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REGULAR ARTICLE

The Cycle of Daily Stress and Sleep: Sleep Measurement Matters

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Abstract

Background Disturbed sleep can be a cause and a consequence of elevated stress. Yet intensive longitudinal studies have revealed that sleep assessed via diaries and actigraphy is inconsistently associated with daily stress.

Purpose We expanded this research by examining daily associations between sleep and stress using a threefold approach to assess sleep: sleep diaries, actigraphy, and ambulatory single-channel electroencephalography (EEG).

Methods Participants were 80 adults (mean age = 32.65 years, 63% female) who completed 7 days of stressor and sleep assessments. Multilevel models were used to examine bidirectional associations between occurrence and severity of daily stress with diary-, actigraphy-, and EEG-determined sleep parameters (e.g., total sleep time [TST], sleep efficiency, and sleep onset latency, and wake after sleep onset [WASO]).

Results Participants reported at least one stressor 37% of days. Days with a stressor were associated with a 14.4-min reduction in actigraphy-determined TST ($\beta = -0.24$, $p = 0.030$), but not with other actigraphy, diary, or EEG sleep measures. Nights with greater sleep diary-determined WASO were associated with greater next-day stressor severity ($\beta = 0.01$, $p = 0.026$); no other diary, actigraphy, or EEG sleep measures were associated with next-day stressor occurrence or severity.

Conclusions Daily stress and sleep disturbances occurred in a bidirectional fashion, though specific results varied by sleep measurement technique and sleep parameter. Together, our results highlight that the type of sleep measurement matters for examining associations with daily stress. We urge future researchers to treat sleep diaries, actigraphy, and EEG as complementary—not redundant—sleep measurement approaches.

Keywords: Electroencephalography · Stress · Actigraphy · Sleep diary · Longitudinal · Repeated measures

Daily experiences of stress and nightly sleep are closely linked. Elevated stress during the day may lead to rumination and hyperarousal that makes falling asleep, staying asleep, and obtaining good-quality sleep more difficult [1–4]. Conversely, nightly sleep loss or discontinuity may amplify negative perceptions of stress, prolong stress reactivity and recovery, dampen one's ability to cope with stress, or serve as a stressor itself [5, 6]. Indeed, many studies have shown that people reporting stress are more likely to report sleep disturbances and vice versa [7, 8].

Multiple theoretical models have been proposed to explain the complex interactions between stress and sleep disturbances. For example, the stress–diathesis and "three-factor" behavioral model of insomnia state that stress may be a precipitating factor that interacts with predisposing (e.g., personality) and perpetuating factors (e.g., stimulus control) to predict the onset and maintenance of disturbed sleep duration, timing, and efficiency [7–9]. Similarly, the cognitive model of insomnia states that sleep-related worries and excessive negatively toned cognitions increase arousal, which interferes with sleep initiation and maintenance [10]. This fear of sleep loss

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or sleep loss itself may exacerbate stress perceptions [10]. Physiologically, both the stress response and sleep loss and fragmentation activate the sympatho-adrenomedullary system and hypothalamic–pituitary–adrenal (HPA) axis [11, 12]. Activation of these systems, in turn, influences cardiovascular, catecholamine, cortisol, and inflammatory cytokine outputs and may result in a potentially toxic feedback loop between stress and sleep disturbances [11, 12].

Intensive longitudinal studies have confirmed that days with greater stress are associated with subsequent impairments in sleep and vice versa (e.g., [13–17]]. However, empirical results for daily stress and sleep appear to vary based on whether sleep is assessed using self-report (i.e., sleep diaries), inferred methods (i.e., actigraphy), or objective (i.e., polysomnography [PSG]) measures. Most daily longitudinal studies of stress and sleep have relied solely on self-report or inferred methods (e.g., [14, 16–19]), which may not comprehensively assess sleep. With recent advances in noninvasive sleep measurement devices, research is needed to understand bidirectional associations between daily stress and more direct measures of sleep, as well as how these results may contrast with the standard methods used to naturalistically assess sleep. This study built on previous literature by examining how daily stress is bidirectionally associated with sleep assessed via three simultaneous ambulatory methods: diaries, actigraphy, and a single-channel electroencephalography (EEG) device.

