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Original Article

ORIGINAL ARTICLE

Meta-analysis of age and actigraphy-assessed sleep characteristics across the lifespan

Marissa A. Evans[1,*], Daniel J. Buysse[2], Anna L. Marsland[1], Aidan G. C. Wright[1], Jill Foust[3], Lucas W. Carroll[2], Naina Kohli[2], Rishabh Mehra[2], Adam Jasper[2], Swathi Srinivasan[2] and Martica H. Hall[2]

[1]Department of Psychology, University of Pittsburgh, Pittsburgh, PA, [2]Department of Psychiatry, University of Pittsburgh, Pittsburgh, PA and [3]Health Sciences Library System, University of Pittsburgh, Pittsburgh, PA

*Corresponding author. Marissa A. Evans, Western Psychiatric Hospital, 3811 O'Hara Street, Rm E-1116, Pittsburgh, PA 15213. Email: marissa.evans@pitt.edu.

Abstract

Study Objectives: Sleep quantity and continuity vary across the lifespan. Actigraphy is a reliable and widely used behavioral measure of sleep in research and personal health monitoring. This meta-analysis provides a novel examination of whether age (in years) is associated with actigraphy-assessed sleep across the lifespan.

Methods: A systematic search of PubMed, Embase.com, Cochrane CENTRAL, and PsycINFO using "actigraphy" and "sleep" terms provided 7079 titles/abstracts; studies of individuals with known psychiatric or medical comorbidities were excluded. Ninety-one articles (N = 23 365) provided data for six meta-analyses examining sleep duration (k = 89), sleep efficiency (k = 58), bedtime (k = 19) and waketime (k = 9) for individuals ages 6–21, and bedtime (k = 7) and waketime (k = 7) for individuals ages 22 and older.

Results: At older ages, sleep duration was shorter (r = –0.12) and sleep efficiency was lower (r = –0.05). Older age was associated with later bedtime (r = 0.37) and wake-up time (r = 0.24) from ages 6–21, whereas older age was associated with earlier bedtime (r = –0.66) and wake-up time (r = –0.59) for ages 22 and above. The strength of these associations was modified by study continent, but not by any other moderator.

Conclusions: Age was negatively associated with actigraphy-assessed sleep duration and efficiency, but the effects were small in magnitude. On the other hand, large associations were observed between age and sleep timing, despite a smaller literature and the absence of analyzable data for ages 30–60. Changes in sleep timing, rather than changes in sleep duration or continuity, may better characterize the effects of age on human sleep.

Statement of Significance

Sleep changes across the lifespan. The extent to which this is true for multiple sleep characteristics assessed by actigraphy, collected in the home environment across multiple nights, has not been examined using meta-analysis. Additionally, key demographic moderators of the age-sleep association have not been explored. The current meta-analysis addresses these limitations using 91 articles and 23 365 participants with no known comorbidities. We report small effects of age (in years) on sleep duration and efficiency, but large effects of age for sleep timing. Changes in sleep timing, rather than changes in sleep duration or continuity, may better characterize the effects of age on human sleep.

Key words: meta-analysis; age; sleep timing; sleep duration; sleep efficiency

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Introduction

Multiple dimensions of optimal sleep, such as adequate duration, continuity, timing, and regularity, are associated with health and well-being [1]. Compelling evidence from previous meta-analyses demonstrates differences in these sleep characteristics as a function of age (in years). In child and adolescent samples, self-reported sleep duration was shorter and bedtimes were later at older ages [2]. In adult samples, polysomnography-assessed sleep duration was shorter, wake after sleep onset was higher, and sleep latency was longer at older ages [3–5]. Assessing sleep using actigraphy has several advantages including reliability [6], data collection in the participant's habitual environment (rather than the laboratory), and widespread use as a behavioral measure of sleep in research and personal health monitoring [7]. To our knowledge, only two meta-analyses have examined age-related differences in actigraphy-assessed sleep. One meta-analysis of individuals aged 0–18 indicated that actigraphy-assessed sleep duration was shorter and bedtimes were later at older ages, but wake-up time and sleep efficiency were not associated with age [8]. Another meta-analysis reported that among individuals over the age of 5, actigraphy-assessed sleep duration was negatively associated with age, but other actigraphy measures were not examined [5]. Thus, the current study sought to examine age-related differences in actigraphy-assessed sleep duration, continuity, timing, and regularity across the lifespan.

Identifying individuals or groups with the strongest age-sleep associations could inform future data analytic strategies (e.g. stratifying analyses) and may identify relevant demographic characteristics. Previous review and meta-analytic evidence have demonstrated that there are stronger associations among age and sleep for: studies that screened for and excluded participants with mental health disorders, sleep disorders, and physical illnesses [5]; males when objective sleep measures are used, females when subjective sleep is assessed [9]; and Asian adolescents compared to North American adolescents [2]. Though there are replicable racial/ethnic [10] differences in sleep, previous meta-analyses have had insufficient data to test whether this is a moderator of the age-sleep association [3]. Moreover, the number of nights of data collection [11] and the actigraphy device type [12] can affect study results, but have yet to be tested as moderators of the age-sleep association.

In the current study, we evaluated the strength of the meta-analytic associations between age and actigraphy-assessed sleep duration, efficiency, timing, and regularity. Age is assessed in years throughout this study. We included participants who were ages 6 and older, who were not specifically recruited to the study for a medical, psychiatric, or sleep disorder comorbidity, and whose data were collected before any intervention or manipulation in their habitual environment. Any study design (e.g. cross-sectional, longitudinal) that met these aforementioned criteria was included. We hypothesized that sleep duration and sleep efficiency would be negatively associated with age, that sleep timing would be positively associated with age (i.e. delayed) across ages 6–21, and negatively associated with age (i.e. advanced) thereafter [13]. We also hypothesized that regularity of sleep timing would be positively associated with age (i.e. greater regularity at older ages [14]). Finally, we evaluated the effects of the following moderators on age-sleep associations: whether studies screened for and excluded participants with comorbid mental health, medical, and sleep disorders, sex, race/ethnicity, continent of the study, number of nights of data collection, and actigraphy device type.

Methods

This meta-analysis was pre-registered on the international prospective register of systematic reviews, PROSPERO (CRD42019137424). This meta-analysis was written per the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [15].

Study retrieval strategy

We searched PubMed, EMBASE, and Cochrane CENTRAL, according to recommendations from the Cochrane handbook [16], as well as PsychINFO. We did not restrict the dates of publication or the language. Search terms (Supplementary Table S1) were developed and tested by a medical librarian with expertise in systematic reviews and meta-analyses (JF). The search strategy was completed on June 5, 2019.

Inclusion and exclusion criteria

Inclusion criteria were studies that: recruited participants ages 6 and older, collected nocturnal sleep characteristics in the participants' habitual environment, and reported on the association between age and at least one actigraphy-assessed sleep characteristic: duration, efficiency, timing, or regularity. Sleep duration was operationalized as the number of minutes a participant was asleep. Sleep efficiency was operationalized as sleep duration divided by time in bed and multiplied by 100 to render percent values. Sleep timing was measured by bedtime, wake-up time, or sleep midpoint. Bedtime was operationalized as the time that the participant pressed an event marker on the actigraph to indicate bedtime or the actigraphy-defined sleep onset. Wake-up time was operationalized as the time that the participant pressed an event marker on the actigraph to indicate wake-up time or the actigraphy-defined sleep offset. Sleep midpoint was operationalized as the middle of the sleep period, halfway between sleep onset and sleep offset. Sleep regularity was operationalized as the standard deviation of sleep midpoint, standard deviation of sleep duration, standard deviation of bedtime, and/or standard deviation of wake-up time.

Exclusion criteria were studies that were not peer-reviewed, studies of non-human animals, conference abstracts or summaries, unpublished data, narrative reviews, systematic reviews, meta-analyses, commentaries, and study protocol descriptions. We also excluded articles that *only* recruited individuals with a specifically assessed comorbidity (mental health disorder, medical condition, or sleep disorder) but did not have a control group. Our rationale for this exclusion criterion is that, while specific comorbidities may moderate age-sleep associations, a control group is necessary to test such moderation. We included studies of individuals with a specifically assessed comorbidity if they included a control group. Studies of shift workers without a comparison group of day workers were also excluded, as shift work systematically alters sleep-wake patterns. We excluded articles that manipulated sleep without data for baseline, assessed sleep only in a novel environment (e.g. in the laboratory),

and intervention studies without data for baseline. Studies of daytime naps without nocturnal sleep were excluded. Finally, we excluded studies of children from birth through age 5, given the rapid and complex changes observed in sleep-wake cycles across this age range [17].

Consistent with language traditionally used in meta-analyses [18], we use the term "effect size" for the statistical associations extracted from the articles, as well as for the overall effects observed in our meta-analyses. However, it is worth noting that there may be residual confounding present at the study and meta-analytic level.

Study selection

Records were processed using DistillerSR (Evidence Partners, Ottawa, Canada). Data processing included three stages (flow chart in Figure 1). First, the title and abstract of 7,079 records were screened for eligibility by two independent raters (MAE screened all title/abstracts; AJ, RM, or SS served as second rater, each rating one-third of the total abstracts; weighted Cohen's kappa = 94%). Records were excluded at this stage if the study design or participants were ineligible, or if at least one actigraphy-assessed sleep measure of interest was not included. Articles were included if both raters voted to include. If there was a discrepancy between raters (n = 424 records), a third independent rater (AJ, RM, or SS) evaluated the record, and the title/abstract was included if two out of three raters voted for inclusion. A total of 5410 records were excluded at the screening stage.

Second, we located the full-text articles for records that were deemed eligible at stage one (n = 1,669). Full-text articles were deemed ineligible at the second stage if they did not report on the association between age and at least one actigraphy-assessed measure of sleep; if the effect size was already captured from the same dataset in another article with a larger sample size; or if the sample represented hunter-gatherer tribes (excluded post-hoc due to a small number of studies and lack of generalizability). We emailed authors that reported that the age-sleep association was significant or nonsignificant to request the effect size (n = 21), and excluded studies if the authors did not respond to our request (n = 8). A total of 1578 articles were excluded at this stage (see Figure 1 for the breakdown of exclusions).

