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Associations between daily affect and sleep vary by sleep assessment type: What can ambulatory EEG add to the picture?

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ABSTRACT

Objective/Background: Disrupted sleep can be a cause and a consequence of affective experiences. However, daily longitudinal studies show sleep assessed via sleep diaries is more consistently associated with positive and negative affect than sleep assessed via actigraphy. The objective of the study was to test whether sleep parameters derived from ambulatory electroencephalography (EEG) in a naturalistic setting were associated with day-to-day changes in affect.

Participants/Method: Eighty adults (mean age = 32.65 years, 63% female) completed 7 days of affect and sleep assessments. We examined bidirectional associations between morning positive affect and negative affect with sleep assessed via diary, actigraphy, and ambulatory EEG.

Results: Mornings with lower positive affect than average were associated with *higher* diary- and actigraphy-determined sleep efficiency that night. Mornings with higher negative affect than average were associated with *longer* actigraphy-determined total sleep time that night. Nights with longer diary-determined total sleep time, greater sleep efficiency, and shorter sleep onset latency than average were associated with *higher* next-morning positive affect, and nights with lower diary-determined wake-after-sleep-onset were associated with *lower* next-morning negative affect. EEG-determined sleep and affect results were generally null in both directions: only higher morning negative affect was associated with longer rapid eye movement (REM) sleep that night.

Conclusions: Self-reported sleep and affect may occur in a bidirectional fashion for some sleep parameters. EEG-determined sleep and affect associations were inconsistent but may still be important to assess in future studies to holistically capture sleep. Single-channel EEG represents a novel, ecologically valid tool that may provide information beyond diaries and actigraphy.

A large body of literature has examined the reciprocal links between sleep and affect.[1-5] Higher positive affect, such as feelings of happiness and joy, and lower negative affect, such as feelings of anger and sadness, are both associated with better sleep outcomes (ie, better sleep quality, longer sleep duration, shorter sleep latency).[6] Conversely, better sleep is associated with higher positive affect and lower negative affect.[6] A main limitation of this work is the reliance on self-reported assessment of sleep. A few studies have attempted to alleviate this limitation by using inferred measures of sleep (eg, actigraphy), but have found inconsistent associations between sleep and affect.[7-10] In general, self-reported sleep parameters are more strongly associated with affect than actigraphy-derived sleep parameters.[6] Research is needed to clarify the daily associations between affect and sleep using rigorous, comprehensive, and more direct measures of sleep.

Studies of sleep and affect often trade the benefits of well-controlled laboratory measures with more ecologically valid ambulatory measures. Many experimental laboratory-based studies have also confirmed that sleep and affect are strongly associated.[2,11-18] Longer total sleep time, higher sleep quality, shorter sleep onset latency, less wake-after-sleep-onset, and longer rapid eye movement (REM) sleep have each been bidirectionally associated with lower negative and higher positive affect in laboratory settings.[2,11-18] Although

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laboratory studies of sleep or affect manipulation allow for increased experimental control, they likely do not generalize to an individual's everyday experience of affect or sleep.

Ambulatory studies of affect and diary- and actigraphy-determined sleep

One alternative to laboratory-based studies of sleep and affect that offers increased ecological validity is ambulatory-based studies, which assess sleep and affect in individuals' everyday environments using noninvasive methods. Typically ambulatory studies measure sleep using self-report sleep diaries[19] and/or actigraphy.[20] Sleep diaries are the gold standard of subjective sleep measurement and capture an individual's *perception* of their sleep/wake cycle.[19] Sleep diary parameters correlate moderately well with both polysomnography and actigraphy in clinical and healthy samples.[21-23] Actigraphy is a wrist-worn accelerometer that captures motion and light to determine sleep/wake and is considered an inferred measure of sleep. Both sleep diaries and actigraphy are useful ways to measure sleep but capture somewhat different information. Sleep diaries are based on recall and capture an individual's subjective perceptions of sleep and wake patterns. In contrast, actigraphy reflects behavioral quiescence (ie, activity levels that can be used to infer sleep/wake patterns).[22,24]

In general, evidence from ambulatory studies using sleep diaries and actigraphy suggests affect and sleep are bidirectionally associated. However, findings appear to differ by how sleep is assessed (ie, via sleep diary or actigraphy) and by sleep parameter (ie, sleep quality, total sleep time, or sleep efficiency). For example, higher levels of daytime positive affect are associated with better self-reported subsequent-night sleep quality[3,4,25-27] and longer self-reported total sleep time.[3,7] Similarly, higher levels of daytime negative affect are associated with more self-reported sleep disturbances[3,5,25] and poorer self-reported ratings of sleep quality the subsequent night.[28] Across multiple studies, better self-reported sleep quality, longer total sleep time, and shorter sleep onset latency are associated with higher next-day positive affect and lower next-day negative affect.[29,30]