Ambulatory studies, which assess individuals in their everyday environments using noninvasive methods, are ideal for examining how daily processes unfold across time. Such studies enhance the ecological validity of results and allow for examination of both person-to-person variation, as well as within-person variation across time. Yet ambulatory studies of daily stress and sleep have revealed inconsistent associations. Typically, ambulatory studies measure sleep using self-report sleep diaries [20] and/or actigraphy [21]. Sleep diaries are the gold standard of subjective sleep measurement and capture an individuals' perception of their sleep/wake cycle [20]. Actigraphy is a wrist-worn accelerometer that captures motion, as well as light, to determine sleep/wake and is considered an inferred behavioral measure of sleep [21]. Both sleep diaries and actigraphy are important ways to measure sleep but capture distinct information. Sleep diaries capture an individual's reduction in perceptual awareness and mental activity, whereas actigraphy reflects behavioral quiescence [22]. In general, evidence from ambulatory studies using sleep diaries and actigraphy supports that stress and sleep are bidirectionally associated; however, findings appear to be dependent on how sleep is assessed (i.e., via self-report or actigraphy).

Daily Stress and Self-Reported Sleep

In some ambulatory within-person studies, higher levels of daily stress have been associated with poorer self-reported nightly sleep quality and shorter self-reported total sleep time (TST) [13, 17, 23, 24]. For example, in one study [17], every 1 unit increase in evening perceived stress (on a 0 to 10 scale) was associated with a 3 min decrease in self-reported TST. However, two other studies reported null associations between daily stressor occurrence or severity with subsequent self-reported sleep [14, 16]. When examining reverse pathways from sleep to next-day stress, three studies have shown that nights with poorer sleep quality, lower sleep efficiency (SE), or shorter sleep duration are associated with greater odds of experiencing a stressor or greater stress severity the next day [14, 16, 17]. Together, this body of research suggests that sleep diary-determined sleep appears to be bidirectionally associated with daily stress, although findings vary by specific sleep parameters.

Daily Stress and Actigraphy-Determined Sleep

Daily stress has also been inconsistently associated with actigraphy-determined sleep parameters. A few studies have shown that greater daily stress severity is associated with shorter actigraphy-determined TST that night [17, 19, 24]. Yet, in one study of healthy women, greater daily stress frequency and severity were associated with higher actigraphy SE (i.e., TST divided by time in bed [TIB] × 100) [18]. When looking at reverse pathways, two studies examining actigraphy-determined sleep parameters on next-day stress severity found that greater SE and shorter TST were associated with higher next-day stress severity [17, 19]. Together, this research demonstrates that the association between actigraphy-determined sleep and daily stress appears to be bidirectionally associated, but—like findings with sleep diaries—there is inconsistency in results across specific sleep parameters.

The Potential of Single-Channel EEG

Overall, findings from ambulatory actigraphy and sleep diary studies suggest associations between stress and sleep vary not only by how sleep is measured (diary vs. actigraphy) but also by specific sleep parameter (e.g., TST vs. SE vs. sleep quality) and the directionality of effects (i.e., stress to sleep or sleep to stress). Yet, few studies use both sleep diaries and actigraphy, and neither sleep diaries nor actigraphy allow for the determination of sleep staging (e.g., slow-wave sleep [SWS] or rapid eye movement [REM] sleep). Single-channel EEG devices

can capture sleep staging over the course of multiple nights, maintaining considerable ecological validity and limiting participant burden.

To our knowledge, only two studies have examined associations between stress and sleep in an ambulatory setting using EEG or PSG measures [25, 26]. Petersen et al. [26] found that individuals in a high work stress condition had lower SE as determined from one night of in-home PSG. Similarly, Mezick et al. [25] found that stressful life events were associated with increased nightly variability in TST and sleep fragmentation. However, both studies only assessed recent stressors or stressful life events and PSG sleep across one or two nights, which may not generalize to an individual's everyday experience of stress and sleep. Use of an EEG measure of sleep and daily stress assessed across multiple days may help supplement results from prior studies that have relied primarily on sleep diary- or actigraphy-assessed sleep.

The Current Study

Given numerous theoretical models on stress and sleep and inconsistencies in daily stress and sleep findings, we sought to clarify previous research using a threefold approach to assess sleep. Specifically, we examined whether daily stressor occurrence and severity predicted that night's sleep diary-, actigraphy-, and single-channel EEG-determined sleep and whether these same sleep parameters predicted next-day stressor occurrence and severity. We hypothesized that days when a stressor occurred and days with greater stressor severity than an individual's average would be associated with shorter TST, lower SE, longer sleep onset latency (SOL), more wake after sleep onset (WASO), less REM sleep, and less SWS. We also hypothesized that nights with shorter TST, lower SE, longer SOL, less REM sleep, and less SWS than an individual's average would be associated with greater odds of experiencing a next-day stressor and greater stressor severity. Together, these results will strengthen the inferences of causality between stress and sleep in daily life and clarify how results may vary by sleep measurement modality.