Third, data extraction was entered into forms created by MAE in the software DistillerSR. Data extraction was conducted by two independent raters (AJ, LC, NK, RM, or SS; weighted Cohen's kappa = 73%) from eligible studies for the meta-analysis (n = 91). A third independent rater (MAE) evaluated and resolved all discrepancies between the two raters.

For the primary aim of examining the association of age and sleep, we extracted sample size, effect size of associations between age and sleep parameters, mean and standard deviation of the age of participants, and mean and standard deviation of the sleep variables. We extracted data on the following moderators: continent (North America, Asia, or Europe), sex (male or female), race/ethnicity (Black, Hispanic, Asian, or Non-Caucasian), actigraphy device type (Philips, AMI, ActiGraph, Other), number of nights of actigraphy recording (e.g. seven nights), and whether the study excluded participants for mental health disorders, medical conditions, and/or sleep disorders.

Race/ethnicity analyses were only conducted for studies in the United States. Specifically, we evaluated the percent of the sample that was African American, Hispanic, Asian, or non-Caucasian. Meta-analysis accounts for sample size and precision of estimates with weighting [18], so we included both community and convenience samples to cast a wider net of potential studies. However, it is plausible that estimates may vary as a function of study design, so we compared effect sizes for representative samples vs. convenience samples.

We had insufficient case-control studies to evaluate age-sleep associations among control samples compared to participants with a comorbidity (1 study of individuals with dementia, 1 study of individuals with diabetes). We therefore only included the control groups from these studies. Instead, we tested three dichotomous (yes/no) moderators of whether the study specifically screened for (e.g. clinical interview) and excluded participants for mental health disorders, medical conditions, or sleep disorders. A previous meta-analysis of age and polysomnography-assessed sleep evaluated similar moderators and reported larger effect sizes for studies that screened for and excluded participants with mental health disorders, sleep disorders, and physical illnesses [5].

Analytic strategy

Meta-analysis, which evaluates aggregated data from published studies, was selected due to its systematic, quantifiable, efficient, and reproducible properties. This approach allowed aggregation of data from 23 365 individuals between 6 and 92 years of age from studies conducted in multiple laboratories. Descriptive statistics for the overall meta-analysis were calculated, including the average values for each sleep characteristic across each decade of life. Scatter plots were created to visualize the association between age and sleep characteristics. R version 3.4.3 [19] was used for descriptive statistics and the package ggplot 2 was used for scatter plots [20].

We chose *a priori* to conduct a meta-analysis if five or more effect sizes were available; while a meta-analysis can be conducted with a minimum of two studies, the median number of studies included in meta-analyses on Cochrane Database of Systematic Reviews Central is six [18]. Thus, we had insufficient studies to conduct meta-analyses for the association of age and any operationalization of sleep regularity: standard deviation of sleep duration (n = 4), standard deviation of sleep midpoint (n = 0), standard deviation of bedtime (n = 1), or standard deviation of wake-up time (n = 0). Other definitions of sleep regularity were observed, such as the coefficient of variation for sleep duration (n = 1), and the coefficient of variation combining bedtime and wake-up time (n = 1), but these definitions also had insufficient effect sizes. We also did not have sufficient studies to conduct a meta-analysis for age and sleep midpoint (n = 3), one operationalization of sleep timing. We evaluated post-hoc power analyses for all of the meta-analyses that we conducted [18].

Data were analyzed using Comprehensive Meta-Analysis (CMA) software, version 3.3.07 [21]. All effect sizes were initially converted to Pearson correlation coefficients (r), and transformed into Fisher's z (to separate the effect size from its variance).

Random effects meta-analyses were then used to evaluate the strength of the association between age and sleep characteristics with sufficient data—sleep duration, sleep efficiency,

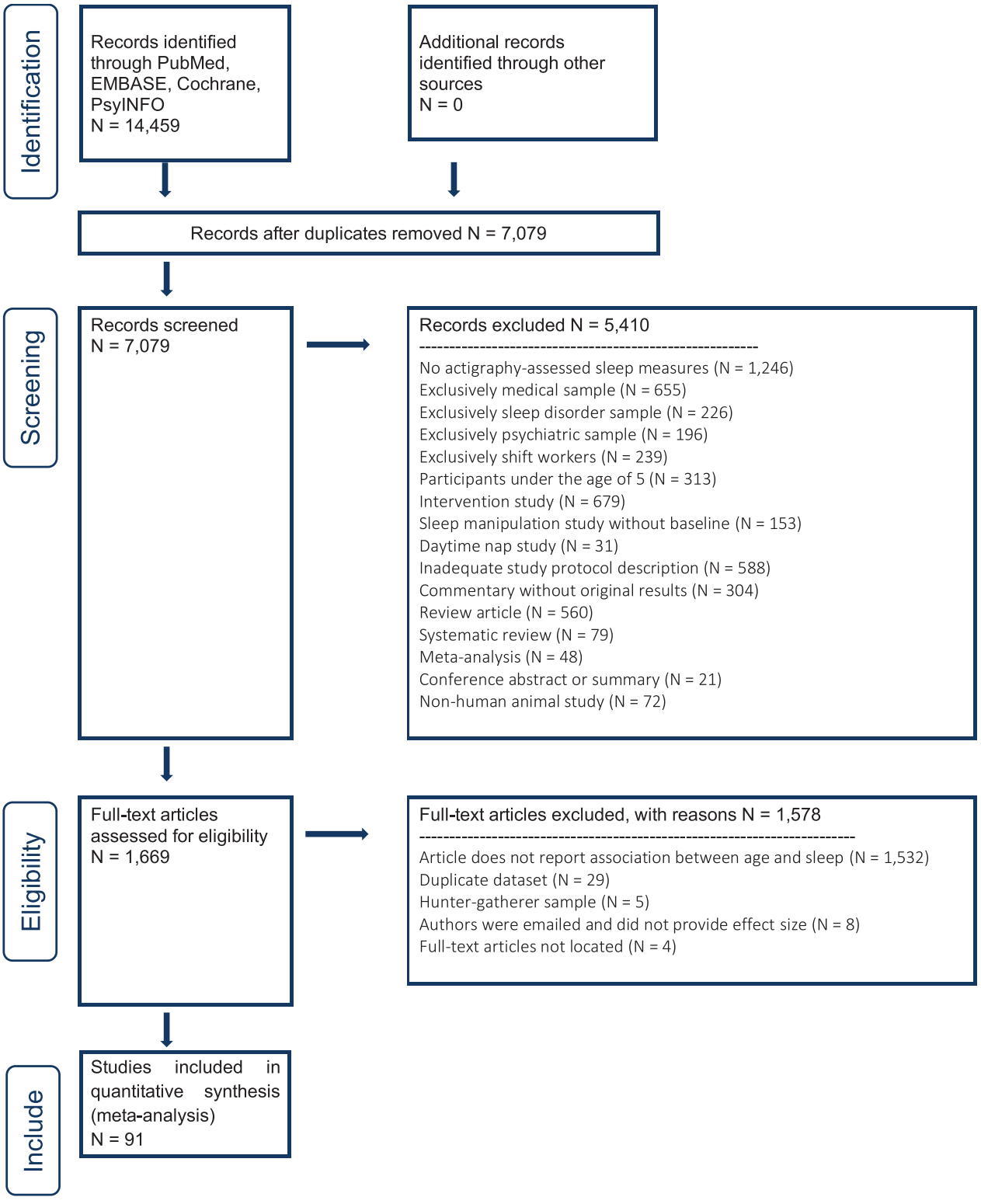

Figure 1. PRISMA Flow Diagram.

bedtime, and wake-up time. The effect sizes were transformed back to Pearson correlations for ease of interpretation, and forest plots were created to visualize the associations across studies. The 95% confidence intervals surrounding Pearson's *r* in forest plots may be non-symmetrical because they are based on the r-to-z then z-to-r transformation [18]. Heterogeneity across studies was assessed using both T^2, which estimates the variance of the true effect sizes (between-studies variance), and I^2, which can be interpreted as the proportion of observed variance that reflects true differences in effect size [18].

We evaluated the risk of publication bias by removal of one study, funnel plots, and Duval and Tweedie's trim and fill method [22]. Removal of one study systematically removes each individual study from the meta-analysis to ensure that one effect size is not unduly affecting the meta-analytic estimate. Funnel plots include the studies' effect size on the x-axis and the standard error of the study on the y-axis; if no publication bias is present, studies are symmetrically distributed around the meta-analytic effect size [21]. Duval and Tweedie's trim and fill method imputes unpublished studies to the left and the right of the meta-analytic effect size, and evaluates the extent to which the imputed studies change the meta-analytic effect size [22].

Moderation analyses were conducted to probe heterogeneity in effect sizes. Random effects models with separate estimates of T^2 for each subgroup were used. We restricted moderator analyses to those with more than ten effect sizes available per subgroup (per the guidelines of the Cochrane handbook [16]). For categorical moderators (continent, exclusion of comorbidities, actigraphy device type), we used the Z-test, which is comparable to the t-test used in an empirical study to test whether a regression coefficient is significantly different from zero [18]. For continuous moderators (sex, race, number of nights of actigraphy, and mean age of participants), we used meta-regression. This technique is similar to linear regression, but the covariates are at the level of the study and the dependent variable is the effect size [18]. Given the significant number of categorical and continuous moderators (n = 36), we applied Bonferroni corrections to adjust alpha to <.001, and only interpret moderators that were statistically significant at this level and/or that had a medium effect size ($R^2 \geq 13\%$ [23]). All of these moderation analyses were pre-registered.

We then evaluated the risk of bias (ROB) at the level of individual studies, specifically, sample bias (exclusion of mental health disorders, exclusion of medical conditions, exclusion of sleep disorders) and bias in outcome measurement (heterogeneity in actigraphy device and number of nights of actigraphy). We reported the number of studies that had ROB in these categories and evaluated whether these factors modified meta-analytic associations.