In some ambulatory studies, positive affect and negative affect have also been associated with subsequent impairments in actigraphy-determined sleep parameters, but findings are less consistent than when using sleep diaries. For example, several studies have found null associations between positive affect and subsequent night's total sleep time,[7-10] but one study showed that higher levels of daytime negative affect are associated with longer actigraphy-determined sleep onset latency the subsequent night.[8] Multiple studies have demonstrated that actigraphy-determined total sleep time, sleep efficiency, and sleep onset latency are not associated with next-day positive affect or negative affect.[8,9,31] Yet a few other studies have shown that actigraphy-determined sleep efficiency and total sleep time seem to be associated with higher next-day positive affect,[7,10] and lower sleep onset latency is associated with higher positive affect and lower next-day negative affect.[7,8,32]

The utility of single-channel electroencephalography

Although actigraphy may provide different information than sleep diaries, it is still a relatively indirect and inferred measure of sleep. One additional way to assess sleep more directly in ambulatory settings is via single-channel electroencephalography (EEG). The gold standard for assessing sleep—in-laboratory polysomnography (PSG; which assesses EEG and other physiological measures)—represents challenges for obtaining multiple nights of high-quality sleep while allowing participants to keep their typical schedules, routines, and sleep environments. However, ambulatory EEG devices that participants can wear at home represent a promising tool to assess sleep objectively, while still maintaining considerable ecological validity and low participant burden. Unlike sleep diaries and actigraphy, EEG devices can capture sleep staging (eg, REM and slow wave sleep), as well as other common sleep parameters (eg, total sleep time, sleep efficiency, wake after sleep onset) more directly than actigraphy or sleep diaries. Because EEG devices capture scalp electrical activity reflecting neural activity, they can be considered closer to the gold standard of PSG. It is possible that EEG devices may capture neurocognitive correlates of sleep disturbances that are unable to be detected by sleep diaries or actigraphy. To our knowledge, no studies have examined bidirectional associations between affect and EEG-determined parameters of sleep using ambulatory repeated measures. Combining EEG measures of sleep with sleep diaries and actigraphy may provide a more holistic assessment of an individual's everyday experiences of affect and sleep.

The current study

We examined the bidirectional associations between daily positive affect and negative affect with sleep diary-, actigraphy-, and single-channel EEG-determined parameters of sleep over the course of 7 days. Hypotheses were preregistered on Open Science Framework (https://osf.io/dwrg3/?view_only=ba322d35a01a4cfda7554932899841d0). The first aim was to test the general conclusions from Konjarski et al's (2018) review[6] by examining how affect was bidirectionally associated with sleep diary- and actigraphy-determined sleep parameters. We hypothesized that days with greater positive affect and lower negative affect would be associated with longer total sleep time, greater sleep efficiency, shorter sleep onset latency, and shorter wake-after-sleep-onset that night. Furthermore, we hypothesized that nights with longer total sleep time, greater sleep efficiency, shorter sleep onset latency, and shorter wake-after-sleep-onset would be associated with higher next-day positive affect and lower next-day negative affect. The second aim was to expand on these findings by examining the same associations with EEG-determined sleep parameters. We hypothesized that the days with greater positive affect and lower negative affect would be associated with EEG-determined longer total sleep time, greater sleep efficiency, shorter sleep onset latency, and shorter wake after sleep onset that night; and that nights with EEG-determined longer total sleep time, greater sleep efficiency, shorter sleep onset latency, and shorter wake after sleep onset would be associated with higher next-day positive affect and lower next-day negative affect. Additionally, we hypothesized that days with greater positive affect and lower negative affect would be associated with longer REM duration and longer slow wave sleep, and that nights with longer REM duration and longer slow wave sleep would be associated with higher next-day positive affect and lower next-day negative affect.

Material and methods

Participants

Participants were recruited from the surrounding community using emails, flyers, and listservs. Interested individuals were directed to an informed consent and a brief online screening survey that assessed the following inclusion criteria: (1) willingness to participate for at least 7 days, (2) ability to travel to the research lab, (3) English language fluency, (4) over the age of 18, (5) had a phone number at which they could be regularly reached, and (6) had regular (daily) Internet and personal email access. The only exclusion criterion was having a pacemaker, cardiac defibrillator, or other medical electronic device that would interfere with the EEG device. Initially, 120 people expressed interest in the study. One hundred 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 N = 80 were included in the current analyses (1 person was removed from analyses due to no EEG data). Most participants were female (n = 50, 63%), non-Hispanic White (n = 71, 89%), married or in a relationship (n = 33, 41%), and employed full time (n = 71, 89%). Approximately 15% of participants met clinical cutoff scores for insomnia (ie, Insomnia Severity Index scores $\geq$ 15; n = 12)[33] and 16% met clinical cutoff scores for depression (ie, Quick Inventory of Depressive Symptoms scores $\geq$ 11; n = 13).[34]

