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REVIEW PAPER

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# Actigraphy in sleep research with infants and young children: Current practices and future benefits of standardized reporting

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## Abstract

Actigraphy is a cost-efficient method to estimate sleep–wake patterns over long periods in natural settings. However, the lack of methodological standards in actigraphy research complicates the generalization of outcomes. A rapidly growing methodological diversity is visible in the field, which increasingly necessitates the detailed reporting of methodology. We address this problem and evaluate the current state of the art and recent methodological developments in actigraphy reporting with a special focus on infants and young children. Through a systematic literature search on PubMed (keywords: sleep, actigraphy, child *, preschool, children, infant), we identified 126 recent articles (published since 2012), which were classified and evaluated for reporting of actigraphy. Results show that all studies report on the number of days/nights the actigraph was worn. Reporting was good with respect to device model, placement and sleep diary, whereas reporting was worse for epoch length, algorithm, artefact identification, data loss and definition of variables. In the studies with infants only ($n$ = 58), the majority of articles (62.1%) reported a recording of actigraphy that was continuous across 24 hr. Of these, 23 articles (63.9%) analysed the continuous 24-hr data and merely a fifth used actigraphy to quantify daytime sleep. In comparison with an evaluation in 2012, we observed small improvements in reporting of actigraphy methodology. We propose stricter adherence to standards in reporting methodology in order to streamline actigraphy research with infants and young children, to improve comparability and to facilitate big data ventures in the sleep community.

KEYWORDS

accelerometry, actimetry, diary, guidelines, nap, rules, sensor

## 1 | INTRODUCTION

Actigraphy is a non-intrusive method using wristwatch-like devices to monitor movements over extended periods. The objective estimation of sleep–wake patterns from actigraphy is based on the observation that there is less movement during sleep than during wake. Validation studies have shown that sleep estimation by actigraphy correlates well with sleep scored from polysomnography (Ancoli-Israel

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[Correction added after first online publication on 20 August 2020: All mentions of the reference Meltzer, Walsh, Traylor, & Westin (2012) are incorrect. These have been amended in the text and reference list to refer to (Meltzer, Montgomery-Downs, Insana, & Walsh (2012).]

et al., 2003; Sadeh, Lavie, Scher, Tirosh, & Epstein, 1991). Actigraphy is a convenient and cost-efficient method to record sleep data over multiple days in a natural environment. This is especially useful in infants and young children, who might not sleep well in a laboratory environment (Sadeh, Alster, Urbach, & Lavie, 1989; Sadeh et al., 1991). However, a disadvantage of current actigraphy research is the variation in study procedures, including usage of different devices, and differences in data processing and analysis (Ancoli-Israel et al., 2003). Currently, there are no standardized and unique scoring rules for actigraphy, unlike Rechtschaffen and Kales gold-standard sleep scoring rules for polysomnography (Rechtschaffen & Kales, 1968). This affects outcomes and comparability across actigraphy studies (Acebo & LeBourgeois, 2006). Over the last decades, the use of actigraphy in sleep and paediatric research has significantly increased (Meltzer, Montgomery-Downs, Insana, & Walsh, 2012) as the field is undergoing rapid technological progress. The variability across actigraphy studies may further increase over the next years due to the introduction of new devices and smart phone applications. One core problematic that accompanies this technological development is that sleep variables cannot systematically be quantified in a comparable way. This has severe consequences for determining normative data and identifying clinical cut-offs for sleep problems in children. This rapidly growing methodological diversity urgently necessitates a move towards standardized reporting criteria.

Detailed information about the device, the simultaneous use of a sleep diary, data collection, data processing and sleep variables would facilitate comparability between studies (Meltzer, Montgomery-Downs, Insana, & Walsh, 2012). Standardized guidelines for defining and scoring daytime sleep are especially relevant for infants and young children (Galland, Meredith-Jones, Terrill, & Taylor, 2014), as daytime sleep accounts for up to 20% of sleep in the first year of life and persists until later childhood (at age 6 years, 5% of children are still napping) (Iglowstein, Jenni, Molinari, & Largo, 2003). Currently, either non-validated night-time rules are used for defining daytime sleep, or else actigraphy analysis is restricted to night-time data only (Galland et al., 2014). The latter is common, but it unfortunately considerably underestimates total sleep time and therefore leads to mischaracterization of infants' overall sleep . If possible and feasible, the inclusion of daytime sleep is strongly encouraged, unless the research question exclusively relates to night-time sleep (e.g., wakings in the night). Further, pronounced irregularity of sleep timing in infants and external movement due to variability of their sleep conditions (being carried/in a pushchair) and bed sharing , complicate the quantification of sleep in infants and young children. The investigation of both daytime and night-time sleep thus would benefit from standardized methodological reporting.

Specific recommendations for reporting of actigraphy were published in 2012 (Meltzer, Montgomery-Downs, et al., 2012). Since then, no follow-up review has evaluated reporting practices in the published literature. Our study summarizes the current state of the art, as well as recent methodological developments in actigraphy reporting, with a focus on infants and young children.