Finally, the quality of the body of evidence was evaluated using a modified version of the Community Preventive Services methods [24]. We chose not to use GRADE methodology as an assessment tool, as GRADE considers RCTs to be the gold-standard and meta-analyses with observational studies are automatically demoted to the category of "low" quality evidence. Our research question could not be answered by an RCT, as it is impossible to randomly assign participants to ages. Table 1 shows the details of how this methodology was applied to the current study.

Results

Study characteristics

Ninety-one articles [25–116] met inclusion criteria. These studies contained 189 effect sizes in a total of 23 365 participants. We conducted six meta-analyses, which included 89 effect sizes for sleep duration, 58 effect sizes for sleep efficiency, 19 effect sizes for bedtime ages 6–21, 7 effect sizes for bedtime ages 22 and older, 9 effect sizes for wake-up time ages 6–21, and 7 effect sizes for wake-up time ages 22 and older.

Descriptive statistics for each meta-analysis are presented in Table 2 (sample size, mean age, percent female, and number of nights of actigraphy data); we do not report average percent of non-Caucasian individuals included in studies, as less than half of the studies reported race/ethnicity composition. Supplementary Table S2 shows each individual study's characteristics, including the study name, country, sample size, mean age and standard deviation of age, and which sleep characteristic(s) the study contributed. Three studies evaluated within-person change in sleep, four studies compared sleep between distinct age groups (e.g. 23-year-olds compared to 66-year-olds), and 84 studies examined between-person associations. Overall, 63% of the studies were conducted in North America, 19.3% in Europe, 5.6% in Asia, 5.6% in South Africa, 4.5% in the Middle East, and 2.2% in Australia.

Table 1. Guidelines for evaluating the quality of the evidence—Based on a modification of the Community Preventive Services methods

Domains	Operationalization
Execution	
Was the study population well-described?	Included the mean and standard deviation of age
Did the authors specify their screening criteria?	Specified how participants were included and/or excluded
Were the outcome measures reliable?	At least 7 days of actigraphy data
Was attrition low?	Less than 10% of missingness
Good, fair, or limited execution	*Good:* at least 70% of studies met criteria in 4 categories *Fair:* at least 70% of studies met criteria in 2–3 categories *Limited:* at least 70% of studies met criteria 0–1
Greater or lesser design suitability	*Greater:* at least 70% of studies were longitudinal
Sufficient number of studies	"Yes" indicates > 5 studies for all meta-analyses (a priori rule)
Consistent or inconsistent effect sizes	*Consistent:* at least 70% of studies fall into the negative (effect size less than -0.10) or positive (effect size greater than 0.10) association category
Small, sufficient, or large effect sizes	*Small:* r = 0–0.29 *Sufficient*: r = 0.3–0.49 *Large*: $r \geq 0.5$
Strong, sufficient, or insufficient quality of evidence	*Strong*: execution was good or fair, greater design suitability, 5 studies, had a consistent association, and had a sufficient or large effect size *Sufficient*: execution was good or fair, design suitability was of greater or lesser suitability, ≥5 studies, had a consistent association, and had a sufficient or large effect size

Descriptive associations of age and sleep characteristics

We created a table with the average values for each sleep characteristic by decade of life, using mean age and mean sleep characteristic for each study included in the meta-analyses (Table 3). Table 3 shows the limited data available for sleep efficiency between ages 30–40 and 50–60, and the absence of analyzable data for bedtime and wake-up time between ages 30–60 and 80–90.

We characterized the associations between mean age and mean sleep duration and mean sleep efficiency using scatter plots, where each point represents a study (Figure 2). It is important to interpret these figures with caution, because they are descriptive and not the results of the meta-analyses. The association of age and sleep duration was better characterized by a quadratic than a linear regression (R^2 = 39.5% and 23.2%, respectively, $p < .001$), with an inflection point at age 50. We conducted an exploratory moderation analysis to further probe this observation. Consistent with our hypotheses, the descriptive scatterplots suggest that the association of age and sleep efficiency is linear (R^2 = 5.1%). We did not create scatterplots for sleep timing, given the absence of available data for ages 30–60 and the limited data for other age ranges, which makes it impossible to accurately assess whether associations are linear or quadratic.

Because we could not determine a precise age at which the relationship between age and sleep timing changes from delayed to advanced due to data availability, and because we hypothesize based on prior literature that the association is positive during adolescence and negative in adulthood, we conducted meta-analyses separately for individuals ages 6–21 and 22 and older.

Table 4 summarizes the results of the six meta-analyses, which are presented in detail below. Using the sample sizes, effect sizes, and variance for post-hoc power analyses, we found that all six meta-analyses achieved 100% power [18].

Meta-analysis of age and actigraphy-assessed sleep duration

This meta-analysis included 78 articles with 89 effect sizes and 21 242 participants. Although the scatterplot for age and sleep duration suggested a quadratic association (Figure 2), in this section, we evaluated the linear association based on our a priori hypothesis. In our section on "Moderators of meta-analyses," we probe the quadratic association. Figure 3 shows a forest plot of effect sizes, confidence intervals, and the relative weights of each study. The overall effect size was r = –0.12, 95% CI [–0.16, –0.08], $p < .001$, which indicates a small magnitude correlation between older age and lower actigraphy-assessed sleep duration. The T^2 of 0.05 suggests that the estimated amount of between-studies variation in the effect size is small. There was moderate heterogeneity across studies, with the I^2 indicating that 48.5% of the variation in effect size was due to true differences in effect size and not sampling error. Removal of any one published effect size did not change the meta-analytic association (range of estimates r = –0.11 to –0.13). Based on examination of the funnel plot (Supplementary Figure S1) and Duval and Tweedie's trim and fill method (imputed point estimate of r = –0.18, 95% CI [–0.23, –0.13]), it seems implausible that unpublished studies substantially affected the meta-analytic estimate.

Meta-analysis of age and actigraphy-assessed sleep efficiency

This meta-analysis included 53 articles with 58 effect sizes and 11 525 participants. The overall effect size was r = –0.05, 95% CI [–0.10, –0.001], p = .05, T^2 = 0.02, I^2 = 42.24% (Figure 4), indicating a small correlation between older age and lower sleep efficiency. Removal of any one of 31 published effect sizes included in the meta-analysis rendered the overall association nonsignificant ($p > .05$), with a range of the point estimate after removal of individual studies from –0.04 to –0.06. These findings indicate a small and inconsistent correlation between older age and lower

Table 2. Descriptive statistics for each meta-analysis of age and actigraphy-assessed sleep

	Sleep duration	Sleep efficiency	Bedtime, ages 6–21	Bedtime, ages 22 and older	Wake-up time, ages 6–21	Wake-up time, ages 22 and older
	M (range)	*M* (range)	*M* (range)	*M* (range)	*M* (range)	*M* (range)
Sample size	247.0 (12–3055)	202.2 (14–3055)	290.9 (21–1231)	323.4 (11–3055)	186.2 (21–417)	503.3 (15–3055)
Mean age	31.8 (6.5–91.9)	36.4 (6.5–91.9)	11.2 (7.6–17)	44.6 (22.5–91.9)	10.9 (9.23–15.5)	38.7 (22.5–91.9)
% Female	59.8 (0–100)	60.9 (0–100)	49.75 (28.6–77)	42.7 (0–68.2)	50.5 (28.6–68.2)	35.9 (0–63.9)
Number of nights	6.6 (1–29)	6.4 (2–20)	5.8 (2–7.1)	7.2 (5–13.6)	6.0 (2–7)	6.6 (5.2–7)

M indicates mean. Number of nights indicates number of nights of actigraphy data collected.

Table 3. Averages of sleep characteristics across each assessed decade of the lifespan

	6–9.99	10–19.99	20–29.99	30–39.99	40–49.99	50–59.99	60–69.99	70–70.99	80–89.99	90–99.99
Sleep duration, hour	8.63	7.18	7.20	6.42	6.78	6.83	6.28	6.80	6.35	8.97
Number of studies	16	25	11	7	8	7	5	5	5	1
Sleep efficiency, %	84.10	87.20	87.79	77.88	86.77	85.00	74.52	85.36	86.86	89.70
Number of studies	8	12	9	3	5	2	5	8	5	1
Bedtime, hh:mm	21:34	22:35	0:23				23:03	23:24		21:34
Number of studies	9	9	4	0	0	0	1	2	0	1
Wake-up time, hh:mm	7:05	7:10	8:07				6:58			6:55
Number of studies	5	3	4	0	0	0	1	2	0	1

actigraphy-assessed sleep efficiency. To assess publication bias, we evaluated the funnel plot (Supplementary Figure S2) with the trim and fill method and found that the inclusion of seven imputed studies did not substantially change the overall effect size (r = –0.09, 95% CI [–0.13, –0.04]).

Meta-analysis of age and actigraphy-assessed bedtime

Results for participants ages 6–21.

This meta-analysis included 15 articles with 19 effect sizes and 3055 participants. The overall effect size was r = 0.37 (95% CI [0.23, 0.49], p < .001, T^2 = 0.11, I^2 = 48.7%) indicating a moderate correlation between older age and later actigraphy-assessed bedtimes (Figure 5). Removal of individual studies does not substantially change the estimated meta-analytic effect size (r = 0.33 to 0.42). The funnel plot (Supplementary Figure S3) and the trim and fill method (which did not impute any studies) suggest no impact of publication bias.

Results for participants ages 22 and older.

This meta-analysis included seven articles with seven effect sizes and 3681 participants. The overall effect size for the association of age and bedtime for participants aged 22 and older was r = –0.66 (95% CI [–0.87, –0.24], p = .004, T^2 = 0.34, I^2 = 38.3%, Figure 6). This indicates a large correlation between older age and earlier actigraphy-assessed bedtime. Removal of individual studies indicates that the strength of the effect size may be moderate to large (range of r = –0.42 to –0.73), but in all cases remained statistically significant. There is little evidence for publication bias (Supplementary Figure S4), with only one imputed study using the trim and fill method (r = –0.73, 95% CI [–0.94, –0.12]).

Meta-analysis of age and actigraphy-assessed wake-up time

Results for participants ages 6–21.