Procedures

All procedures were approved by the University of North Texas Institutional Review Board prior to data collection. Participants completed the brief screening measure that assessed the inclusion/exclusion criteria described above, and eligible participants were contacted and given the opportunity to complete the baseline measures online at home via a secure online data collection tool (REDCap) after providing online consent.[35] All participants were then scheduled for their first in-person appointment in the sleep laboratory, during which they were trained in study procedures and reviewed and provided informed consent. Participants were trained to use the Zmachine, an ambulatory EEG data collection device, via videos provided by the equipment manufacturer and hands-on demonstration. Participants were trained in use of actigraphy via verbal instruction from the research assistants and hands-on demonstration. Participants were trained in use of daily sleep and affect 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. Participants were then given a Zmachine, actigraph, and written instructions for all items.

Participants used the Zmachine, actigraph, and sleep/affect diary in their typical sleep environment for 7 days. Each morning, participants received a link for the sleep/affect diary via email, and then received up to 2 additional reminders at 3-hour intervals if they did not complete the diary. Additionally, if they had not completed the diary by noon, research assistants messaged the participants to remind them to complete it. On average, participants completed the morning surveys at 8:37 AM (standard deviation [SD] = 2.38 hours), and an average of 76.99 minutes (SD = 134.71 minutes) after they reported waking.

Measures

Single-channel EEG

The Z-machine is an ambulatory device manufactured by General Sleep, Inc. (Cleveland, OH, USA) that processes a single-channel of EEG data using information from 2 mastoid-placed electrodes and 1 neck-placed ground electrode. The Z-machine is capable of differentiating between wake, light sleep (stages N1 and N2), deep or slow wave sleep (stage N3), and REM sleep. A previous study demonstrated that the Z-machine sleep scoring algorithm (when compared to polysomnography technologists) was able to accurately discriminate between time spent asleep and awake, with an overall sensitivity of 95.5%, a specificity of 92.5%, and an overall Cohen's Kappa of 0.85.[36] Additionally, a second study found substantial agreement between the Z-machine algorithm and 4 polysomnography technologists (Cohen's Kappa values ranging from 0.60 to 0.80) for detecting sleep architecture (ie, wake, N1-N3, and REM).[37] The following sleep parameters were derived from the recording: total sleep time, sleep onset latency, sleep efficiency, wake-after-sleep-onset, slow wave sleep, and REM sleep. The Z-machine electrodes are single-use and were self-applied by the participant 30 or more minutes prior to bedtime each night. After participants completed the study and returned the equipment, we used the Z-machine's "sensor check" function (which notifies the researcher if the sensors were applied incorrectly) to inspect for faulty data which were then excluded from analyses. The device conducts an impedance check when the sensors are first connected, and every 15 minutes thereafter. The default impedance limits are set at 40k Ohms for the ear sensors, and 60k Ohms for the neck sensor or ground.

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, we used Philips Respironics Actiwatch Spectrum actigraphs and analyzed data with Respironics Actiware version 6.0. Participants were instructed to wear the Actiwatch continuously and only remove the device when showering, swimming, or participating in contact sports. On-off wrist detection indicated a high degree of adherence among participants. Data were scored by 2 trained scorers using a previously validated scoring hierarchy that relies on a combination of event markers, sleep diaries, light levels, and activity levels.[22,38] Briefly, if participants provided event markers that matched sleep diary bed and rise times within 30 minutes, event marker bed and rise times were used. If event markers and sleep diary times were >30 minutes 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 minutes, 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 minutes, diary bed and rise times were used. If diaries and activity and light level reductions were >30 minutes discrepant, light and activity levels were used. Using this scoring hierarchy, the initial percent agreement between the 2 scorers was 94.8%, suggesting high inter-rater reliability. Settings used for data export in Actiware were the following: low threshold (activity count: 10), 20 epochs inactivity for sleep onset/offset. Actigraphy has high sensitivity (0.97) and accuracy (0.86) compared to in-lab PSG, as well as strong correlations with in-lab PSG wake after sleep onset (r = 0.61).[39]