**Practice Points**

When using actigraphy

- Specify exact device (manufacturer, name, model and version)
- Devices with access to raw data and open-source software should be preferred
- Provide epoch length for both recording and analysis (if resampling is carried out)
- Report algorithm for analysis of sleep–wake variables, including a reference to the computation
- Use a diary for cross-comparison and to identify artefacts and specify whether a paper, digital or telephone diary was used
- Artifacts and missing data are sources of error or bias, for which identification and handling procedures need to be reported
- Measure and analyse actigraphy across 24 hr, especially in infants and young children
- State whether daytime sleep was taken into account or not in the calculation of total sleep time in infants and young children
- Articles with limited format or with data reanalysis nonetheless benefit from providing the above methodological anchors

## 2 | METHODS

### 2.1 | Search strategies and generation of article catalogue

Based on a systematic literature search on PubMed, we identified original English-language publications with a publication date from the year 2012 until August 15, 2019. The following keywords were used and combined with the Boolean operators "or" and "and": sleep, actigraphy, child *, preschool, children and infant. Only articles published in or since 2012, the year when the recommendations for methodological reporting of actigraphy were published (Meltzer, Montgomery-Downs, et al., 2012), were included. An overview of the number of selected articles is presented in Figure 1. In total, 447 articles were identified through the PubMed search and seven additional articles were added from a literature database generated as part of a student course (Biomedicine, University of Zurich, Switzerland). After removing duplicates, the database search yielded 454 articles. Conference abstracts, case studies, review articles, comments, study protocols and articles with non-human participants were excluded ($n = 50$). Only studies with participants with a mean age below 6.0 years, or a subgroup of participants with separately reported sleep data, were included ($n = 259$ excluded). Also, presentation of mean data from actigraphy recordings for sleep was required for inclusion ($n = 15$ excluded). Therefore, articles reporting

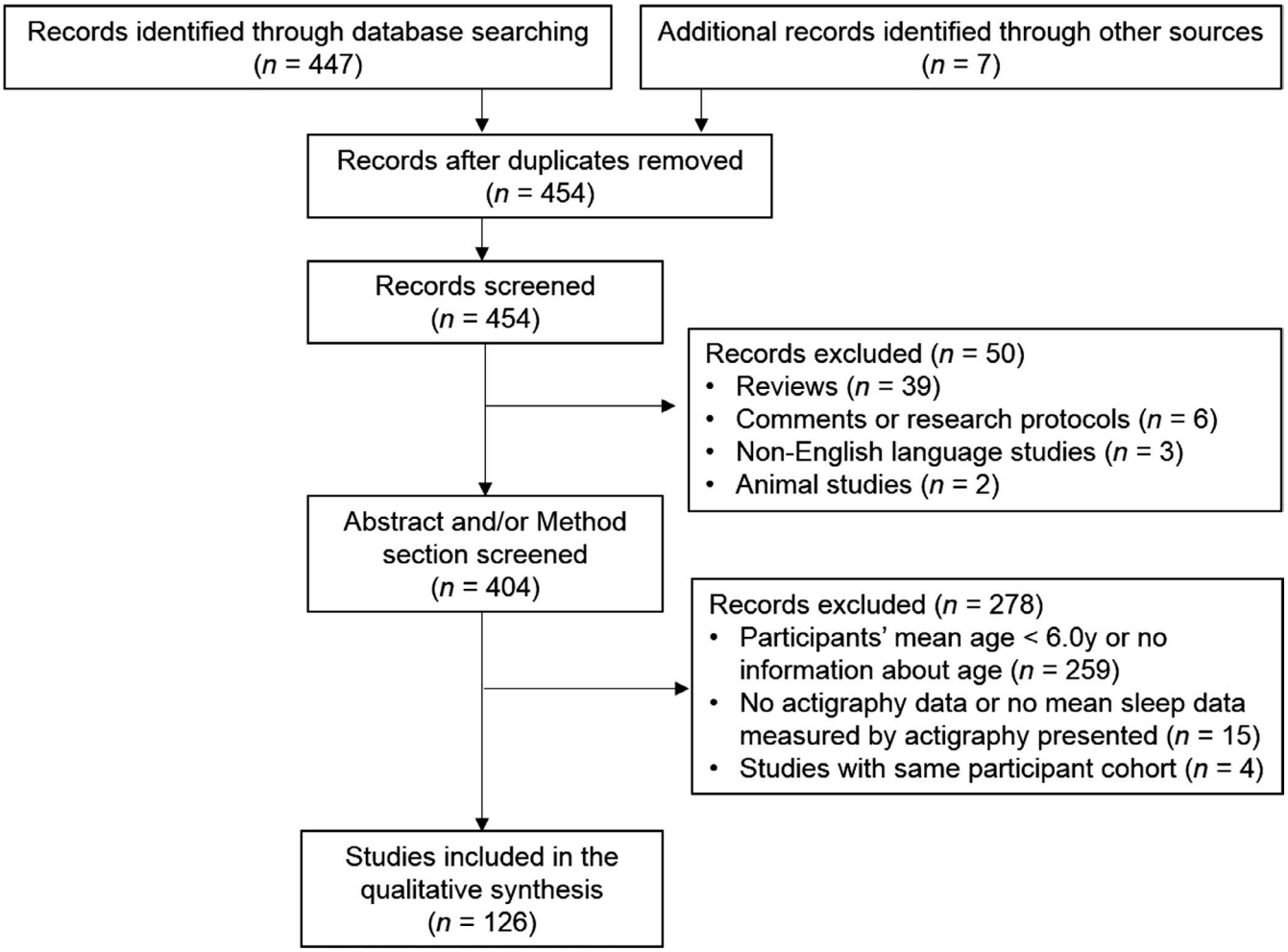


**FIGURE 1** Flow chart of study participants

outcomes without further specification of sleep–wake variables or rhythmicity (i.e., only reporting sensitivity and specificity) and articles including only data regarding physical activity counts were excluded. Eight studies (four pairs) used the same participant cohort (identified by authorship, sample size, participant age and funding), of which only the first-published article from each pair was included in our analysis. This resulted in a collection of 126 articles (as marked in the reference list) that were subjected to classification according to study content and methodological quality rating.