This meta-analysis included seven studies with nine effect sizes and 748 participants. The meta-analytic effect size for age and wake-up time for ages 6–21 is r = 0.24 (95% CI [0.05, 0.41], p = .01, T^2 = 0.06, I^2 = 24.3%, Figure 7), which indicates a moderate correlation between older ages and later actigraphy-assessed wake-up times. Removal of individual effect sizes suggests that the association ranges from r = 0.18 to 0.31, with removal of one effect size (15-year-olds in ref. [34]) rendering the meta-analytic association nonsignificant. The funnel plot (Supplementary Figure S5) and the trim and fill method (which did not impute any studies) suggest no impact of publication bias.

Results for participants ages 22 and older.

This meta-analysis included seven studies with seven effect sizes and 3625 participants. The meta-analytic effect size for age and wake-up time for ages 22 and older is r = –0.59 (95% CI [–0.83,

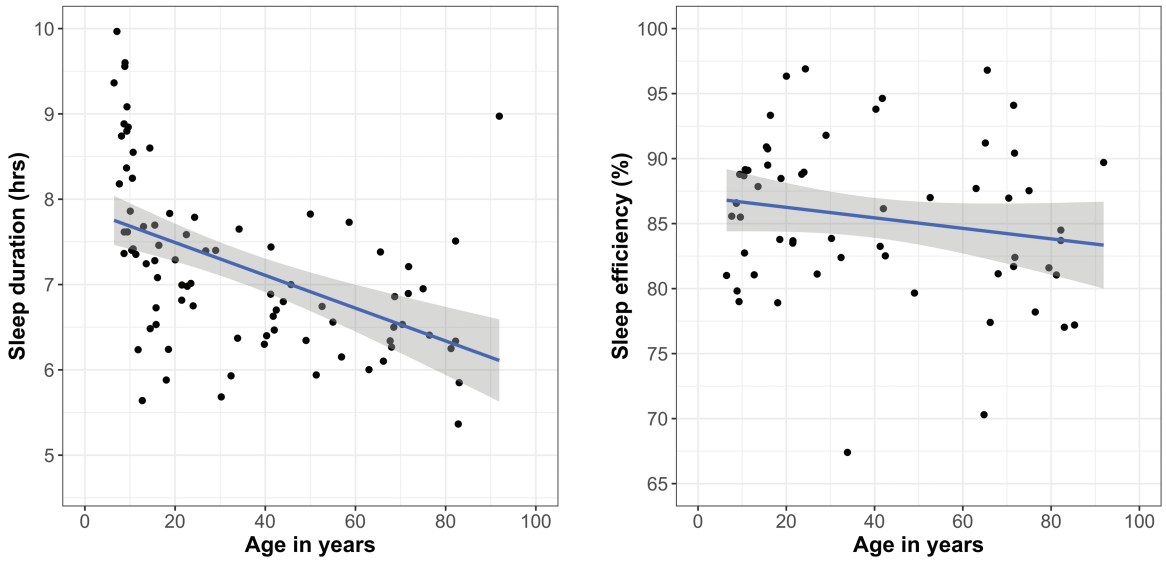

Figure 2. Scatterplots of the associations between age and actigraphy-assessed sleep duration and sleep efficiency.

Table 4. Results of meta-analyses of the association of age and actigraphy-assessed sleep characteristics

	k	Participants	Meta-analytic effect size [95% CI], *p*-value
Overall	189	23 365	
Sleep duration	89	21 242	r = –0.12 [–0.16, –0.08], p < .001
Efficiency	58	11 525	r = –0.05 [–0.10, –0.001], p = .05
Bedtime, ages 6–21	19	3055	r = 0.37 [0.23, 0.49], p < .001
Bedtime, ages 22 and older	7	3681	r = –0.66 [–0.87, –0.24], p = .004
Wake-up time, ages 6–21	9	748	r = 0.24 [0.05, 0.41], p = .01
Wake-up time, ages 22 and older	7	3625	r = –0.59 [–0.83, –0.15], p = .01

k indicates number of effect sizes.

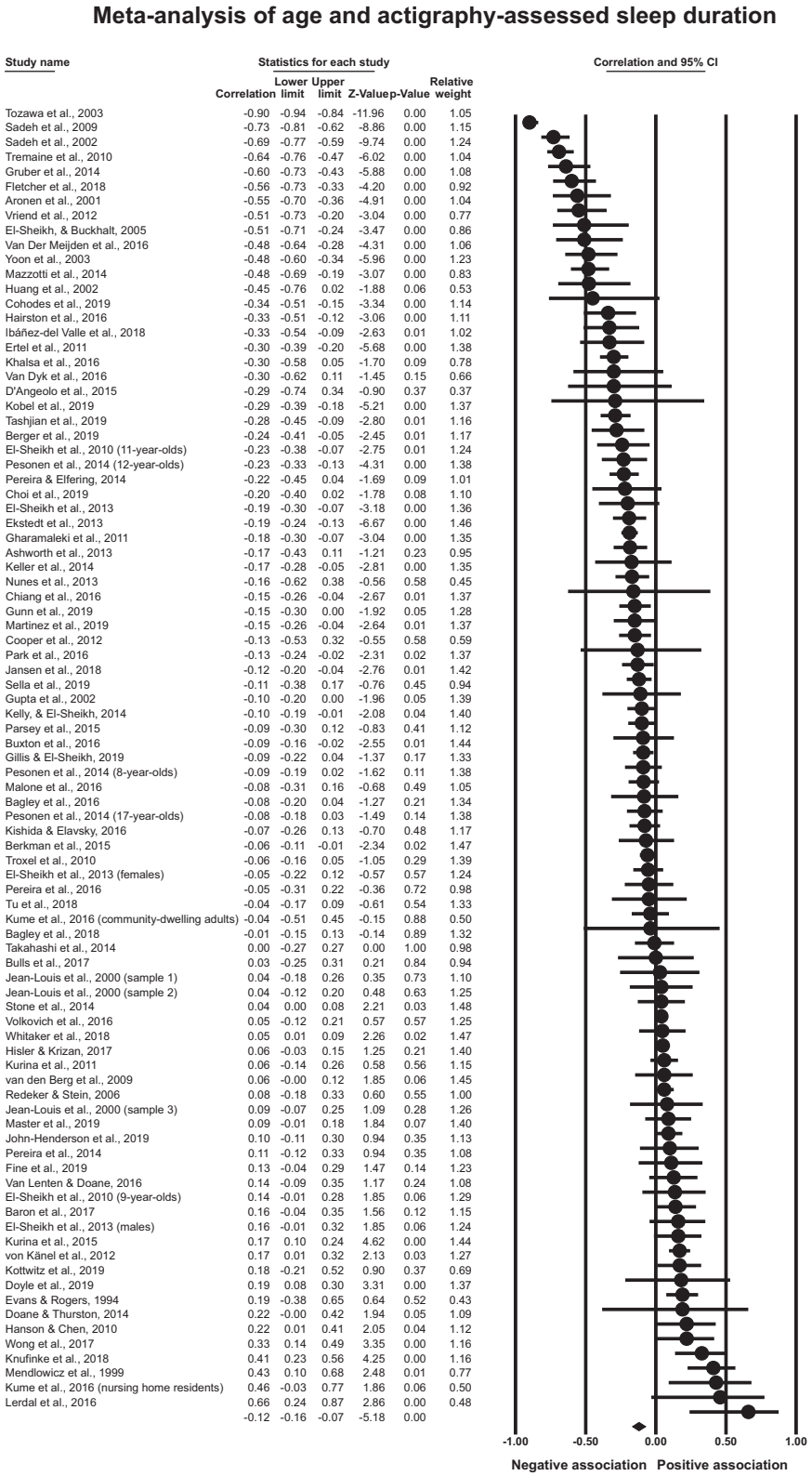

Figure 3. Meta-analysis of age and actigraphy-assessed sleep duration.

–0.15], p = .01, T^2 = 0.15, I^2 = 23.2%; Figure 8), which indicates a large association between older ages and earlier actigraphy-assessed wake-up times. Removal of individual studies suggests that the association ranges from r = 0.01 to 0.53, with removal of one effect size [101] rendering the meta-analytic association nonsignificant. There is little evidence of publication bias (Supplementary Figure S6), with two imputed studies using the trim and fill method (r = –0.73, 95% CI [–0.93, –0.10]).