Sleep diaries

An electronic version of the Consensus Sleep Diary[19] 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 (eg, bedtime, sleep onset latency, wake-after-sleep-onset, terminal wakefulness, rise time). From these variables, total sleep time was calculated by subtracting total wake time (sleep onset latency + wake-after-sleep-onset + terminal wakefulness) from time in bed (ie, the interval between bedtime and rise time). Sleep efficiency was calculated by taking total sleep time divided by time spent in bed (with the intention of sleeping) multiplied by 100. Sleep diaries were collected using electronic data capture software (REDCap).[35] Sleep diaries are considered the gold standard for subjective sleep assessment significantly correlated with PSG on wake-after-sleep-onset, total sleep time, and sleep efficiency (r = 0.46-59) in people with insomnia and are considered more valid than single-point retrospective estimates of sleep.[40]

Daily positive and negative affect

Positive and negative affect were assessed during the morning diary using items from the Positive and Negative Affect Schedule.[41] Each morning, participants reported the extent to which 10 negative affect items (distressed, upset, irritable, guilty, scared, hostile, ashamed, nervous, jittery, afraid) and 10 positive affect items (interested, excited, strong, enthusiastic, proud, alert, inspired, determined,

attentive, active) reflected how they felt *at the present moment* on a scale of 1 (very slightly or not at all) to 5 (extremely). The 10 items in each scale were averaged together within participants for each day. The positive affect and negative affect scales are highly internally consistent at the daily level (positive affect α = 0.90; negative affect α = 0.87) and uncorrelated with each other.[41] In the current study, the coefficient alphas for positive affect and negative affect across each of the 7 days ranged from 0.94 to 0.96 and from 0.84 to 0.90, respectively. Daily positive affect and negative affect were not significantly correlated on 5 of the 7 days (rs = −0.11 to 0.21, $ps > 0.05$).

Statistical analysis plan

Analyses were conducted in the statistical program R.[42] Multilevel linear models were conducted using the R package *nlme*,[43] and 2-level models included days (Level 1) nested within people (Level 2). All Level 1 repeated measures independent variables were person-mean centered so that values represented deviations from an individual's average taken across all 7 days. Positive affect and negative affect were examined simultaneously to predict each separate subsequent-night sleep variable, and each sleep variable was used to predict next-morning positive affect or negative affect (controlling for the other affect scale). Restricted maximum likelihood techniques were used for estimation and intercepts were allowed to vary randomly across people. All models controlled for day of the week (day of the week = 0, weekend = 1), gender (0 = male, 1 = female), and age, unless otherwise noted, given previous studies showing robust differences in sleep by day of the week, gender, and age.[44-46] Checking model assumptions revealed no violations (ie, level 1 error terms were independent and normally distributed, with a mean of 0 and a variance of σ^2; level 1 and level 2 predictors were independent of level 1 and 2 error terms; level 2 random errors were multivariate normal, with a mean of 0 and a variance of θ). For analyses examining current affect predicting subsequent night's sleep, affect data were lagged +1 day (eg, so current affect on morning 1 predicted sleep the subsequent night, which was actually reported on morning 2). For analyses examining sleep predicting subsequent morning affect, non-lagged data were used, as sleep from the previous night and current morning affect were reported/collected at the same time in the morning survey. An example equation for negative affect (NA; reported the previous day) predicting the random intercept of sleep that night (reported the next morning; controlling for age, gender, and day of the week) is displayed below:

$$\text{Level 1 (days): Daily sleep}_{ij} = \beta_{0j} + \beta_{1j}\text{Daily NA}_{ij} + \beta_{2j}\text{Day of the week}_{ij} + r_{ij}$$
$$\text{Level 2 (people): } \beta_{0j} = \gamma_{00} + \gamma_{01}\text{Gender}_{j} + \gamma_{02}\text{Age}_{j} + u_{0j}$$
$$\beta_{1j} = \gamma_{10}$$
$$\beta_{2j} = \gamma_{20}$$

where: β_{0j} is the within-person intercept of daily sleep, modeled as a function of the grand mean for sleep when all other predictors equal 0 (γ_{00}), the overall effect of gender on daily sleep (γ_{01}), the overall effect of age on daily sleep (γ_{02}), and a person-level residual from the grand mean (u_{0j}); β_{1j} is the within-person slope between daily negative affect and sleep, modeled as a function of an overall slope (γ_{10}); and β_{2j} the within-person slope between day of the week and sleep, modeled as a function of an overall slope (γ_{20}).

As this was a secondary data analysis of a parent study, we did not calculate *a priori* power for the current analyses. However, post hoc power calculations using the R package longpower revealed a mixed effects model with an AR(1) correlation structure, a retention rate of 90%, a medium effect size of 0.60, an AR(1) correlation parameter of 0.80, and a sample size of 80 participants across 7 timepoints yielded 73% power to detect significant effects.