## 2.2 | Article classification according to study content

All 126 articles were marked according to the description of their design and study content. First, we identified "validation studies" (including validation of device, algorithm, questionnaire, etc.). Second, we assigned the use of actigraphy-based variables to "sleep–wake variables" (e.g., sleep duration, nocturnal waking and sleep efficiency), "rhythmicity" (e.g., midsleep point, daytime sleep duration and autocorrelogram) and/or "physical activity counts" (e.g., sports activities, activity index to compute sedentary/non-sedentary, activity score). Third, we assigned the use of actigraphy data to compute "main" sleep variables or "secondary/control" measures (e.g., for confirming adherence to a specific protocol, or to identify sleep/wake in relation to other physiological measures such as body temperature, etc.). Fourth, we differentiated between inclusion of only "healthy" or also "clinical" paediatric participants with a diagnosed disorder (the latter with inclusion of a healthy control group). Prematurely born children or children with a developmental disorder, sleep problems, insomnia or night-time fears were assigned to "clinical". Fifth, age groups were assigned as "infants" (group mean age 0–12 months/0–1 year) or "young children" (13–72 m/1–5 year). Studies that investigated both infants and young children were included in the infant analysis.

## 2.3 | Methodological quality rating

Methodological aspects of the included studies were rated using a predefined scoring system (Table 1). This was developed in accordance with a previously published checklist (table 5 in Meltzer, Montgomery-Downs, et al., 2012). The following four overarching classifications were used, with nine items in total: (a) device and system information (four items), (b) concomitant use of a sleep diary

**TABLE 1** Overview of rating criteria based on recommendations by Meltzer, Montgomery-Downs, et al. (2012)[a]

| No. | Category | Rating |
|---|---|---|
| (a) | Device/system information | |
| 1 | Device | 1 if reported, 0 if not reported |
| 2 | Placement (body part where actigraph was attached) | 1 if reported, 0 if not reported |
| 3 | Epoch length (resolution with which activity counts were stored) | 1 if reported, 0 if not reported |
| 4 | Algorithm | 1 if a commonly used name (Cole, Sadeh, etc.) was indicated, 0 if just software name was provided but not the algorithm, or 0 also if neither the algorithm nor the software was reported (terms such as "manufacturer's algorithm" or merely reporting the sensitivity settings were counted as 0); this was not scored for articles that did not estimate sleep/wake behaviour |
| (b) | Sleep diary | |
| 5 | Sleep diary | 1 if use of sleep diary reported, 0 if not reported |
| | In the articles that did report the use of a sleep diary, 3 additional criteria were rated: | |
| 5.1 | Diary type | 1 if a digital sleep diary was used, 0 if not reported |
| 5.2 | Diary keeper (person completing sleep diary) | 1 if reported, 0 if not reported |
| 5.3 | Diary completion frequency | 1 if reported, 0 if not reported |
| (c) | Data collection and processing | |
| 6 | Number of days/nights | 1 if reported , 0 if not reported |
| 7 | Artefact identification (methods used to identify and handle missing data or potential artifacts) | 1 if reported, 0 if not reported. 1 was further assigned if the statistical approach was accounting for missing data (i.e., regression and path models using full likelihood estimation). Furthermore, 1 was also assigned if data were corrected for external motion or co-sleeping reported in a log or diary (whereas diary for measuring actigraphy removal alone was not counted) |
| 8 | Data loss | 1 if data loss was reported either due to technical failure, non-adherence or artefacts |
| (d) | Data variables | |
| 9 | Definition of sleep variables | 1 when definition of at least 1 sleep variable was provided, or a reference to the definition of particular sleep variables |

*Note:* Points 5.1–5.3 did not count towards the total score of each article.

[a]Rating criteria are based on the proposed standard checklist for reporting actigraphy in paediatric sleep research literature presented in table 5 in Meltzer, Montgomery-Downs, et al. (2012).

during actigraphic recording (one item), (c) procedures of data collection and processing (three items), and (d) definition of sleep variables (one item). We identified information on device model and brand, as well as on device placement, epoch length, analysis algorithm, handling of artefacts, etc., for each study representing the number of fulfilled rating criteria. Sum scores ranged from 0 to 9 points, with higher scores indicating more complete reporting of methodological quality in the respective study. All three authors rated the categories for each of the 126 articles. Uncertainties were discussed among the three authors until a consensus was reached.

### 2.4 | Rating of daytime sleep recording in infants

Apart from the nine-item score, in the articles investigating infants, we additionally scored whether or not actigraphy was collected continuously across 24 hr (as opposed to recording intervals restricted to night or day only) and whether actigraphy was analysed across the 24-hr day. We rated articles on whether they reported on daytime sleep (e.g., naps) and whether this quantification was based on diary or actigraphy.