Method

Participants

Participants were recruited from the surrounding campus and community area using a combination of emails, flyers, and list servs. Recruitment materials directed interested individuals to an informed consent and a brief online screening survey that assessed the following inclusion criteria: (a) willingness to participate for at least 7 days, (b) ability to travel to the research lab, (c) English language fluency, (d) over the age of 18, (e) had a phone number at which they could be regularly reached, and (f) had regular (daily) internet and personal email access. The only exclusion criterion was having a pacemaker, cardiac defibrillator, or other medical electronic device which would interfere with the EEG device. Initially, 120 people expressed interest in the study. One-hundred and one participants completed the screening questionnaire, and 87 completed the baseline questionnaire. A total of 81 participants attended the first lab appointment and completed some measures, and a final 80 participants were included in the current analyses (1 person was removed due to missing EEG data). Most participants were female, non-Hispanic White, married or in a relationship, well-educated, and employed full time (Table 1).

Procedures

All procedures were approved by the affiliated institution's institutional review board prior to the start of data collection. Informed consent was obtained from all participants included in the study. After completing the brief screening measure, eligible participants were contacted via email and given the opportunity to complete the baseline measures online at home via a secure online data collection tool (REDCap) [27]. Participants were then scheduled for their first in-person appointment in the sleep laboratory, where they were trained in study procedures. Participants were trained to use the Zmachine, an ambulatory EEG data collection device, via manufacturer-provided videos and hands-on demonstration. Participants were also trained in the use of actigraphy via verbal instruction from the research assistants and hands-on demonstration. Participants were trained in the use of daily sleep and stress diaries via a sample survey sent to their internet-enabled device and hands-on demonstration. Participants and research assistants mutually chose a time for participants to receive the first survey reminder each morning of the study (typically within the first hour of their expected wake time). Participants were then given a Zmachine, actigraph, paper diaries (in case of website malfunction), and written instructions for all items.

Participants used the Zmachine, actigraph, and sleep/stress diary in their typical environment for 7 days. Each morning, participants received a link for the sleep diary via email, and then received up to two additional reminders at 3 hr intervals if they did not complete the sleep diary. Additionally, if they had not completed the diary by noon, research assistants messaged the participants to remind them to complete it. The compensation offered for participation in the study was (a) $20, (b) a comprehensive report of the participant's sleep over the study duration and sleep disorders resources, and (c) a decorative magnet.

Table 1. Participant characteristics

	M or *n*	*SD* or %	Amount of between-person variation	Amount of within-person variation
Age	32.65	10.07	–	–
Gender	50	62.5% female	–	–
Race	71	88.8% White	–	–
Ethnicity	71	88.8% non-Hispanic/Latinx	–	–
Married	33	41.3% married	–	–
Employment status	49	61.3% working full time	–	–
Education (years)	16.81	2.26	–	–
EEG TST (min.)	381.14	73.73	20%	80%
EEG SE (%)	82.57	8.77	46%	52%
EEG SOL (min.)	30.73	29.50	43%	57%
EEG WASO (min.)	43.75	43.86	22%	78%
EEG REM (min.)	93.56	41.84	39%	61%
EEG SWS (min.)	83.57	29.66	48%	52%
Acti TST (min.)	387.06	73.90	32%	68%
Acti SE (%)	83.01	7.18	41%	59%
Acti SOL (min.)	13.72	15.33	28%	72%
Acti WASO (min.)	46.55	23.92	50%	50%
Diary TST (min.)	405.91	90.54	24%	76%
Diary SE (%)	86.63	13.84	22%	78%
Diary SOL (min.)	20.70	29.65	38%	62%
Diary WASO (min.)	15.01	17.50	22%	78%
Daily stressor frequency	0.57	0.57	31%	69%
Daily stressor severity	1.65	0.49	1%	99%

Acti actigraphy; *Diary* sleep diary; *EEG* electroencephalogram; *REM* rapid eye movement sleep (in minutes); *SD* standard deviation; *SE* sleep efficiency (TST/time in bed × 100); *SOL* sleep onset latency (in minutes); *SWS* slow wave sleep (in minutes); *TST* total sleep time (in minutes); *WASO* wake after sleep onset (in minutes).

Measures

Sleep diaries

An electronic version of the Consensus Sleep Diary [20] was used to prospectively assess self-reported sleep each day. Upon awakening, participants were asked to provide an estimate of their sleep the previous night (e.g., bedtime, SOL, WASO, terminal wakefulness [TWAK], and rise time). From these variables, TST was calculated by subtracting total wake time (SOL + WASO + TWAK) from TIB (interval between bedtime and rise time). SE was calculated by taking TST and dividing by TIB and multiplying by 100. Sleep diary parameters have been shown to correlate moderately well with both PSG and actigraphy in clinical and healthy samples [28–30]. Sleep diaries were collected using electronic data capture software (REDCap) [27].