Results

Descriptive results

Data collection resulted in 554 diaries out of a possible 560 (ie, 7 days × 80 participants), for a diary compliance rate of 99%. Participants provided 524 usable days of actigraphy data (94% compliance) and 476 usable days of EEG data (85% compliance). Participants had an average EEG-determined total sleep time of 6.35 hours (SD = 1.23), an average actigraphy-determined total sleep time of 6.45 hours (SD = 1.23), and an average sleep diary-determined total sleep time of 6.77 hours (SD = 1.51, Table 1). Participants had an average EEG-determined sleep efficiency of 82.57% (SD = 8.77), an average actigraphy-determined SE of 83.01% (SD = 7.18), and an average sleep diary-determined sleep efficiency of 86.63% (SD = 13.84, Table 1). EEG-determined total sleep time was strongly correlated with both actigraphy- (r = 0.75, $p < .001$) and sleep diary-determined total sleep time (r = 0.70, $p < .001$). EEG-determined SE was also moderately correlated with actigraphy- (r = 0.33, p = .005) and diary-determined SE (r = 0.39, $p < .001$). Examination of intraclass correlation coefficients derived from the multilevel models revealed that for all EEG-determined sleep parameters, more variation existed at the within-person (ie, day-to-day) level than the between-person (ie, person-to-person) level (Table 1). Conversely, for positive and negative affect, more variation existed at the between-person level than the within-person level (Table 1).

Morning affect predicting subsequent night sleep

The results for morning affect predicting subsequent night sleep across measurement type are presented in Table 2.

Sleep diary results

Mornings with lower positive affect than an individual's average were associated with greater sleep diary-determined sleep efficiency the subsequent night (b = -0.21, SE = 0.09, p = .018; Table 2). Morning negative affect was not associated with any subsequent night's sleep parameters (Table 2).

Actigraphy results

Mornings with lower positive affect than an individual's average were associated with greater sleep efficiency the subsequent night (b = -0.16, SE = 0.07, p = .032; Table 2). Mornings with higher negative affect than an individual's average were associated with longer total sleep time the subsequent night (b = 0.06, SE = 0.02, p = .009; Table 2).

EEG results

Morning PA was not associated with any of the subsequent night's EEG-determined sleep parameters (Table 2). Mornings with higher negative affect than average were associated with longer REM sleep the subsequent night (b = 0.03, SE = 0.01, p = .008; Fig. 1, Table 2).

Sleep predicting subsequent morning affect

The results for sleep predicting subsequent morning affect across measurement type are presented in Table 3.

Sleep diary results

Nights with longer sleep diary-determined total sleep time (b = 0.36, SE = 0.16, p = .024), higher sleep efficiency (b = 0.05, SE = 0.02, p = .044), and shorter sleep onset latency (b = -0.03, SE = 0.01, $p < .001$) than an individual's average were associated with higher next-morning positive affect (Table 3). Nights with greater sleep-diary determined wake-after-sleep-onset than an individual's

Table 1
Participant characteristics

	M	SD	Intraclass correlation coefficients: amount of between-person variation	Intraclass correlation coefficients: amount of within-person variation
Age	32.65	10.07	–	–
Depressive symptoms	6.40	4.01	–	–
Insomnia symptoms	8.88	5.66	–	–
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%
Positive affect	22.89	8.44	76%	24%
Negative affect	12.45	3.31	58%	42%

M, mean; SD, standard deviation; EEG, electroencephalogram; TST, total sleep time (in minutes); SE, sleep efficiency (TST/time in bed × 100); SOL, sleep onset latency (in minutes); WASO, wake-after-sleep-onset (in minutes); REM, rapid eye movement sleep (in minutes); SWS, slow wave sleep (in minutes). Acti = actigraphy. Diary = sleep diary. Depressive symptoms were measured using the total score on the Quick Inventory of Depressive Symptoms scale (range of possible scores = 0-18). Insomnia symptoms were measured using the Insomnia Severity Index (range of possible scores = 0-25).

average were associated with higher next-morning negative affect (b = 0.02, SE = 0.01, p= .011; Table 3).

Actigraphy results

No actigraphy-determined sleep parameters were associated with next-morning positive affect or negative affect (Table 3).

EEG results

No EEG-determined sleep parameters were associated with next-morning positive affect or negative affect (Table 3).

Discussion

This was the first study to examine bidirectional associations between affect and multiple parameters of sleep determined from self-report (ie, sleep diary), inferred (ie, actigraphy), and neurocognitive measures (ie, EEG) in a naturalistic setting. Across the 3 sleep assessment methods, we found affect was more consistently associated with subsequent night sleep than sleep with next-morning affect. However, contrary to our expectation that lower positive affect and higher negative affect would be associated with worse sleep, we found that lower positive affect was associated with greater diary- and actigraphy-determined sleep efficiency. Higher negative affect was associated with longer actigraphy-determined total sleep time and longer EEG-determined REM sleep. In contrast, no actigraphy- or EEG-determined sleep parameters were associated with next-morning affect, and only diary-determined sleep was associated with next-morning positive affect and negative affect. These results suggest positive affect and negative affect may be more consistently related to subsequent sleep, regardless of sleep assessment method, while only diary-determined sleep is associated with next-morning affect. Each of these results is discussed in further detail below in the context of existing literature.