## 3 | RESULTS

The 126 articles included a total of $n$ = 11,032 participants assessed with actigraphy. The studies contained an average of 88 participants (standard deviation [*SD*] = 111; median, 56.5; range, 5–802). Fourteen of the 126 studies (11.1%) were validation studies for either devices, algorithms or questionnaires. Most studies (94.4%) used actigraphy to assess sleep–wake patterns. Thirty-four of the 126 articles (27.0%) investigated rhythmicity and 12 (9.5%) used actigraphy to quantify physical activity (multiple categories possible; one outcome was defined in 71.4% of the articles, two in 26.2% of the articles, and three in 2.4%). One hundred and thirteen of the 126 articles (89.7%) used actigraphy as the main outcome

measure, whereas only a fraction used actigraphy as a secondary "control" variable (10.3%). Sixty-eight of the 126 articles (54.0%) investigated young children and 58 articles (46.0%) investigated infants, of which 18 articles (14.3%) investigated both infants and young children. Forty-four of the 126 articles (34.9%) included a clinical population.

### 3.1 | Methodological quality rating

On average, 7.4 of the nine rating criteria (*SD* = 1.4; range, 2–9) presented in Table 1 were reported per article. Most articles reported on eight (28.6%) or seven and nine rating criteria (both 23.8%). Twenty-six articles (20.7%) reported on five or six criteria and four articles (3.2%) reported on less than five rating criteria. The frequency of articles reporting each rating criterion is presented in Figure 2.

### 3.2 | Device/system information

One hundred and thirteen of the 126 articles (89.7%) reported the device model of the actigraph used in the respective study. These models included: Actiwatch2, AW64, Actiwatch Spectrum, Actiwatch-L and Actical (from Philips Respironics/Minimitter); Micromini Motionlogger, Motionlogger Basic, Micro Motionlogger Sleep and AMA32 (from Ambulatory Monitoring, Inc.); Actiwatch 4/Actiwatch Plus, Actiwatch mini, Motionwatch 8 and Actiheart (from Camntech); GENEactiv (from Activinsights); wActisleep-BT, GTX-BT, GT3X+, GT3X and Actisleep+ (from Actigraph); Visi Grey Flash (from Stowood); and Somnowatch (from Somnomedics). The frequency of reported actigraphy devices and brands is shown in Table 2 (for all articles and separately for articles investigating infants and young children). Twenty-one different device models were used in the 126 articles. The most common were the Actiwatch2 (Philips Respironics), which was the most frequently used model among studies with young children, and the Micromini Motionlogger (Ambulatory Monitoring, Inc.), which was the most frequently used model among studies with infants. Seven different brands were used. The brand name was reported by all articles (100%). The most common brands were Philips Respironics and Ambulatory Monitoring, Inc. Although Ambulatory Monitoring, Inc. was the most frequently used brand among studies with infants, Philips Respironics was most popular among studies with young children.

The reporting frequency of device placement, epoch length and algorithm is presented in Table 3. One hundred and nineteen of the 126 articles (94.4%) reported the device placement on the body. Both ankle/calf/leg and arm/wrist placements were common, at 38.1% and 37.3%, respectively. Ankle/calf/leg placements were most common in studies with infants and arm/wrist placements in studies with young children. Epoch length was reported in 97 of the 126 articles (77.0%). Nearly half of the studies used an epoch length of 1 min (49.2%). One hundred and eighteen of the 126 articles (93.7%) presented data on algorithm-based variables. Sixty-two of the 118 articles (52.5%) specified the algorithm used for identifying sleep and wake (by name or by providing a reference), 43 articles (36.4%) reported only the software (yet no algorithm) applied to analyse the data (including sensitivity threshold), and 13 articles (11.0%) reported neither. The most common algorithms applied for infants and young children were Sadeh, Acebo, Seifer, Aytur, and Carskadon (1995), Sadeh (1994) and Sadeh et al. (1989). A few articles analysed their data by multiple algorithms (4%).

### 3.3 | Sleep diary

One hundred and five of the 126 articles (83.3%) reported the use of a sleep diary. None of these articles reported the use of a digital diary. One hundred and two of the 105 articles (97.1%) reported the person who completed the diary ("diary keeper") and 72 articles (68.6%) reported how often the diary was filled out.