Actigraphy

Actigraphs are wrist-worn, watch-like devices that prospectively capture light exposure and contain an accelerometer to capture motion as a proxy for activity. In the current study, Philips Respironics Actiwatch Spectrum devices were used, and data were analyzed with Respironics Actiware version 6.0.1. Data were scored by two trained scorers using a previously validated scoring hierarchy that relied on a combination of event markers, sleep diaries, light levels, and activity levels [30, 31]. Briefly, if participants provided event markers that matched sleep diary bed and rise times within 30 min, event marker bed and rise times were used. If event markers and sleep diary times were >30 min discrepant, activity and light levels were used to confirm whether event markers corresponded to an approximate 50% reduction in light and activity levels. If event markers matched light and activity data within 30 min, event markers were used. If they did not match or if event markers were missing, but diaries matched activity- and light-level reductions within 30 min, diary bed and rise times were used. If diaries and activity- and light-level reductions were >30 min discrepant, light and activity levels were used. Using this scoring hierarchy, the initial percentage agreement between the two scorers

was 94.8%, suggesting high interrater reliability. All discrepancies were resolved by an expert third scorer [initials redacted for review]. Settings used for data export in Actiware were the following: low threshold (activity count: 10) and 20 epochs inactivity for sleep onset/offset. Actiware uses a proprietary algorithm to analyze activity and estimate sleep parameters based on the scored data and data export settings [21].

Electroencephalography

The Zmachine Insight is an ambulatory device manufactured by General Sleep, Inc. (Cleveland, OH) that processes a single channel of EEG data using information from two electrodes placed behind each ear (i.e., at the mastoid) and one ground electrode placed on the neck (i.e., a reference electrode that allows for conduction of signals). The Zmachine electrodes are single use and were self-applied by the participant 30 or more minutes prior to bedtime. The Zmachine is capable of differentiating between wake, light sleep (stages N1 and N2), deep sleep (stage N3), and REM sleep [32]. A previous study has shown that the sensitivity and specificity for detecting sleep using the Zmachine algorithm (compared to a PSG technologist) are 95.5% and 92.5%, respectively, indicating that the Zmachine can accurately discriminate between time asleep and time awake [32]. Data for the current study were scored using manufacturer-provided firmware (version 5.0), and Data Viewer software (version 3.5.0) was used to display sleep parameter results. Two independent reviewers reviewed all data and scored as good, bad, or unknown. A third reviewer then checked concordance and made a final determination for any discrepancies.

Daily stressor occurrence and severity

In the morning survey, participants reported on the frequency and severity of seven different stressors they experienced the previous day using a modified version of the Daily Inventory of Stressful Experiences (DISE) [33]. Previous studies have shown that the full DISE has good reliability and validity [33]. For the current study, participants reported whether they experienced seven types of stressors: (a) an argument or disagreement with anyone, (b) events that could have turned into an argument but that they decided to let pass in order to avoid a disagreement, (c) events at work or school most people would consider stressful, (d) events at home that most people would consider stressful, (e) discrimination on the basis of reasons such as race, sex, or age, (f) events that happened to a close friend or relative that turned out to be stressful for the respondent, and (g) any other event that most people would consider stressful. If participants answered "yes" to any of these questions, they were then prompted to rate how stressful each event was using a scale of 0 (not at all) to 3 (very). When individuals did not experience a particular stressor, they were not prompted to rate stressor severity. To calculate daily *stressor occurrence*, if participants reported experiencing *any* of the seven possible stressors that day, stressor occurrence was coded as 1; if they reported experiencing none of the seven stressors, stressor occurrence was coded as a 0. This dichotomous approach was adopted in alignment with previous daily stress research, which suggests that most people report either one or no stressors each day (with at least one stressor occurring about 36%–54% of days and multiple stressors only occurring about 11%–33% of days) [14, 33, 34]. To calculate daily *stressor severity*, stressfulness ratings were averaged for any of the stressors the participants reported experiencing that day. Due to a survey programming malfunction, a small random subset of participants (n = 18, across 54 days, or <1% of the 554 sleep diary days) did not receive stressor severity items on days they reported a stressor occurrence. However, examination of these data revealed it appeared to be missing completely at random; therefore, it was unlikely to bias results.

