trend of miscoding active sleep as wake may be a byproduct of indirect methods more broadly that holds true for our data as well.

The third measurement choice, coding procedure, was considered in our comparison of actigraphy algorithms. Sensitivity to movement is the key differential feature between the Sadeh Infant and Sadeh. As the central nervous system develops over the first year, infants move less during their sleep (Anders & Keener, 1985). Therefore, a developmentally attuned algorithm should increase its specificity and more readily classify movements as wake with age. Congruent with this, the Sadeh algorithm consistently scored more minutes as wake, while the Sadeh Infant was more tolerant of movement and scored more minutes as sleep. A final consideration is that, on the one hand, the Sadeh algorithms can be specified—as we did here—to control for aspects such as timing. The Nanit algorithm, on the other hand, is out of the researchers' control.

In addition to accuracy, research methods should also be considered in terms of the amount and fidelity of data collected. Nanit provides more data about the sleep environment, including parent interventions and full videos of infant nighttime sleep. For longitudinal data collections in particular, Nanit was the preferred option because fewer data points were lost to human error. On several occasions, for example, parents forgot to place the actigraph around the infant's ankle, causing researchers to extend the data collection period. As long as Nanit was plugged in and connected to WiFi, data were recorded. However, it cannot account for instances in which infants are taken out of the crib and should be validated against a full PSG.

Limitations

The present study is primarily limited by its sample size. The use of only nine participants allowed the researcher to examine individual patterns of results longitudinally across the first year of life. However, increasing the sample size would improve normality and permit more elaborate statistical analysis. Additionally, the sample is homogenous.

A second limitation is that the true value for all sleep parameters was unknown. EEG data are the gold standard to distinguish between sleep and wake states. Because both actigraphy and Nanit rely on behavioral aspects of sleep (movement), they risk misidentifying quiet wakefulness as sleep or active sleep as wake. To account for this, averages of both objective measures were used as the "true" value in accordance with the Bland-Altman method, but a comparison with EEG would have been more precise.

Future directions

Technological advances in sleep measurement technologies are paramount in moving the field forward. Easier data collection procedures promote fidelity and can support longitudinally following infants as they progress through the most significant period of sleep development. Importantly, all the described methods have their place in research design and contribute to our knowledge in unique ways. Future work plans to capitalize on these measurement-specific perspectives. One way of doing so is by polling parent perceptions and attitudes about infant sleep and relating their responses to subjective reports of infant sleep schedules.

Another future line of work will be to use Nanit's nightly video recordings to deepen our understanding of motor behavior during sleep. While our modality differed across techniques,accelerometer versus video, both were purportedly measuring the same thing—movement—which makes the discrepancies between them more puzzling. A more specific inquiry using video to examine the kinds of movements that infants are making during sleep could shed light on the reason for this (DeMasi, Berger, Horger, & Allia, 2020).

Conclusions

Sleep is frequently included in investigations of development, both as an outcome and as a predictor variable. However, a critical examination of the design for studying this phenomenon is often lacking in interdisciplinary work, outside the field of sleep medicine. We compared researcher choices using three concurrent sleep measurement techniques: parent report, actigraphy, and Nanit. Based on the Bland-Altman analysis, actigraphy and Nanit could be used interchangeably for two of three outcome measures. Despite this, and perhaps most importantly, the measures were not consistent in their portrayal of developmental change, with each measure producing a different relationship between sleep and age, from linear to quadratic. In the developmental literature, researchers have raised critiques about sampling choices and argue that present theories of development may not accurately depict developmental change (Adolph & Robinson, 2011; Adolph, Robinson, Young, & Gill-Alvarez, 2008). Researchers must further consider not only how often sampling must occur, but also the tools used to do so. Small errors in sampling may be compounded with error introduced by less than perfect measurement tools.

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Data availability statement

Data that support the findings of this study are available from the corresponding author upon reasonable request.

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