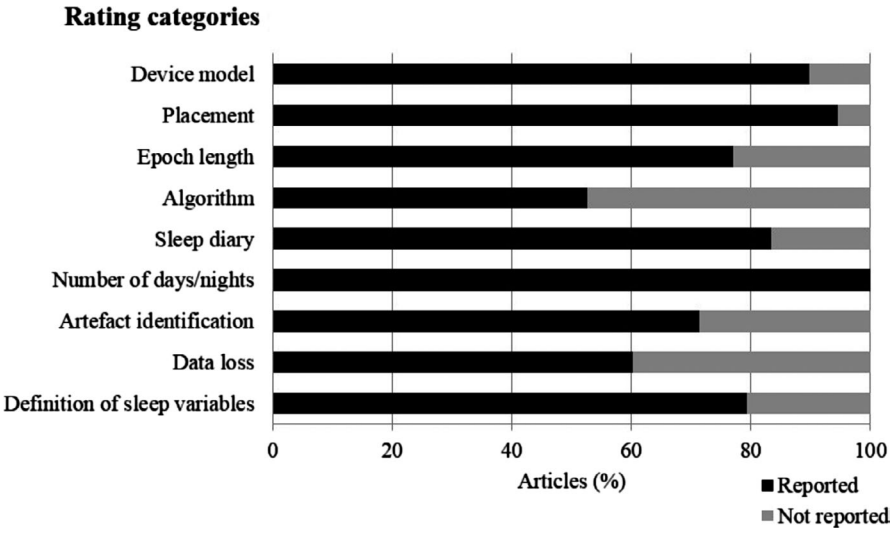


**FIGURE 2** Frequencies of articles reporting predefined methodological aspects of actigraphy ($n$ = 126 articles)

**TABLE 2** Frequency of reported actigraphy devices and brands in article catalogue, presented for all articles and separately for articles investigating infants and young children

| | All articles ($n = 126$), % | Articles including infants ($n = 58$), % | Articles including young children ($n = 68$), % |
|---|---|---|---|
| *Device model* | | | |
| Actiwatch2 (Philips Respironics) | 20.6 | 14.0 | 22.7 |
| Micromini Motionlogger (Ambulatory Monitoring, Inc.) | 16.7 | 19.3 | 15.9 |
| AW64 (Philips Respironics) | 11.9 | 10.5 | 12.5 |
| Actiwatch Spectrum (Philips Respironics) | 9.5 | 3.5 | 11.4 |
| Motionlogger Basic (Ambulatory Monitoring, Inc.) | 6.3 | 1.8 | 8.0 |
| Micro Motionlogger Sleep (Ambulatory Monitoring, Inc.) | 6.3 | 12.3 | 3.4 |
| Actiwatch 4/Actiwatch Plus (Camntech) | 4.8 | 7.0 | 3.4 |
| Actiwatch mini (Camntech) | 3.2 | 5.3 | 1.1 |
| Actical (Philips Respironics/Minimitter) | 3.2 | 5.3 | 2.3 |
| Actiwatch-L (Philips Respironics) | 2.4 | 3.5 | 1.1 |
| GENEactiv (Activinsights) | 1.6 | 1.8 | 1.1 |
| AMA32 (Ambulatory Monitoring, Inc.) | 1.6 | 1.8 | 1.1 |
| wActisleep-BT (Actigraph) | 0.8 | 0 | 1.1 |
| Visi Grey Flash (Stowood) | 0.8 | 0 | 1.1 |
| Somnowatch (Somnomedics) | 0.8 | 0 | 1.1 |
| Motionwatch 8 (Camntech) | 0.8 | 0 | 1.1 |
| GTX-BT (Actigraph) | 0.8 | 0 | 1.1 |
| GT3X+ (Actigraph) | 0.8 | 1.8 | 1.1 |
| GT3X (Actigraph) | 0.8 | 0 | 1.1 |
| Actisleep+ (Actigraph) | 0.8 | 1.8 | 0 |
| Actiheart (Camntech) | 0.8 | 1.8 | 1.1 |
| Not reported/identifiable | 10.3 | 14.0 | 10.2 |
| *Brand* | | | |
| Philips Respironics | 48.4 | 36.8 | 52.3 |
| Ambulatory Monitoring, Inc. | 37.3 | 47.4 | 33.0 |
| Camntech | 7.9 | 10.5 | 6.8 |
| Actigraph | 4.0 | 3.5 | 4.6 |
| Activinsights | 1.6 | 1.8 | 1.1 |
| Somnomedics | 0.8 | 0.0 | 1.1 |
| Stowood | 0.8 | 0.0 | 1.1 |
| Not reported | 0.0 | 0.0 | 0.0 |

*Note:* Eight studies contained multiple devices and brands and were thus included in each respective item.

### 3.4 | Data collection and processing

All studies (100%) described the length of assessment duration, varying from a few hours up to 1 month. Ninety of the 126 articles (71.4%) reported the procedure for identification and correction of artefacts. Seventy-six of the 126 articles (60.3%) reported on data loss.

### 3.5 | Data variables

One hundred of the 126 articles (79.4%) defined at least one of the sleep variables used in the study.

### 3.6 | Reporting of daytime sleep in articles with infants

We next specifically focused on the reporting of actigraphy-based daytime sleep in articles that included infant participants ($n = 58$ out of the 126 articles; Figure 3). Thirty-six of the 58 studies (62.1%) recorded actigraphy across 24 hr. The remainder either recorded data during shorter intervals (e.g., from bedtime in the evening to wake-up time in the morning, 32.8%) or else it was unclear which timeframe was recorded (5.2%, "not reported" in Figure 3). Of the 36 articles that recorded continuously across 24 hr, 23 articles (63.9%) analysed 24-hr data. Twenty-one of the 58 articles (36.2%) reported