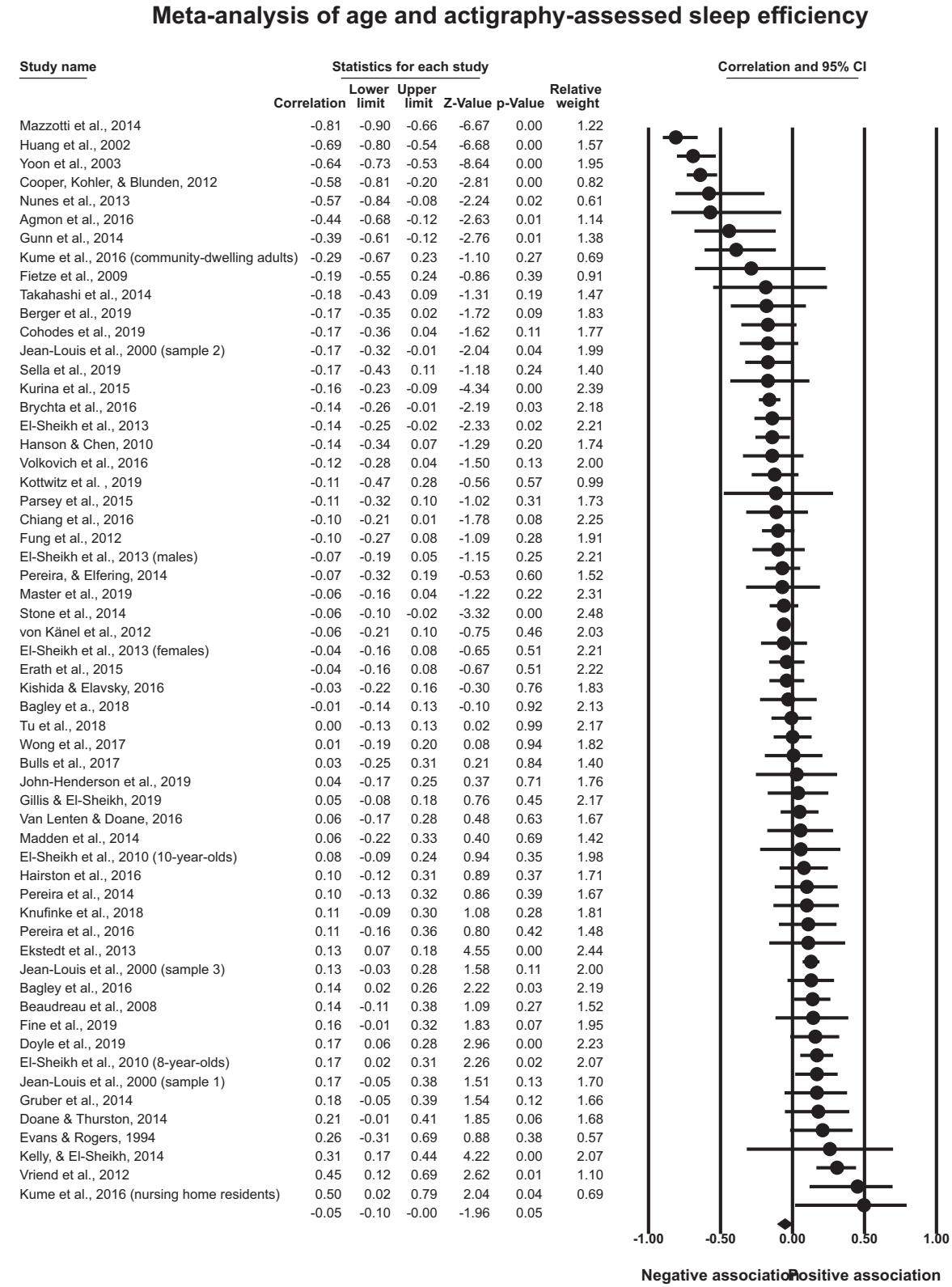

Figure 4. Meta-analysis of age and actigraphy-assessed sleep efficiency.

Moderators of meta-analyses

We evaluated moderators for three meta-analyses: sleep duration, sleep efficiency, and bedtime for individuals ages 6–21. We could not conduct moderation analyses for the other three meta-analyses because there were fewer than 10 studies in each moderator category. For categorical moderators (Table 5), we report the effect size within each subgroup of the moderator, test whether the moderator is statistically significant,

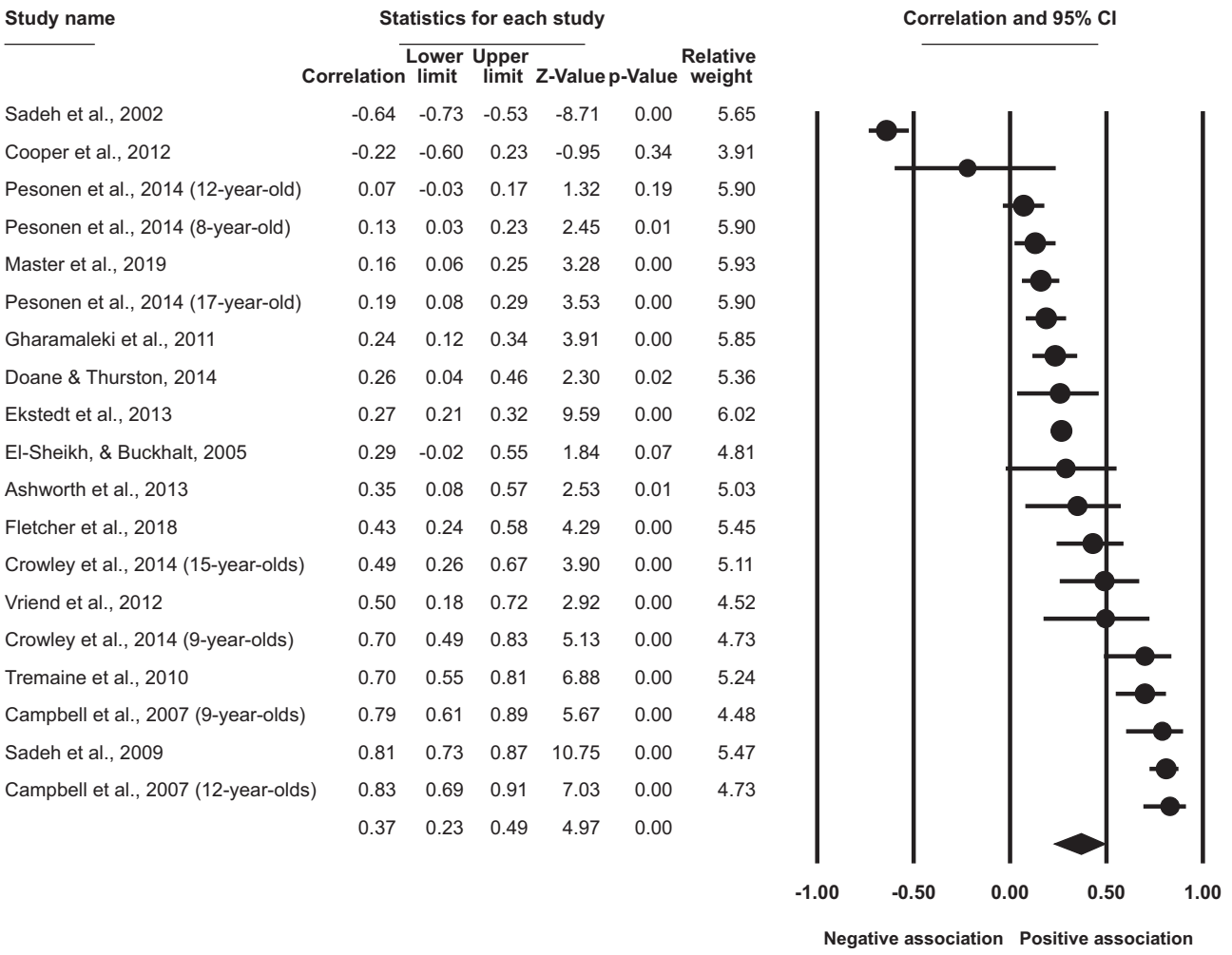

Figure 5. Meta-analysis of age and actigraphy-assessed bedtime, ages 6–24.

and test the variance explained in the meta-analytic effect size by the moderator, or the R^2. For continuous moderators (Table 6), we report the strength of the association as an unstandardized beta with standard error, as well as the R^2. While we report all moderation analyses in tables, we only discuss in-text the moderators that were statistically significant (at the Bonferroni-corrected alpha of <.001) and/or had a medium effect size ($R^2 \geq 13\%$).

Table 5 shows that 39% of effect sizes were from studies that excluded mental health disorders, 35% from studies that excluded medical conditions, and 31% from studies that excluded sleep disorders. In the 91 included articles, 38 studies used Philips Respironics devices, 33 used Ambulatory Monitoring Inc, 8 used ActiGraph, 12 used "other" devices (four used Sensewear Pro3 Armband, four used Actillume, one used Actiwatch Score, one used Actiwatch Mini, one used Actiheart, and one used Actigraph from Gaewhiler), and none used consumer wearables. Table 5 shows the number of studies that used each device type in each meta-analysis.

Continent of study was a significant moderator for actigraphy-assessed sleep duration and sleep efficiency, such that the strength of the association was stronger for studies conducted in Asia compared to North America or Europe (*p*s < .001, R^2 = 10–16%, Table 5). The association between age and sleep duration was moderated by mean age of the participants (R^2 = 24%, p < .001, Table 6), which is consistent with the scatterplot suggesting a quadratic association (Figure 2). Further testing indicated that the association between age and sleep duration was negative for participants ages 6–49 (k = 69; r = –0.17, 95% CI [–0.22, –0.12], p < .001) but weakly positive for individuals over the age of 50 (k = 20; r = 0.06, 95% CI [0.01, 0.10], p = .02). These findings suggest that the age-sleep duration association weakens across the lifespan.

Though not statistically significant at the Bonferroni-corrected alpha, exclusion of mental health disorders (R^2 = 15%, p = .008) contributed substantially to the variance in the effect size for actigraphy-assessed bedtime (Table 5). The association between age and actigraphy-assessed sleep duration was weaker in samples with more females (p < .001), although this did not contribute to the variance (R^2 = 0%).

No other moderators were statistically significant or contributed substantially to the variance in the effect size.