Statistical analysis plan

All analyses were conducted in the open-source statistical program R [35]. Multilevel models were conducted using the R package *nlme* [36] and tables were created using the R package *sjPlot* [37]. For all multilevel models, Level 1 days were nested within Level 2 people. Logistic multilevel models were used when the outcome was odds of stressor occurrence. All Level 1 continuous independent variables were person-mean centered so that values represented deviations from an individual's average taken across all 7 days. Restricted maximum likelihood (REML) techniques were used. REML is comparable to full information maximum likelihood techniques, which are considered one of the most robust methods for handling missing data, as all available information is used to estimate the model [38]. Intercepts were allowed to vary randomly across people. Models used an autoregressive 1 covariance matrix to account for the expectation that the variance of measurements taken closer in time would be more strongly associated. All models controlled for day of the week (weekday = 0 and weekend = 1), gender (0 = male and 1 = female), and age, given previous studies showing robust differences in sleep by these variables [39–41]. For analyses examining sleep predicting subsequent stress, stress data were lagged back 1 day (as stress was reported in the morning, reflecting on stress experienced the previous day). For analyses examining stress predicting subsequent sleep, data were not lagged (as previous day's stress and previous night's sleep were reported simultaneously).

Results

Descriptive Results

Rates of missing data were relatively low across all measures. Data collection resulted in 554 usable sleep diaries out of a possible 560 sleep diaries (i.e., 7 days × 80 participants) for a diary compliance rate of 99%. Only three stressor occurrence observations were missing (0.5% missing data). Participants provided 531 usable days of actigraphy data (95% useable data from the total possible 560 observations) and 482 usable days of EEG data (86% useable data from the total possible 560 observations).

Participants had an average EEG-determined TST of 6.35 hr (standard deviation [*SD*] = 1.23), an average actigraphy-determined TST of 6.45 hr (*SD* = 1.23), and an average sleep diary-determined TST of 6.77 hr (*SD* = 1.51; Table 1). Participants had an average EEG-determined SE of 82.57% (*SD* = 8.77), an average actigraphy-determined SE of 83.01% (*SD* = 7.18), and an average sleep diary-determined SE of 86.63% (*SD* = 13.84; Table 1). Sleep parameters were correlated at the within-person level (i.e., when examining within-person, daily deviations from each person's mean score) across the three sleep measurement techniques (e.g., $r = 0.71$ to 0.79 for TST; $r = 0.28$ to 0.42 for SE; $r = 0.40$ to 0.44 for SOL).

Participants reported at least one stressor on 37% of the days (one stressor 23% of all days, two stressors 10% of all days, and three or more stressors 4% of all days). Participants reported an average of 0.57 (*SD* = 0.57, range = 0 to 5, and median = 0.43) stressors per day (out of seven possible stressors). Average stressor severity was relatively low (mean = 1.65 and median = 1.75, out of possible scores of 3), with little variation (*SD* = 0.49). The three most common stressors individuals reported experiencing were: (a) avoiding arguments, (b) a stressor at home, and (c) an argument or disagreement. Examination of intraclass correlation coefficients revealed that, for all sleep parameters and stress variables, more variation existed at the within-person (i.e., day-to-day) level than the between-person (i.e., person-to-person) level (Table 1).

Sleep Diary Results

Supplementary Material display tables of results that were not statistically significant across all sleep parameters. Daily stressor occurrence was not associated with sleep diary-determined TST, SE, WASO, or SOL (Supplementary Table S1). Daily stressor severity also was not associated with sleep diary-determined TST, SE, WASO, or SOL (Supplementary Table S2). When examining reverse pathways, sleep diary-determined TST, SE, WASO, and SOL were not associated with odds of experiencing a next-day stressor (Supplementary Table S3). Nights with greater sleep diary-determined WASO were associated with greater next-day stressor severity ($\beta = 0.01$, 95% confidence interval [CI]: 0.00 to 0.01, $p = 0.024$; Table 2). Nightly TST, SE, and SOL were not associated with next-day stressor severity (Table 2).

Actigraphy Results

Days with a stressor reported were associated with a 14.4 min reduction in actigraphy-determined TST ($\beta = -0.24$, 95% CI: −0.45 to −0.02, $p = 0.030$; Table 3; i.e., −0.24 slope multiplied by 60 min [as TST was in hours] = 14.4 min reduction). Daily stressor occurrence was not associated with actigraphy-determined SE, WASO, or SOL (Table 3). Daily stressor severity was not associated with actigraphy-determined TST, SE, WASO, or SOL (Supplementary Table S4). When examining reverse pathways, actigraphy-determined TST, SE, WASO, and SOL were not associated with odds of experiencing a next-day stressor (Supplementary Table S5). Nightly actigraphy-determined TST, SE, WASO, and SOL were not associated with next-day stressor severity (Supplementary Table S6).