**TABLE 3** Frequency of reported actigraphy device placements, epoch length and algorithm

| | All articles ($n = 126$), % | Articles including infants ($n = 58$), % | Articles including young children ($n = 68$), % |
|---|---|---|---|
| *Device placement* | | | |
| Ankle/calf/leg | 38.1 | 75.4 | 13.6 |
| Arm/wrist | 37.3 | 8.8 | 51.1 |
| Waist/hip | 3.2 | 0 | 4.5 |
| Chest | 0.8 | 1.8 | 1.1 |
| *Multiple device placements within the same study* | | | |
| Ankle or wrist | 12.7 | 8.8 | 17.0 |
| Wrist or shoulder | 1.5 | 0 | 2.3 |
| Ankle or waist | 0.8 | 1.8 | 1.1 |
| Not reported | 5.6 | 3.5 | 8.0 |
| *Epoch length* | | | |
| < 1 s | 2.4 | 5.3 | 0 |
| 15 s | 7.1 | 8.8 | 5.8 |
| 30 s | 17.5 | 19.3 | 17.2 |
| 1 min | 49.2 | 49.1 | 50.6 |
| 2 min | 0.8 | 1.7 | 0 |
| Not reported | 23.0 | 15.8 | 26.4 |
| *Algorithm* | | | |
| Sadeh et al. (1995) | 23.7 | 46.9 | 15.6 |
| Sadeh (1994) | 9.3 | 6.1 | 11.1 |
| Sadeh et al. (1989) | 9.3 | 4.0 | 10.0 |
| Oakley/Respironics (1997) | 9.3 | 2.0 | 11.1 |
| Cole, Kripke, Gruen, Mullaney, and Gillin (1992) | 5.1 | 4.1 | 4.4 |
| Galland, Kennedy, Mitchell, and Taylor (2012) | 3.3 | 6.1 | 2.2 |
| Others | 2.4 | 2.0 | 3.3 |
| Not reported | 47.5 | 36.7 | 46.7 |

*Note:* Five studies used multiple algorithms.

at least one variable quantifying daytime sleep by using either actigraphy (20.7%) or a sleep diary (15.5%).

## 3.7 | Comparison with previous methodological reporting

To derive trends in methodological reporting of actigraphy over the last few years, we compared our results with the report of Meltzer, Montgomery-Downs, et al. (2012) (Meltzer, Montgomery-Downs, et al., 2012). Comparison of reported brands, epoch length, device placement and algorithm between the study by Meltzer, Walsh, et al. (2012) and our study is presented in Table 4. Since the evaluation of 2012, the same device brands are predominantly used. Yet, our study revealed less use of Ambulatory Monitoring, Inc. and Camntech, whereas Philips Respironics was more frequently used. All articles reported the brand in our study, whereas a small number of studies did not report it in the evaluation by Meltzer, Montgomery-Downs, et al. (2012). Although in Meltzer, Montgomery-Downs, et al. (2012) a predominance of device placement on the wrist/arm was obvious, we also found common placement on the ankle, calf or leg. Furthermore, whereas Meltzer, Montgomery-Downs, et al. (2012) only included the wrist/arm and ankle/calf/leg, our analysis revealed frequent reporting of other device placements, such as on the shoulder and multiple device placements. Among various possible epoch lengths, the use of 1 min is still the most frequent, yet with a tendency towards the use of finer resolutions. Also, the lack of reporting epoch length was less frequent in our study compared to in the evaluation by Meltzer, Montgomery-Downs, et al. (2012). Compared to the study by Meltzer, Montgomery-Downs, et al. (2012), fewer

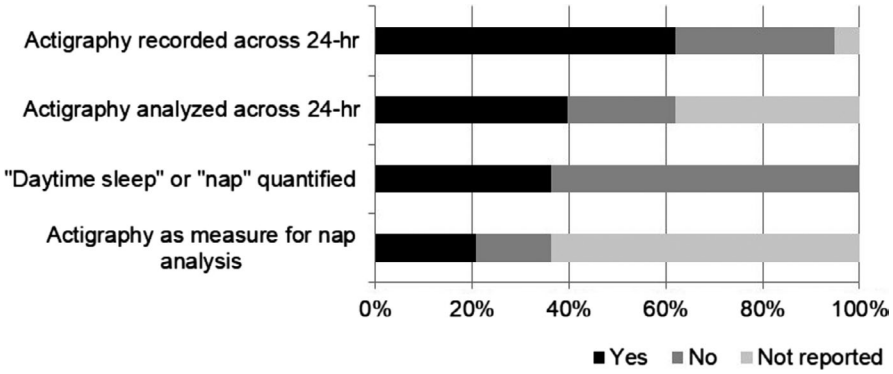


**FIGURE 3** Frequencies of reported daytime sleep in articles investigating infant participants ($n$ = 58 articles)

articles used the Sadeh algorithm and more articles did not report the algorithm in our study.

## 4 | DISCUSSION

We performed a comprehensive analysis of recent actigraphy research in infants and young children to identify developments in actigraphy methodology for sleep research. Through an extensive and systematic literature search, we identified 126 articles, which were evaluated for reporting of actigraphic methodology based on evidence-based recommendations (Meltzer, Montgomery-Downs, et al., 2012). Reporting on the number of days/nights the actigraph was worn was excellent, as it was indicated in all articles. Reporting was good (i.e., >80%) with respect to device, placement and sleep diary. Reporting for epoch length, algorithm, artifact identification, data loss and definition of variables was worse and would benefit from improvement in the future.