Morning affect predicting subsequent night sleep

When examining pathways from affect to sleep, we found that, counterintuitively, worse morning mood was associated with *better* sleep diary-, actigraphy-, and EEG-determined sleep. Specifically, every one-unit decrease in morning positive affect was associated with a 0.21% increase in diary-determined sleep efficiency and a 0.16% increase in actigraphy-determined sleep efficiency. Every one-unit increase in morning negative affect was associated with a 3.6-minute increase in actigraphy-determined total sleep time and a 1.8-minute increase in EEG-determined REM sleep. It may be that when people wake up in a worse mood, they engage in adaptive strategies to combat their bad mood (eg, exercising, problem-focused coping). These strategies may be indirectly beneficial for sleep and should be examined as potential mediators in future research. It may also be that lower positive affect predicts greater sleep efficiency because people experience higher overall levels of arousal when in a positive mood, which could impair their ability to obtain good sleep. Ratings of positive affect are often collinear with affective arousal.[47] An alternative explanation for results with poorer morning affect predicting better sleep is the length of time between these measurements. Current morning affect was used to predict sleep typically initiated 12 hours later (and reported 24 hours later for diary measures). Affect fluctuates substantially over the course of the day.[48] Morning affect may not accurately reflect average daily affect or affect prior to bedtime, which could be more influential for that night's sleep. Timing of affect assessments in relation to sleep varies widely across previous studies. For example, out of the 29 studies examined in Konjarski et al's (2018) review,[6] 3 assessed affect in the morning upon awakening, 1 in afternoon, 10 in the evening prior to sleep onset, 1 allowed participants to rate their mood at their preferred time, and 14 studies collected multiple ratings of PA and NA per day (ranging from 4 to 12 reports across waking hours). It is plausible that affect assessed closer to the initiation or termination of the sleep period may have a stronger association with sleep parameters. Ideally, future studies would

Table 2
Morning positive and negative affect predicting sleep that night

		TSTp			SEp			WASOp			SOLp			REMp			SWSp		
	Predictors	*b*	95% CI	*P*	*b*	95% CI	*P*	*b*	95% CI	*P*	*b*	95% CI	*P*	*b*	95% CI	*P*	*b*	95% CI	*P*
EEG	Fixed effects																		
	Daily PA (lagged)	<0.01	−0.03 to 0.03	.814	0.01	−0.18 to 0.20	.938	<0.01	−0.01 to 0.01	.928	<0.01	−0.01 to 0.01	.382	<0.01	−0.01 to 0.02	.569	0.01	−0.00 to 0.01	.183
	Daily NA (lagged)	0.05	−0.01 to 0.10	.085	0.16	−0.18 to 0.50	.365	<0.01	−0.02 to 0.02	.944	<0.01	−0.02 to 0.01	.600	0.03	0.01-0.05	**.008**	0.01	−0.01 to 0.02	.527
	Random effects																		
	σ^2	1.32			56.24			0.23			0.15			0.24			0.12		
	τ_{00}	0.42 $_{id}$			56.63 $_{id}$			0.31 $_{id}$			0.11 $_{id}$			0.16 $_{id}$			0.13 $_{id}$		
	ICC	0.24						0.57			0.42			0.4			0.51		
	N	77 $_{id}$			77 $_{id}$			78 $_{id}$			78 $_{id}$			78 $_{id}$			78 $_{id}$		
	Observations	407			407			412			412			412			412		
	Marginal R^2 / conditional R^2	0.031 / 0.265			0.074 / N/A			0.047 / 0.592			0.066 / 0.458			0.059 / 0.433			0.022 / 0.520		
		TSTa			SEa			WASOa			SOLa								
	Predictors	*b*	95% CI	*P*	*b*	95% CI	*P*	*b*	95% CI	*P*	*b*	95% CI	*P*						
Actigraphy	Fixed effects																		
	Daily PA (lagged)	−0.02	−0.04 to 0.01	.124	−0.16	−0.31 to −0.01	**.032**	0.01	−0.46 to 0.48	.975	0.25	−0.17 to 0.66	.239						
	Daily NA (lagged)	0.06	0.01-0.10	**.009**	0.17	−0.08 to 0.42	.188	0.24	−0.54 to 1.02	.548	−0.21	−0.90 to 0.48	.548						
	Random effects																		
	σ^2	1.09			39.36			395.32			311.21								
	τ_{00}	0.56 $_{id}$			24.67 $_{id}$			392.52 $_{id}$			113.65 $_{id}$								
	ICC	0.34																	
	N	75 $_{id}$			75 $_{id}$			76 $_{id}$			76 $_{id}$								
	Observations	448			448			454			454								
	Marginal R^2 / conditional R^2	0.054 / 0.374			0.109 / N/A			0.015 / N/A			0.023 / N/A								
		TSTd			SEd			WASOd			SOLd								
	Predictors	*b*	95% CI	*P*	*b*	95% CI	*P*	*b*	95% CI	*P*	*b*	95% CI	*P*						
Diary	Fixed effects																		
	Daily PA (lagged)	−0.02	−0.05 to 0.01	.179	−0.21	−0.38 to −0.04	**.018**	0.02	−0.37 to 0.41	.914	0.30	−0.14 to 0.74	.179						
	Daily NA (lagged)	0.04	−0.01 to 0.08	.13	−0.16	−0.45 to 0.14	.295	−0.14	−0.81 to 0.52	.677	0.08	−0.67 to 0.83	.833						
	Random effects																		
	σ^2	1.52			56.38			292.58			372								
	τ_{00}	0.54 $_{id}$			17.44 $_{id}$			104.25 $_{id}$			176.83 $_{id}$								
	ICC	0.26																	
	N	80 $_{id}$			80 $_{id}$			80 $_{id}$			80 $_{id}$								
	Observations	475			475			476			476								
	Marginal R^2 / conditional R^2	0.032 / 0.288			0.053 / N/A			0.014 / N/A			0.085 / N/A								