EEG Results

Daily stressor occurrence was not associated with EEG-determined TST, SE, SOL, WASO, REM sleep, or SWS (Supplementary Table S7). Daily stressor severity also was not associated with EEG-determined TST, SE, SOL, WASO, REM sleep, or SWS (Supplementary Table S8). When examining reverse pathways, EEG-determined TST, SE, REM sleep, SWS, WASO, and SOL were not associated with odds of experiencing a next-day stressor (Supplementary Table S9). EEG-determined TST, SE, REM sleep, SWS, WASO, and SOL also were not associated with next-day stressor severity (Supplementary Table S10).

Discussion

Previous research on daily stress and sleep has largely not addressed how the type of sleep assessment may impact results. To our knowledge, this was the first study to examine the daily bidirectional associations between stress and multiple sleep parameters measured via sleep diary, actigraphy, and single-channel EEG. We expanded on previous literature by incorporating the assessment of objective sleep using a noninvasive single-channel EEG device that participants were able to wear in their everyday environments across multiple days, enhancing

Table 2. Sleep-diary-determined sleep predicting next-day stressor severity

	Next-day stressor severity		
Predictors	*β*	95% CI	*p*
(Intercept)	1.72	1.49 to 1.95	**<.001**
Total sleep time	0.04	−0.07 to 0.16	.459
Age	0.01	−0.01 to 0.02	.398
Gender	0.10	−0.16 to 0.36	.448
Weekday	−0.08	−0.32 to 0.16	.500
Random effects			
σ^2	0.38		
$\tau_{00\ id}$	0.02		
N_{id}	52		
Observations	128		
(Intercept)	1.72	1.48 to 1.96	**<.001**
Sleep efficiency	−0.00	−0.03 to 0.02	.742
Age	0.01	−0.01 to 0.02	.379
Gender	0.09	−0.17 to 0.35	.479
Weekday	−0.06	−0.30 to 0.17	.594
Random effects			
σ^2	0.38		
$\tau_{00\ id}$	0.03		
N_{id}	52		
Observations	128		
(Intercept)	1.73	1.49 to 1.96	**<.001**
Wake after sleep onset	0.01	0.00 to 0.01	**.026**
Age	0.01	−0.01 to 0.02	.306
Gender	0.08	−0.18 to 0.34	.537
Weekday	−0.07	−0.30 to 0.16	.531
Random effects			
σ^2	0.36		
$\tau_{00\ id}$	0.03		
N_{id}	52		
Observations	128		
(Intercept)	1.72	1.49 to 1.95	**<.001**
Sleep onset latency	−0.01	−0.02 to 0.00	.305
Age	0.01	−0.01 to 0.02	.381
Gender	0.10	−0.15 to 0.36	.429
Weekday	−0.09	−0.33 to 0.15	.456
Random effects			
σ^2	0.38		
$\tau_{00\ id}$	0.02		
N_{id}	52		
Observations	128		

Table denotes unstandardized *β* weights for predictors. Bold values indicate $p < .05$ significant effects. 95% CI = 95% confidence intervals for each predictor. σ^2 represents Level 1 variance (within person), τ_{00} represents Level 2 variance (between person). Day of the week is coded as 0 = weekday, 1 = weekend. Gender is coded as 0 = male, 1 = female. Each block in the table represents a separate regression model.

the ecological validity of findings. As expected, our results suggested that days when a stressor was reported were associated with shorter actigraphy-determined TST that night. Nights with greater sleep diary-determined WASO also were associated with greater perceived stressor severity the next day. Daily stress was not associated with any single-channel EEG-determined sleep parameters or vice versa. Overall, although stress and sleep disturbances may occur in a bidirectional fashion, results may vary by specific sleep measurement technique, sleep parameter, and directionality of results. Together, these results highlight that careful attention must be paid to sleep measurement when examining associations with daily stressor occurrence and severity.