Our study shows that all articles reported the actigraphy brand, whereas 10.3% of the articles did not report the specific device model used. Two actigraphy brands are dominant among infants and young children (Philips Respironics and Ambulatory Monitoring). Introduction of new models by manufacturers and the fact that certain devices are no longer developed and some companies have merged (e.g., Mini Mitter with Philips Respironics) can lead to changes in data collection and induce a source of error. Thus, it is important to comprehensively report device information in future studies. Nearly half of the studies (47.5%) did not report on the analysis algorithm used for sleep variable computation, with 32.7% providing partial information (refer to the software/threshold applied, yet lack information on the algorithm itself) and 12.9% providing no information about the algorithm. This is problematic because estimates of sleep–wake variables greatly depend on algorithms, particularly in infants (Schoch, Jenni, Kohler, & Kurth, 2019), and ambiguity arises when the software offers multiple options based on different algorithms or different versions of software might use different algorithms. Algorithm changes in commercial software are generally possible, even without the awareness of users. Furthermore, not every algorithm has been validated in each device for every age group. Consequently, the choice of algorithm depends on the device. Thus, detailed reporting of the algorithm and specific adjustments to the computation are crucial. However, in the case when analysis software is proprietary (and therefore the computational source code is not available), researchers cannot obtain information on the applied algorithm. Additionally, not every software has implemented each algorithm. Thus, the users might be limited in which algorithms they can effectively apply. Nonetheless, providing detailed information is crucial and it should ideally include the analytical formula or reference to an article with the formula. An urgently needed future direction is the cross-comparison of sleep variable outcomes among the existing algorithms and software. Only this advance will allow proper comparison of objective sleep measures in big data ventures and will lead to discoveries of sleep differences among culture, geography, age, health status, etc.

Only 60% of the articles provided information on data loss, which can mainly result from technical failure or participants' non-adherence. However, more details on reasons underlying data loss would be welcomed because it provides essential information about the dropouts from the study and about possible bias of the results. Among the 126 articles, an epoch length of 1 min was most commonly used. The selection of epoch length largely depends on the study design and research question (e.g., high-resolution data sampling for quantification of micro arousals versus longitudinal data across a year). Furthermore, more recent devices offer more setting options for sampling data with higher time resolution. Nonetheless, nearly one-quarter of articles did not report epoch length.

Nearly a fifth of the studies did not use or did not report the use of a sleep diary. Diary use depends on the research question and design of the study, and particularly in polysomnography studies diary use might be less important. However, the inclusion of a diary improves the handling of data loss and artifacts and is preferred to using data without a diary (Tetreault, Belanger, Bernier, & Carrier, 2018). In our study, we also tried to xml:identify which type of diary (paper versus digital versus smartphone) was used. However, this information was frequently unclear. Most studies use a paper diary, which was not explicitly specified in the articles. Considering that novel trends may include more digitized diaries in the future, specifics on diary type (also the paper diary) should be given.

Even though the majority of infant studies measured actigraphy continuously across 24 hr (62.1%), only 64% of these analysed complete 24-hr intervals. This reveals that large parts of the recording are often discarded, even though they contain valuable information about infants' sleep. Furthermore, only 12 of the 58 articles (20.7%) used actigraphy to analyse daytime sleep, a small number given that daytime

**TABLE 4** Frequency of reported brands, epoch length, device placement and algorithm: comparison with Meltzer, Montgomery-Downs, et al. (2012)

| | Meltzer, Montgomery-Downs, et al. (2012)[a] % | Current rating, % |
|---|---|---|
| *Brand* | | |
| Philips Respironics (previously Mini-Mitter) | 21.7 | 48.4 |
| Ambulatory Monitoring, Inc. | 56.0 | 37.3 |
| Camntech (previously Cambridge Actiwatch) | 11.4 | 7.9 |
| Other brands | 4.8 | 7.2 |
| Not reported | 6.0 | 0.0 |
| *Device placement*[b] | | |
| Ankle/calf/leg | 22.9 | 38.1 |
| Arm/wrist | 67.5 | 37.3 |
| Other/multiple | 0.0 | 19.0 |
| Not reported | 9.0 | 5.6 |
| *Epoch length* [c] | | |
| 15 s | 1.6 | 7.1 |
| 30 s | 3.9 | 17.5 |
| 1 min | 62.2 | 49.2 |
| Other | 0.0 | 3.2 |
| Not reported | 32.2 | 23.0 |
| *Algorithm* | | |
| Sadeh [d] | 65.6 | 40.8 |
| Oakley/Respironics [e] | 0.0 | 7.9 |
| Cole-Kripke | 6.5 | 2.4 |
| University of California San Diego | 1.1 | 0.0 |
| Other | 0.0 | 4.8 |
| Not reported | 26.9 | 44.1 |

[a]Limited sample with $n = 166$ was taken for comparison; see second column in table 5 in the publication by Meltzer, Montgomery-Downs, et al. (2012).

[b]'Arm/wrist' in the publication by Meltzer et al. was defined by the sum of the frequency reported for 'non-dominant wrist', 'dominant wrist' and 'wrist unspecified'. Only studies with wrist and ankle actigraphy included.

[c]Due to the fact that the epoch length in Meltzer, Montgomery-Downs, et al. (2012) was presented separately for Ambulatory Monitoring, Inc. and Mini-Mitter, its frequency was combined for comparison.

[d]The different versions of the Sadeh algorithms were summarized.