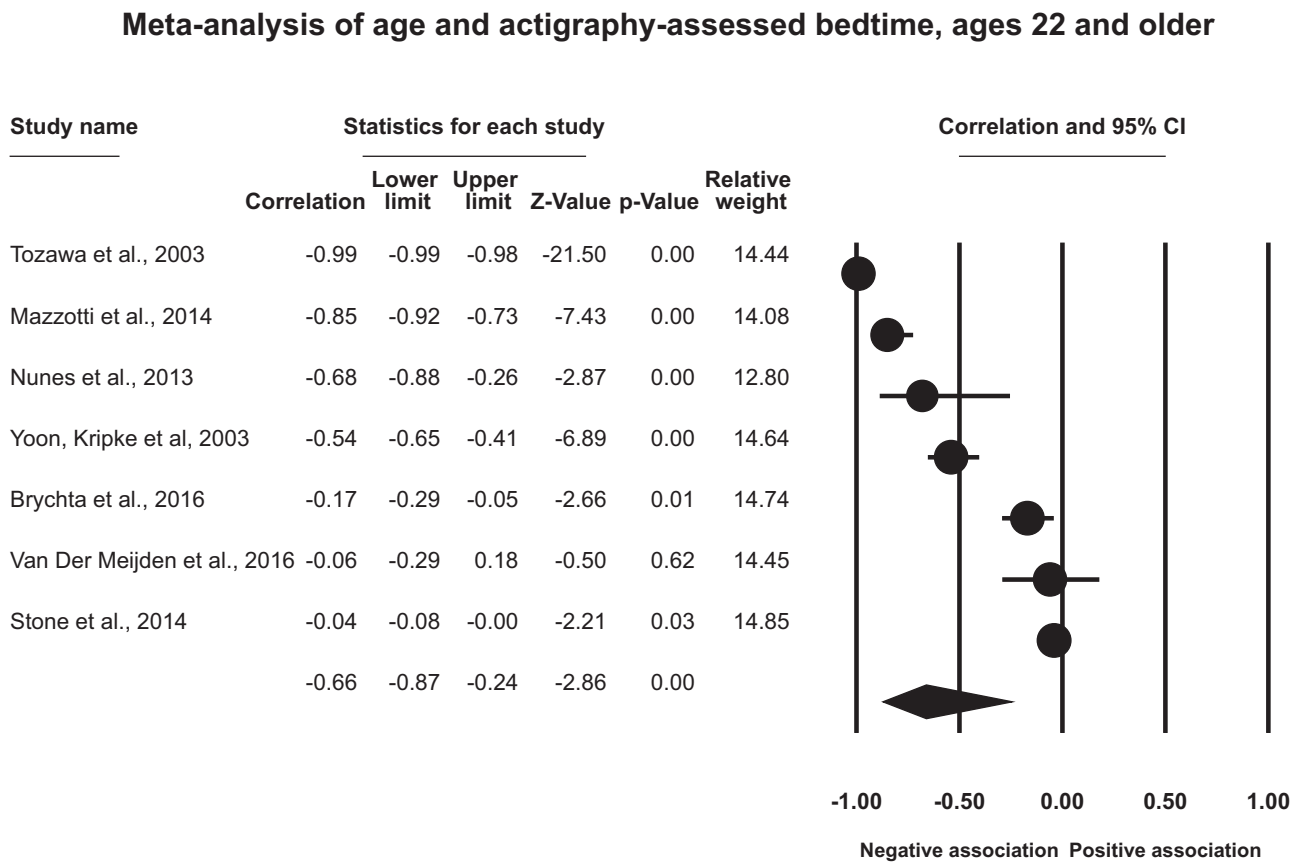

Figure 6. Meta-analysis of age and actigraphy-assessed bedtime, ages 60 and older.

ROB within studies

ROB within each study was assessed by evaluating sample bias (studies that did not screen for and exclude individuals with mental health, medical conditions, or sleep disorders) and bias in outcome measurement (heterogeneity in actigraphy device or less than 7 days of actigraphy data). Of the 91 studies, low sample bias was present in 37 studies that excluded mental health conditions, 52 studies that excluded medical conditions, and 26 studies that excluded sleep disorders. We tested the impact of sample bias on results of the meta-analyses by evaluating each of these as moderators (Table 5). Exclusion of medical conditions or sleep disorders did not modify observed meta-analytic effect sizes. Exclusion of mental health disorders impacted the variance of the effect size for actigraphy-assessed bedtime (R^2 = 15%), but did not impact the effect size for actigraphy-assessed sleep duration or sleep efficiency.

Low bias in outcome measurement was present for the 32 studies that included at least seven nights of actigraphy data. Although there were differences in actigraphy device used across studies, the type of actigraphy device (Table 5) and the number of nights of actigraphy data (Table 6) did not contribute significantly to variance in the meta-analytic effect sizes for actigraphy-assessed sleep duration, sleep efficiency, or bedtime.

Evaluating the quality of the evidence

Using a modified version of the Community Preventive Services methods [24], we evaluated the quality of the body of evidence included in these meta-analyses (Table 7). Because so few studies (0–28.6%) were longitudinal, we could not categorize the quality of evidence as strong for any meta-analysis. The quality of the evidence was sufficient for bedtime ages 6–21, and bedtime and wake-up time ages 22 and older, indicating that there was consistency in the direction of effects across studies, fair execution within studies, and sufficient to large effect sizes. The quality of the evidence was considered insufficient for sleep duration, sleep efficiency, and wake-up time ages 6–21. Although there were the largest number of effect sizes for sleep duration and efficiency, the direction of the associations were inconsistent and effect sizes were small.

Discussion

This review evaluated the associations among age and actigraphy-assessed sleep characteristics across the lifespan. We evaluated the published evidence using meta-analyses based on 189 effect sizes and 23 365 participants. We demonstrated that actigraphy-assessed sleep duration is shorter (r = –0.12) and sleep efficiency is lower (r = –0.05) at older ages, though these associations were small and inconsistent across studies. We found larger effect sizes for sleep timing, such that bedtime and wake-up time were later at older ages for individuals aged 6–21 (r = 0.37, 0.24, respectively), and earlier for individuals aged 22 and older (r = –0.66, –0.59, respectively). These findings may suggest that changes in sleep timing—rather than changes in sleep duration or efficiency—are the most robust hallmarks of age-related differences in sleep.

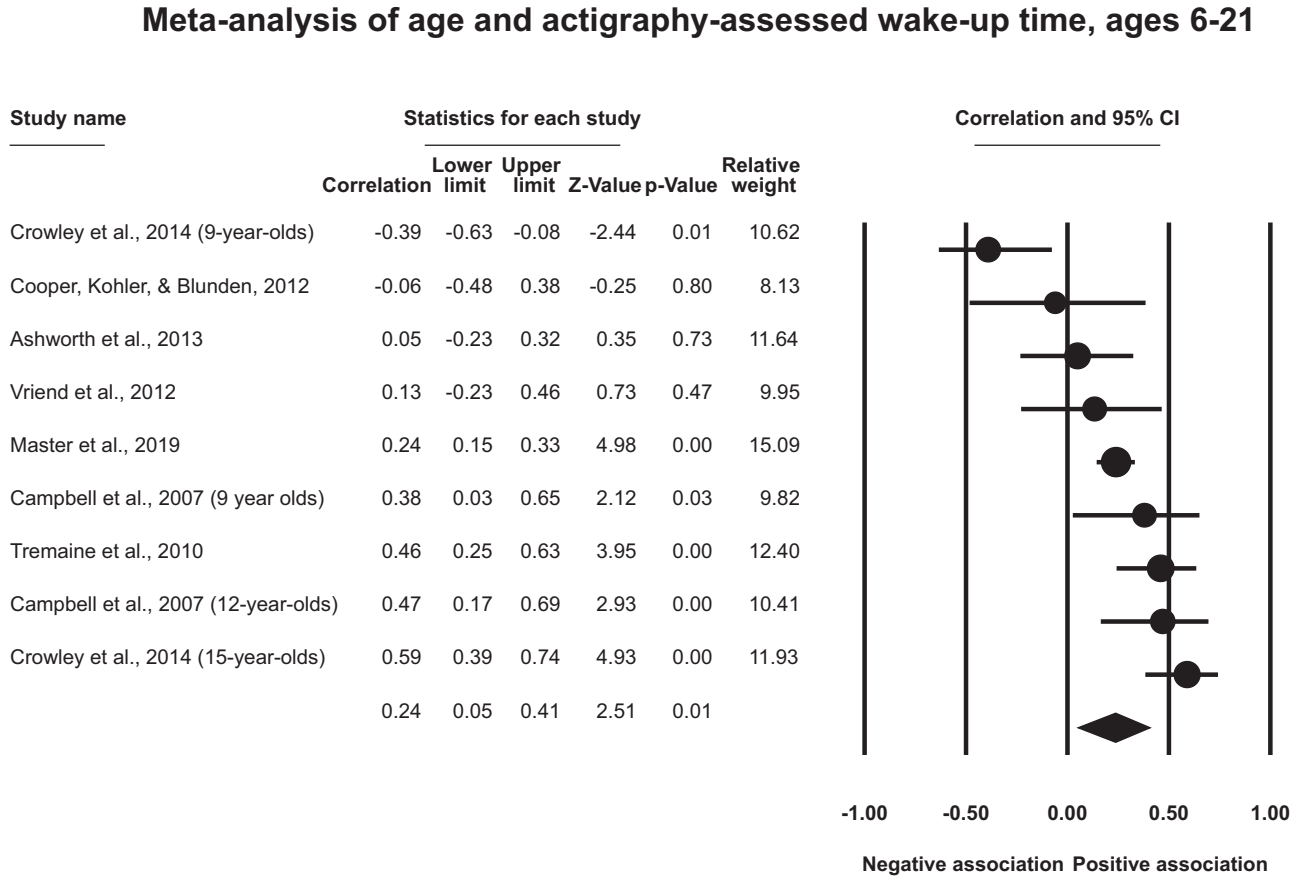

Figure 7. Meta-analysis of age and actigraphy-assessed wake-up time, ages 6–24.

These meta-analyses demonstrate an association between age and later sleep timing among individuals ages 6–21, and an association between age and earlier sleep timing among adults. While this is the first meta-analysis to examine age and actigraphy-assessed sleep timing among adults, these findings are consistent with a previous meta-analysis of actigraphy-assessed sleep among individuals aged 3–18, which reported later bedtime and wake-up times at older ages [8]. Laboratory evidence suggests that adolescents delay bedtime and wake-up time due to changes in both the biological clock and social demands [117], and that middle-aged and older adults demonstrate earlier timing of circadian rhythms compared to younger adults [118]. The meta-analyses for sleep timing included fewer effect sizes compared to analyses for duration and efficiency, and we had no analyzable data of age and sleep timing associations for individuals aged 30–60. This lack of data precludes an analysis of the age at which sleep timing shifts from delaying to advancing. Importantly, for three of these meta-analyses (bedtime ages 6–21, bedtime ages 22 and older, and wake-up time ages 22 and older), the quality of evidence was deemed *sufficient* for strong conclusions, which means that these associations are statistically significant, reliable, and substantial.