Daily Stress Predicting Nightly Sleep

In alignment with previous research, we found that days when a stressor was reported were associated shorter actigraphy-determined TST that night. Stressors were reported relatively frequently—approximately 37% of the days. This maps onto findings from previous studies showing that stressors occur approximately 36%–54% of days [14, 33, 34]. Compared to days when no stressors were reported, on days with a stressor, there was a 14.4 reduction in actigraphy-determined TST. It is possible that these effects may represent a noticeable degradation of sleep for some individuals. Psychologically, exposure to daily stressors may amplify feelings of arousal (via activation of the HPA axis and sympathetic nervous system) or increase negative emotions and ruminative thought, which makes the act of sleeping more challenging [2]. During stressful times, individuals also may have more to do and behaviorally truncate their sleep window to cope. Overall, our results support findings from a few other studies showing that daily stress is associated with subsequent impairments in actigraphy-determined TST [17, 24]. Interestingly, in contrast to other studies [13, 17, 24], we did not find that heightened daily stress was associated with disturbances in other diary- or actigraphy-determined sleep parameters (e.g., WASO, SOL, and SE).

Nightly Sleep Predicting Next-Day Stress

When examining reverse pathways from sleep to next-day stress, we found that greater sleep diary-determined WASO was associated with a greater perceived severity of stressors the next day. This matches findings from one other study, which showed that greater self-reported WASO was associated with more stress the next day [17]. It is possible that perceived nighttime wakefulness could impair next-day mood or interpersonal relationships, which, in turn, makes stressors

Table 3. Daily stressor occurrence predicting actigraphy-determined sleep

	Total sleep time (hr)			Sleep efficiency (%)			Wake after sleep onset (min)			Sleep onset latency (min)		
Predictors	*β*	95% CI	*p*	*β*	95% CI	*p*	*β*	95% CI	*p*	*β*	95% CI	*p*
(Intercept)	6.09	5.76 to 6.42	**<.001**	80.80	78.66 to 82.94	**<.001**	50.23	42.29 to 58.17	**<.001**	16.33	11.37 to 21.30	**<.001**
Stress occurrence	−0.24	−0.45 to −0.02	**.030**	−1.27	−2.57 to 0.02	.054	−0.69	−4.65 to 3.27	.733	0.70	−2.53 to 3.93	.671
Age	0.01	−0.02 to 0.03	.633	0.18	0.04 to 0.31	**.011**	−0.15	−0.66 to 0.35	.542	−0.14	−0.45 to 0.17	.366
Gender	0.37	−0.03 to 0.78	.071	2.12	−0.49 to 4.73	.109	−3.51	−13.27 to 6.26	.477	2.07	−3.95 to 8.10	.495
Weekday	0.38	0.18 to 0.58	**<.001**	0.44	−0.78 to 1.65	.478	2.75	−1.16 to 6.66	.168	−3.27	−6.13 to −0.41	**.025**
Random effects												
σ^2	1.09			39.63			433.84			267.94		
$\tau_{00\ id}$	0.56			22.95			307.30			129.65		
N_{id}	75			75			76			76		
Observations	523			523			530			530		

Table denotes unstandardized *β* weights for predictors. Bold values indicate $p < .05$ significant effects. 95% CI = 95% confidence intervals for each predictor. σ^2 represents Level 1 variance (within person), τ_{00} represents Level 2 variance (between person). Day of the week is coded as 0 = weekday, 1 = weekend. Gender is coded as 0 = male, 1 = female.

seem more severe. Indeed, experimental studies have shown that more fragmented sleep and more nighttime awakenings are associated with poorer next-day mood [42, 43].

Unlike findings from other studies, we did not find that any other sleep diary- and actigraphy-determined sleep parameters (e.g., TST and SE) were associated with next-day stress [14, 17, 19]. Although most of our findings were null, it is important to note that we did run multiple analyses, which may have increased our chances of making a Type 1 error. Future studies should seek to replicate our results using similar methodology in other samples. It is possible that we did not observe many associations between sleep and next-day stress due to the lag between when these measures were assessed. For analyses examining sleep predicting subsequent stress, stress data were reported 1 day later and lagged back a day (as stress reports reflected stress experienced the previous day). This means that there may have been up to 24 hr between when these sleep and stress measures were assessed or reported. Multiple confounding behaviors could have occurred during this time (e.g., substance use and physical activity). Ideally, future studies would assess stress at multiple times throughout the day (e.g., morning, midday, and evening) to avoid this long lag between measurement occasions.

Explanations for Null Results with EEG Sleep

No EEG-determined sleep parameters were associated with daily stressor occurrence or severity or vice versa. There are several potential explanations for these null results. First, there is now consensus that objective, inferred, and self-report measures of sleep may capture equally important yet partially distinct domains of sleep, including the physiological transition, behavioral quiescence, and reduction in perceptual awareness, respectively [22, 30, 44]. Each of these measures may provide unique information with distinct benefits and limitations, and each may be differentially associated with stress. Researchers should seek to incorporate all measures whenever possible to provide a holistic assessment of sleep.