TST, total sleep time; SE, sleep efficiency (TST/TIB × 100); WASO, wake-after-sleep-onset; SOL, sleep onset latency; REM, rapid eye movement; SWS, slow wave sleep; NA, negative affect; PA, positive affect; ICC, intraclass correlation coefficient.
Estimate represents *b* or the unstandardized regression weights, and 95% CI represents confidence intervals.
Bold values represent significant effects of PA or NA on sleep outcomes.
Suffixes represent measurement type: p, EEG; a, Actigraphy; d, Diary. All models controlled for gender, age, and day of the week.

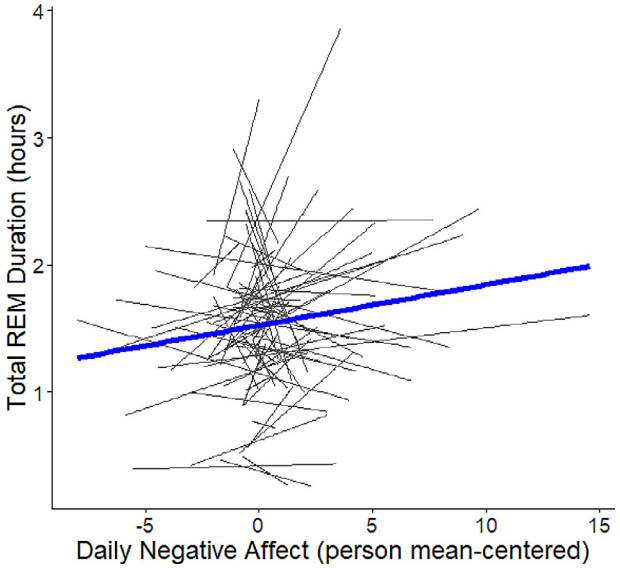

Fig. 1. Daily morning negative affect predicting subsequent single-channel EEG-determined rapid eye movement sleep duration.

Note. Blue line represents estimate *b* or the unstandardized regression weights. EEG, electroencephalogram, REM, rapid eye movement. Daily negative affect is person mean centered, such that scores represent deviations from an individual's average wake-after-sleep-onset across the 7 days. Graph depicts unadjusted relationships.

assess affect multiple times throughout the day (including closer to the sleep interval) to gain a more accurate picture of daily patterns.

Sleep predicting subsequent morning affect

Examining reverse pathway from sleep to affect, results were aligned with our hypotheses for sleep diaries (ie, better sleep predicted higher positive affect and lower negative affect), but results were null for actigraphy and EEG. In general, how people report their affective state is likely to be based on their perceptions of their previous night's sleep.[49] Our findings with diary sleep predicting subsequent affect partially corroborate what other studies have found.[1,3,7,29,30] In our study, we found moderate effects of diary total sleep time, sleep efficiency, and sleep onset latency on next-morning positive affect.[50] By examining the slopes between sleep and affect, we found that for every additional hour of total sleep time obtained, individuals reported a 0.36-unit increase in positive affect; for every additional 5% of sleep efficiency obtained, individuals reported a 0.25-unit increase in positive affect; and for every 10-minute decrease in sleep onset latency, individuals reported a 0.30-unit increase in positive affect. We also found that nights with greater diary wake-after-sleep-onset were associated with higher next-morning negative affect, which supports findings from one other study.[31] Every 10-minute increase in wake-after-sleep-onset was associated with 0.20-unit increase in negative affect. Together, our findings suggest multiple facets of diary-determined sleep are associated with changes in subsequent morning affect.