The largest number of studies allowed examination of the association between age and actigraphy-assessed sleep duration. Consistent with previous meta-analyses based on various measurement modalities [3–5, 8], we observed that actigraphy-assessed sleep duration is shorter at older ages, though the effect was small in magnitude. Laboratory evidence has suggested that, compared to younger adults, older adults have shorter sleep with a 12-hour nocturnal sleep opportunity [119] and have a lower propensity for falling asleep during a daytime sleep window [119–121], which may be due to age-related changes in sleep propensity. However, this study's exploratory meta-analyses revealed that actigraphy-assessed sleep duration is shorter at older ages only until approximately age 50, and is slightly *longer* at ages above 50 years. This could be due to differences between sleep propensity in a controlled laboratory environment compared to sleep duration assessed in the field. The finding of a U-shaped association between age and sleep duration should be interpreted cautiously due to the exploratory nature of the analysis (based on our descriptive scatterplot and test of linearity with 89 effect sizes), but warrants examination in future studies. We choose to focus our discussion of results primarily on our linear association because of this exploratory nature. These inconsistent associations, as well as small effect sizes, led to the quality of the evidence for this meta-analysis being deemed *insufficient* for drawing strong conclusions. Overall, the actigraphy-assessed sleep duration results suggest that inadequate sleep quantity should not be interpreted only as a consequence of aging. Therefore, older adults should be encouraged that their current sleep quantity is not unchangeable due to their age.

Though we report that sleep efficiency is lower at older ages, it was determined to be weakly linear, the meta-analytic effect size was small, and removal of individual studies rendered the association nonsignificant. These small effect sizes and the inconsistency of directions of associations means that the quality of the evidence for this meta-analysis is insufficient for drawing

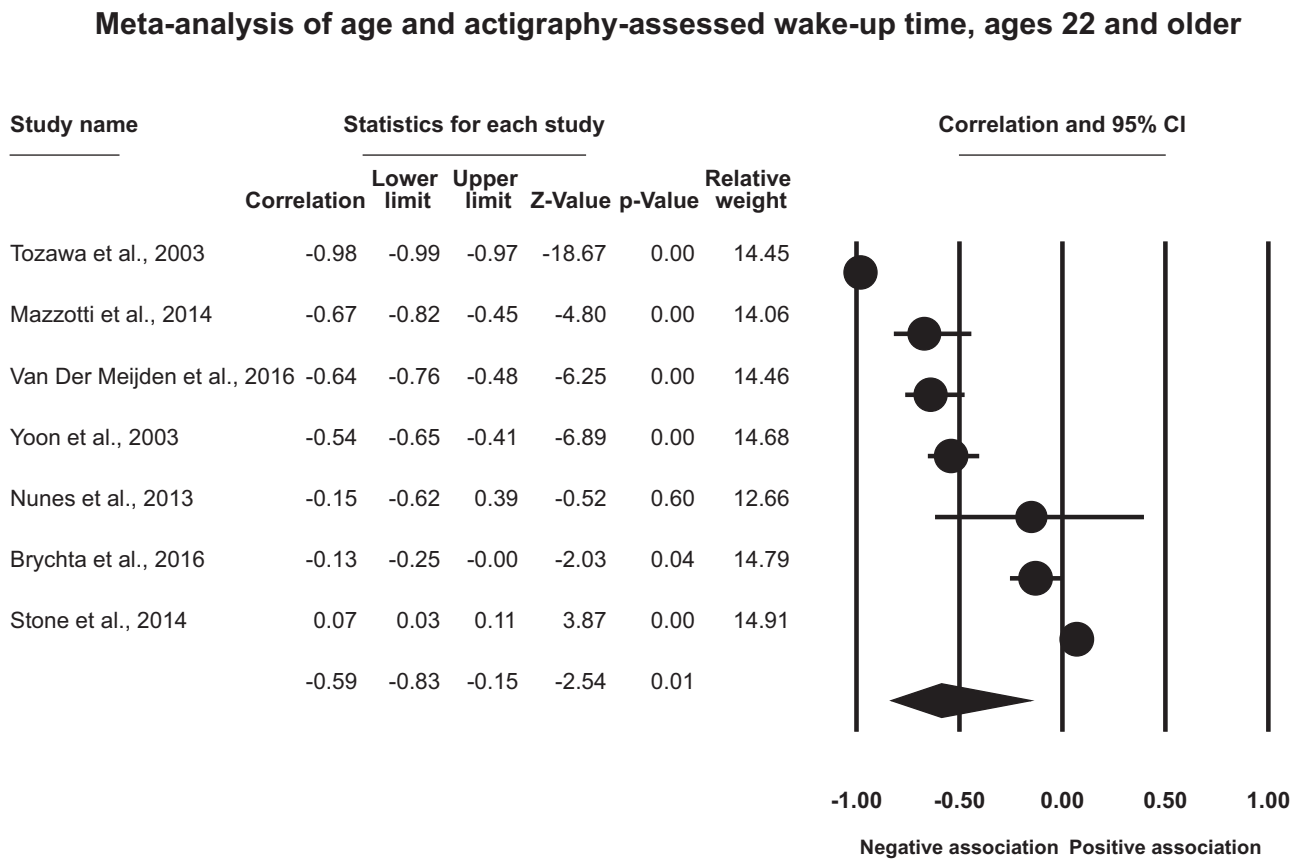

Figure 8. Meta-analysis of age and actigraphy-assessed wake-up time, ages 60 and older.

strong conclusions. While a previous meta-analysis reported that polysomnography-assessed sleep efficiency is lower at older ages [5], these discrepant results may be due to difference in measurement modality [122], and/or study design, as actigraphy allows for a greater number of nights studied and increased environmental validity of home-based assessment. Another possibility is that older adults are more sensitive to nocturnal awakenings in the laboratory compared to the home environment. The present meta-analytic results suggest that age is an unlikely confound in research examining correlates and consequences of actigraphy-assessed sleep efficiency. Additionally, these results suggest that interventions to improve sleep efficiency such as cognitive behavioral therapy for insomnia may be useful across the lifespan; though our review did not include studies of diagnosed insomnia patients, the average sleep efficiency was below 85% (a common threshold for insomnia [123]) for half of the included studies.

In our analysis of demographic moderators, continent of the study (North America, Asia, or Europe; insufficient studies from other regions) was the only consistent moderator. A previous meta-analysis found that continent of study was a modifier of age and subjective sleep associations among adolescent participants [2], and a recent analysis of worldwide commercial devices showed that sleep duration and timing were different across continents [124]. These results could be a macro-level indicator of differences in social environments (e.g. socioeconomic status, race/ethnicity distributions), social demands (e.g. work and school [125]), as well as cultural attitudes and values regarding sleep and its importance. These data suggest that continent of study should be included as a moderator in cross-continental and cross-cultural studies of sleep in relation to age.

Associations among age and sleep were similar in studies that excluded individuals with mental health disorders, medical conditions, or sleep disorders compared to studies that did not evaluate, screen for, or exclude these populations. In contrast, a previous meta-analysis [5] found that the strength of the age-sleep association was stronger for studies that excluded individuals with mental health disorders, medical conditions, or sleep disorders. Their results suggested that these comorbidities may mask the effects of age on sleep across the lifespan. In contrast, the present results suggest that age-related differences in actigraphy-assessed sleep across the lifespan may not be a function of comorbidities. Discrepant results across studies may be a function of modality differences, as Ohayon and colleagues [5] evaluated studies using either polysomnography or actigraphy (13 effect sizes for actigraphy-assessed sleep duration). Alternatively, differences may be related to exclusion criteria at the level of the meta-analysis. Ohayon and colleagues [5] included all studies that evaluated the association between age and sleep, whereas we excluded articles at the title/abstract stage if there was no control group, as these studies would not allow for a direct evaluation of the impact of comorbidities. In both the Ohayon [5] meta-analysis and the present meta-analysis, comparison of age-sleep associations for specific conditions (e.g. depression) to controls was not possible, given the lack of published studies reporting results stratified by comorbidity.

Though all meta-analyses obtained 100% statistical power (determined by number of studies and sample sizes), it is

Table 5. Categorical moderators of meta-analytic associations of age and actigraphy-assessed sleep characteristics

	Sleep duration		Sleep efficiency		Bedtime, ages 6–21	
Moderators	*k*	ES [95% CI]	*k*	ES [95% CI]	*k*	ES [95% CI]
Continent		R^2 = 10%, p < .001		R^2 = 16%, p < .001		R^2 = 0%, p = .20
North America	53	−0.06 [−0.10, −0.02]	37	−0.006 [−0.06, 0.05]	8	Insufficient *N*
Europe	19	−0.13 [−0.22, −0.03]	9	Insufficient *N*	5	Insufficient *N*
Asia	7	Insufficient *N*	5	Insufficient *N*	0	Insufficient *N*
Exclusion criteria						
Mental health		R^2 = 4%, p = .05		R^2 = 0%, p = .57		R^2 = 15%, p = .008
Excluded	34	−0.20 [−0.30, −0.09]*	23	−0.08 [−0.22, 0.07]	7	Insufficient *N*
Included	55	−0.08 [−0.12, −0.03]	35	−0.04 [−0.08, 0.008]	12	0.22 [0.05, 0.38]
Medical		R^2 = 2%, p = .03		R^2 = 0%, p = .12		R^2 = 0%, p = .60
Excluded	41	−0.18 [−0.26, −0.09]*	33	−0.10 [−0.19, −0.005]*	8	Insufficient *N*
Included	48	−0.07 [−0.12, −0.02]	25	−0.01 [−0.07, 0.04]	11	0.32 [0.19, 0.44]*
Sleep disorders		R^2 = 2%, p = .09		R^2 = 0%, p = .61		R^2 = 0%, p = .23
Excluded	26	−0.19 [−0.28, −0.09]*	18	−0.03 [−0.13, 0.07]	8	Insufficient *N*
Included	63	−0.09 [−0.15, −0.04]*	40	−0.06 [−0.12, 0.001]	11	0.28 [0.06, 0.48]
Actigraphy device		R^2 = 0%, p = .34		R^2 = 0%, p = .39		R^2 = 0%, p = .91
Philips	37	−0.11 [−0.17, −0.04]	18	−0.12 [−0.22, −0.01]*	10	0.38 [0.22, 0.52]*
AMI	29	−0.17 [−0.27, −0.07]	25	−0.04 [−0.10, 0.03]	5	Insufficient *N*
ActiGraph	8	Insufficient *N*	3	Insufficient *N*	1	Insufficient *N*
Other	15	−0.05 [−0.15, 0.06]	12	−0.01 [−0.17, 0.15]	3	Insufficient *N*

k, number of effect sizes; ES, effect size, 95% CI, 95% confidence interval; R^2, variance explained in the meta-analytic effect size by the categorical moderator; AMI, Ambulatory Monitoring, Inc.
*p < .001, which is the Bonferroni-corrected threshold for significance.