Second, our sample reported a slightly lower severity and frequency of daily stress (at least one stressor only 37% of days, with an average stressor severity of 1.65 out of 3) compared to other studies [14, 34], which may have led to a restriction of range in stressor frequency and severity values. In samples of individuals experiencing greater levels of stress (e.g., caregivers and students undergoing exams), EEG-determined sleep may be more likely to be associated with disruptions in stress and vice versa. Future studies should investigate these

demographic and health status moderators of associations between daily stress and sleep (e.g., age, chronic pain, gender, and employment status). For example, prior work has shown that older adults tend to report fewer stressors and exhibit less pronounced stress reactivity [34], but more sleep disturbances and insomnia symptoms [45].

Third, as previously discussed, ideally more measurements of stress would be taken over the course of the day instead of having participants reflect on the previous day's stress the next morning. This will likely help reduce reporting bias and may better capture stress as it is experienced. Studies may also benefit from examining other facets of the stress response in relation to sleep, such as stressor reactivity and recovery. Finally, it is possible that the EEG measure we used was unable to capture the facets of objective sleep that may be most important for daily stress (e.g., beta waves). Despite null associations in our study, future studies should seek to incorporate ambulatory EEG measures whenever possible to help further clarify the associations between daily psychological process and objective sleep.

Potential Implications

Our results have potential public health implications for the treatment and prevention of disorders such as insomnia. Heightened stress reactivity is one of the most robust risk factors or correlates of disturbed sleep and insomnia [8, 46]. Our self-report results support the notion that targeting individuals' perceptions of daily stress may lead to improvements in self-reported and behaviorally assessed sleep and that obtaining good sleep may improve abilities to cope with next-day stress. During periods of high stress, people may benefit from maintaining their sleep opportunities and recognizing that their sleep may be temporarily disrupted. After stressors pass, people may benefit from maintaining consistency in their sleep schedules as much as possible to avoid the development of chronic insomnia. Our findings also highlight the potential utility of exploring how ecological momentary interventions may be used to deploy cognitive-behavioral techniques in close to real time to improve stress reactivity and subsequent sleep. Techniques for managing stress as it occurs in daily life (e.g., mindfulness and cognitive reappraisal) may help proactively address stress before it has the potential to impair sleep that night.

Limitations and Future Directions

Although this study has unique strengths (560 possible measurement occasions, three distinct methods to assess sleep, and within-person analyses), there are some limitations warranting further research. First, this sample was relatively young and healthy and experienced relatively few daily stressors and low stressor severity. As previously discussed, it is possible that we did not observe associations between stress and EEG sleep for this reason. The use of a solely clinical sample (e.g., those with depression or insomnia) may reveal different findings. Relatedly, other mediators (e.g., heart rate, blood pressure, rumination, physical activity, and substance use) and moderators (e.g., coping strategies and chronic stress) of the associations between daily stress and sleep that were not assessed in this study should be examined. Finally, as previously mentioned, we assessed sleep and stress concurrently. Future studies would benefit from using multiple assessments of stress throughout the day, particularly closer to the initiation of sleep. However, adding additional measurement time points must always be weighed against potential participant burden.

Conclusion

As behavioral scientists continue to incorporate assessment of sleep into research and appreciate its role in psychological health, it is imperative that we understand how to best capture sleep. We encourage researchers to view self-report, behavioral, and objective sleep measures as complementary, not interchangeable approaches. Particular attention also should be paid to specific sleep parameters (duration vs. efficiency vs. quality), as well as the directionality of effects investigated. Furthermore, given the importance of perceptions of stress and sleep in disorders like insomnia, associations between stress and self-reported sleep should not be discounted. Targeting these perceptions using mindfulness-based stress reduction and cognitive-behavioral techniques may disrupt the toxic cycle of daily stress and sleep.

Supplementary Material

Supplementary material is available at *Annals of Behavioral Medicine* online.

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Compliance with Ethical Standards

Authors' Statement of Conflict of Interest and Adherence to Ethical Standards J.R.D. received study devices from the General Sleep Corporation; however, receipt of devices did not influence the reporting of any study results and authors have no other financial relationship with General Sleep Corporation. All other authors declare no conflict of interest.

Authors' Contributions J.R.D., B.M., B.S., and K.V. collected the data; DCS drafted the manuscript; J.A. and D.C.S. ran analyses; and J.A., B.M., K.V., D.J.T., and J.R.D. edited the manuscript.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all participants included in the study. All data and code are available on Open Science Framework at: https://osf.io/wku6e/?view_only=11ffa520f77d4cfdb625fd23744baf51.

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