[e]Meltzer, Montgomery-Downs, et al. (2012) included algorithms with the Ambulatory Monitoring, Inc, but not with Mini-Mitter devices, which commonly use the Respironics/Oakley algorithm.

sleep accounts for up to 20% of sleep in the first year of life (Iglowstein et al., 2003). Thus, in future studies, it should be clearly stated whether daytime sleep was considered or not in the calculation of total sleep time in infants and young children. In addition, we believe that the research field would benefit from evaluation of daytime sleep and the description of this procedure in as much detail as possible. Current knowledge on sleep regulation indicates that daytime sleep influences night-time sleep, not only in adults (Campbell & Feinberg, 2005), but also young children (Lassonde et al., 2016). Although daytime sleep can be more complex to assess and quantify (involvement of daycare/nannies, external movements during sleep, etc.), we nonetheless strongly recommend the inclusion of daytime sleep if feasible.

Compared to the evaluation by Meltzer *et al.* in 2012 (Meltzer, Montgomery-Downs, et al., 2012), we observed the following recent developments: device, brand, device placement and epoch length reporting have improved over time, although are still not complete. Specifically, we observed increased reporting of the device, although model specification was still lacking in 10.3% of the cases. We also observed a change in popularity of devices: Ambulatory Monitoring, Inc. has been replaced by Philips Respironics. This may be due to costs or availability of validation reports for the device, or due to the fact that a broader age range was included in the study by Meltzer, Montgomery-Downs, et al. (2012) than in our study (0–18 years versus 0–6 years). Additionally, new brands have been introduced in the field. This development is not surprising considering the rapid market growth of wearables. As more commercial devices become available, it is important to keep in mind that these may not be suitable for research with infants and young children, unless validation and replication are provided in the specific age group. Furthermore, a number of devices have analysis algorithms that are not publicly available, which also includes the problem that algorithms are sometimes changed without notice to the user. Another interesting observation was that reporting of device placement increased slightly. It seems to have become more common to allow flexibility with device placements. This might be caused by the investigation of different cohorts, heightened non-compliance of participants with certain placements, studies indicating no differences regarding device placement, or physical activity researchers using waist/hip placements entering into sleep research (which were not looked at in the study by Meltzer, Montgomery-Downs, et al., 2012). For example, in young children, sleep–wake estimates from the ankle and wrist were reported to be comparable (Belanger, Bernier, Paquet, Simard, & Carrier, 2013).

It needs to be mentioned that articles published in 2012 may be under-represented in the analysis by Meltzer et al. and in the current report; however, we only wanted to include articles after publication of the previous article. Furthermore, articles referring exclusively to "accelerometry" were possibly missed.

Non-standardized computation of sleep variables across studies can cause variation in study outcomes. Similarly, study design, device parameters and analysis choices add variability and ultimately prevent cross-comparison among studies. Even though journals limit the length of research articles, there is a need for minimal actigraphy methodological anchors. Although details on actigraphy methodology may be less important in a review article or comment, they are essential to improve reproducibility in articles presenting original data. As daytime sleep can account for up to 20% of total sleep duration in infants and young children, it is crucial that daytime sleep is not neglected in research including infants and young children. The analysis

of daytime sleep is complicated by the variability of sleep conditions with added external movement (e.g., being carried/in pushchair). However, information recorded in the sleep diary supports the addressing of such artefacts and facilitates the identification of daytime sleep (Schoch et al., 2019). Validation of existing algorithms for use with naps without reliance on diary reports will be necessary in the future if naps are to be analysed in large-scale datasets.

We believe that combining actigraphic data from multiple cohorts has large potential for "big data" approaches. Analyses of large datasets have higher statistical power and can provide novel insights (e.g., regarding cultural variability in the development of sleep rhythms). However, pooling data requires detailed reporting for each individual dataset. Validation of each device on the market, including the application of different algorithms as well as specificity for age groups, and direct comparative analysis across devices would support the development of a "gold standard" for actigraphy data analysis. Because we anticipate continued future developments, a database to collect such information on devices would be useful and could be integrated with a database including available datasets.

## 5 | CONCLUSIONS

There is ongoing rapid growth of methodological diversity in actigraphy-based sleep research. This diversity causes large differences in sleep outcome variables (Schoch et al., 2019), which complicates translation to clinical practice. Heterogeneity of sleep monitoring with actigraphy has diverse causes, most of which can be overcome through stricter adherence to methodological standards. Standardized reporting of methodological details should be maintained or improved in the future. The community would benefit from more approaches that directly compare sleep outcomes with different methodologies (Schoch et al., 2019). Comparability across disciplines will facilitate the consolidation of existing data from wearables. Additionally, the integration of daytime sleep will support the understanding of normative sleep, particularly in infants. Providing comprehensive methodological details is a prerequisite for future public data-sharing platforms, which will advance progress in the research of sleep in infants and young children.

### Research Agenda

- Our study should be extended to school-age children and adolescents in order to compare reporting practices between the age groups
- Analysis of daytime sleep is confounded by the variability of sleep conditions (e.g., external movement), yet integrating daytime sleep supports the thorough investigation of infants and young children
- The existing guidelines may be supplemented by standardized reporting criteria for defining and scoring daytime sleep in infants and young children


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## CONFLICT OF INTERESTS

The authors have indicated no financial conflict of interests.

## AUTHOR CONTRIBUTIONS

All authors were involved in the design, literature research, data analysis and writing of the manuscript.


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