Table 6. Continuous moderators of meta-analytic associations of age and actigraphy-assessed sleep characteristics

	Sleep duration				Sleep efficiency				Bedtime, ages 6–21		
Covariate	*k*	*B* (SE)	95% CI	R^2	*k*	*B* (SE)	95% CI	R^2	*k*	*B* (SE)	95% CI	R^2
Female	87	0.004 (0.001)	0.001, 0.006*	0%	57	0.003 (0.001)	0.001, 0.005	0%	19	0.005 (0.009)	−0.006, 0.02	0%
Mean Age	83	0.005 (0.009)	0.003, 0.007*	24%		−0.012 (0.005)	−0.02, −0.002	0%	16	−0.01 (0.02)	−0.05, 0.03	0%
Black	40	0.001 (0.002)	−0.003, 0.006	0%	27	0.001 (0.002)	−0.003, 0.005	0%	4	Insufficient *N*		
Hispanic	33	−0.002 (0.002)	−0.003, 0.003	0%	19	−0.001 (0.002)	−0.006, 0.004	0%	4	Insufficient *N*		
Asian	26	−0.001 (0.001)	−0.004, 0.002	0%	17	−0.002 (0.001)	−0.005, 0.001	12%	3	Insufficient *N*		
Non-Caucasian	47	−0.001 (0.001)	−0.003, 0.001	3%	37	−0.003 (0.001)	−0.005, −0.001	2%	7	Insufficient *N*		
Nights	82	−0.007 (0.006)	−0.02, 0.005	0%	55	−0.006 (0.009)	−0.02, 0.01	0%	18	0.04 (0.04)	−0.04, 0.11	1%

B (SE), unstandardized beta and standardized error; *k*, number of studies; R^2, total proportion of between-study variance explained by the model; CI, confidence interval; Non-Caucasian indicates the percentage of participants who are not Caucasian (Black, Hispanic, Asian, American Indian, or "minority" variously defined); Nights indicates number of nights of actigraphy.
*p < .001, which is the Bonferroni-corrected threshold for significance.

important to note that some of the meta-analyses are limited by the quality of the individual studies that were included. Previous conclusions from sleep clinical practice guidelines have similarly been tempered by the limitations of the extant literature. For example, the use of pharmacological therapy for adults with chronic insomnia disorder is quantified as a weak recommendation based on low-quality evidence [125]. As documented in the present study, the limited number of published longitudinal studies diminished the strength of the evidence regarding the association between age and sleep; though our requirement that greater than 70% of included studies be longitudinal for "greater design suitability" was a high threshold, we observed that only 0%–29% of included studies in our meta-analyses were longitudinal, which is certainly a minority of effect sizes.

Limitations and strengths

Limitations of the present study deserve consideration when evaluating the association between age and key sleep characteristics. First, lack of attention to the issue of age and sleep in published studies continues to limit our understanding of sleep across the lifespan. In the present study, limited published data regarding actigraphy-assessed sleep midpoint and regularity precluded meta-analytic evaluation of these important characteristics. Second, moderators (as well as confounders) have been overlooked in studies of age and sleep, which limited our ability to fully evaluate key putative moderators such as race/ethnicity, sex, and comorbidities. For example, approximately two-thirds of the studies evaluated in the present meta-analysis provided no detail regarding screening for comorbidities. While increasing the generalizability of the present findings, the lack of detail regarding comorbidities limits understanding of the extent to which comorbidities influence the age-sleep link. A greater understanding of the extent to which these factors influence sleep across the lifespan is important both to fundamental questions about sleep and well as the identification of risk factors for and treatment of disturbed sleep. Third, we were limited to the published data available.

Table 7. Quality of the evidence for meta-analyses of age and actigraphy-assessed sleep

	Sleep duration	Sleep efficiency	Bedtime, ages 6–24	Bedtime, ages 60 and older	Wake-up time, ages 6–24	Wake-up time, ages 60 and older
Execution						
Study well-described, %	85.9	86.8	80.0	85.7	85.7	85.7
Specified screening criteria, %	67.9	75.5	66.7	85.7	71.4	100.0
≥7 days data, %	52.6	62.3	53.3	85.7	71.4	85.7
<10% missingness, %	33.3	34.0	53.3	14.3	57.1	14.3
Good, fair, or limited execution	*Limited*	*Fair*	*Fair*	*Fair*	*Fair*	*Fair*
Design suitability						
Longitudinal studies, %	1.3	0	20	0	28.6	0
Cross-sectional studies, %	98.7	100	80	100	71.4	100
Greater or lesser suitability	*Lesser*	*Lesser*	*Lesser*	*Lesser*	*Lesser*	*Lesser*
Number of studies	89	58	20	6	10	6
At least 2, 3, or 5	*At least 5*	*At least 5*	*At least 5*	*At least 5*	*At least 5*	*At least 5*
Consistency						
Negative associations, %	44.9	39.6	13.3	71.4	28.6	85.7
Neutral associations (–0.10, + 0.10), %	34.8	30.2	6.7	28.6	14.3	0.0
Positive associations, %	20.0	30.2	80.0	0.0	57.1	14.3
Consistent or inconsistent	*Inconsistent*	*Inconsistent*	*Consistent*	*Consistent*	*Inconsistent*	*Consistent*
Effect size, Pearson's *r*	–0.12	–0.05	0.35	–0.66	0.24	–0.59
Small, sufficient, or large	*Small*	*Small*	*Sufficient*	*Large*	*Small*	*Large*
Evidence of association						
Strong, sufficient, or insufficient	*Insufficient*	*Insufficient*	*Sufficient*	*Sufficient*	*Insufficient*	*Sufficient*

This means that we were unable to characterize age-sleep associations across the full lifespan because published data were not available for each decade of life and/or each actigraphy-assessed sleep outcome. This limitation was especially evident for sleep timing outcomes, with no studies available for individuals aged 30 to 60 and too few effect sizes to precisely capture the age at which sleep timing profiles shift from delay to advances. Additionally, across individual studies there were inconsistencies in the direction of the association between age and all sleep characteristics, and this was especially pronounced for the associations among age and sleep duration and sleep efficiency. These inconsistencies resulted in smaller meta-analytic effect sizes as well as a lower quality of evidence for the individual studies.

Finally, associations of age and actigraphy-assessed sleep across the lifespan were based primarily on between- versus within-persons analyses due to the limited number of longitudinal sleep studies and the absence of consortia organized to support aggregation, harmonization, and evaluation of individual-level data across studies. Reliance on study- versus individual-level data may obscure our understanding of changes in sleep characteristics across the lifespan due to the influence of study characteristics (e.g. sample selection) on measurement error. Notably, recent comparisons of the performance of meta-analysis compared to individual-patient data show comparable magnitude and direction of effects, which provides greater confidence in the results of the current report [126, 127].

These limitations are offset by several notable strengths. This is the first meta-analysis to evaluate the association of age and key indices of actigraphy-assessed sleep, including duration, efficiency, and timing in studies of children and adults. The present meta-analytic approach affords the opportunity to systematically and quantitatively assess actigraphy data from 23,365 participants ages 6–92. Evaluation of actigraphy-assessed sleep is important given its superior ability to measure sleep over a greater number of days and circumstances compared to polysomnography-assessed sleep. Moreover, the present meta-analysis was pre-registered on PROSPERO, allowing for increased transparency of aims, a priori hypotheses, and study design, thereby enhancing reproducibility. We systematically searched for articles with the assistance of a highly experienced medical librarian, and we used a software for screening articles designed for systematic reviews and meta-analyses (DistillerSR). Clear selection criteria were identified and implemented according to state-of-science methods. Two independent raters conducted title/abstract review and data extraction, with a third independent rater to resolve any discrepancies. Planned evaluation of methods demonstrated good inter-rater reliability. Finally, we evaluated a variety of demographic and methodological moderators chosen for their relevance for research and/or clinical questions.

Conclusion

There are age-related differences in actigraphy-assessed sleep across the lifespan. Actigraphy-assessed sleep duration is shorter and efficiency is lower at older ages, but the effect sizes are small. In contrast, patterns in sleep timing, including bedtime and wake time, differ as a function of age group with small to large effect sizes. Among individuals between 6 and 21 years of age, older age is associated with earlier bed- and wake times, whereas older age is associated with later bed- and wake times in those 22 years of age and older. Moderation analyses suggest that associations among age and actigraphy-assessed sleep may differ as a function of study continent (North America, Asia, or Europe) but are not related to comorbidities, sex, race/ethnicity, number of study nights, or device type, although these results should be interpreted with caution given limitations to the extant literature. Changes in sleep timing, rather than indices of sleep duration

or efficiency, may be the most robust hallmark marker of age effects on actigraphy-assessed sleep.

Supplementary material

Supplementary material is available at *SLEEP* online.

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Conflict of interest statement. Dr. Buysse has served as a paid consultant to Bayer, BeHealth Solutions, Cereve/Ebb Therapeutics, Emmi Solutions, National Cancer Institute, Pear Therapeutics, Philips Respironics, Sleep Number, and Weight Watchers International. He has served as a paid consultant for professional educational programs developed by the American Academy of Physician Assistants and CME Institute, and received payment for a professional education program sponsored by Eisai (content developed exclusively by Dr. Buysse). Dr. Buysse is an author of the Pittsburgh Sleep Quality Index, Pittsburgh Sleep Quality Index Addendum for PTSD (PSQI-A), Brief Pittsburgh Sleep Quality Index (B-PSQI), Daytime Insomnia Symptoms Scale, Pittsburgh Sleep Diary, Insomnia Symptom Questionnaire, and RU_SATED (copyright held by University of Pittsburgh). These instruments have been licensed to commercial entities for fees. He is also co-author of the Consensus Sleep Diary (copyright held by Ryerson University), which is licensed to commercial entities for a fee. Dr. Hall has served as a paid consultant to Eisai and is an author of the Insomnia Symptom questionnaire, what has been licensed to commercial entities for fees. We have no non-financial conflicts of interest to disclose.

Data Availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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