EEG-determined sleep and affect null results

Our analyses with EEG sleep demonstrated that higher morning negative affect predicted longer REM duration that night. Longer REM duration is often a feature in clinical depression and anxiety,[51] and other studies have similarly found that inducing negative affect may cause increases in subsequent REM sleep.[52-54] Our other null results with EEG sleep also support findings from Konjarski et al (2018), who revealed relatively null or inconsistent results in ambulatory studies on actigraphy and affect in nonclinical samples.[8,9,31]

Table 3
Sleep predicting next-morning positive and negative affect

		Positive affect								Negative affect							
		Fixed effects			Random effects					Fixed effects			Random effects				
	Predictors	*b*	95% CI	*P*	$\sigma 2$	$\tau 00$	N	Obs	Marginal R^2/conditional R^2	*b*	95% CI	*P*	$\sigma 2$	$\tau 00$	N	Obs	Marginal R^2/conditional R^2
EEG	TSTp	0.29	−0.08 to 0.66	.126	19.11	66.09 $_{id}$	77 $_{id}$	476	0.180/ N/A	−0.05	−0.26 to 0.16	.631	5.86	9.54 $_{id}$	77 $_{id}$	476	0.159 / N/A
	SEp	0.03	−0.03 to 0.08	.341	19.18	66.07 $_{id}$	77 $_{id}$	476	0.178/ N/A	−0.02	−0.05 to 0.02	.333	5.85	9.55 $_{id}$	77 $_{id}$	476	0.160 / N/A
	REMp	0.64	−0.20 to 1.48	.135	19.02	65.66 $_{id}$	78 $_{id}$	482	0.184/ N/A	−0.15	−0.62 to 0.32	.526	5.80	9.42 $_{id}$	78 $_{id}$	482	0.159 / N/A
	SWSp	0.42	−0.77 to 1.60	.488	19.10	65.65 $_{id}$	78 $_{id}$	482	0.181/ N/A	−0.14	−0.79 to 0.51	.678	5.80	9.42 $_{id}$	78 $_{id}$	482	0.159 / N/A
	WASOp	0.38	−0.50 to 1.26	.396	19.09	65.63 $_{id}$	78 $_{id}$	482	0.182/ N/A	0.17	−0.32 to 0.65	.492	5.80	9.42 $_{id}$	78 $_{id}$	482	0.159 / N/A
	SOLp	−1.01	−2.11 to 0.09	.073	18.97	65.67 $_{id}$	78 $_{id}$	482	0.186/ N/A	0.06	−0.55 to 0.67	.855	5.80	9.42 $_{id}$	78 $_{id}$	482	0.158 / N/A
		Fixed effects			Random effects					Fixed effects			Random effects				
	Predictors	*b*	95% CI	*P*	$\sigma 2$	$\tau 00$	N	Obs	Marginal R^2/conditional R^2	*b*	95% CI	*P*	$\sigma 2$	$\tau 00$	N	Obs	Marginal R^2/conditional R^2
Actigraphy	TSTa	0.25	−0.14 to 0.63	.21	18.84	69.53 $_{id}$	75 $_{id}$	523	0.209/ N/A	−0.15	−0.37 to 0.08	.198	6.53	10.10 $_{id}$	75 $_{id}$	523	0.163 / N/A
	SEa	0.05	−0.01 to 0.11	.13	18.80	69.56 $_{id}$	75 $_{id}$	523	0.211/ N/A	−0.01	−0.04 to 0.03	.754	6.55	10.09 $_{id}$	75 $_{id}$	523	0.160 / N/A
	WASOa	0.01	−0.01 to 0.03	.338	18.71	68.99 $_{id}$	76 $_{id}$	530	0.216/ N/A	0.01	−0.01 to 0.02	.306	6.75	10.01 $_{id}$	76 $_{id}$	530	0.155 / N/A
	SOLa	0.01	−0.01 to 0.03	.418	18.72	68.96 $_{id}$	76 $_{id}$	530	0.216/ N/A	−0.01	−0.02 to 0.01	.321	6.75	10.01 $_{id}$	76 $_{id}$	530	0.155 / N/A
		Fixed effects			Random effects					Fixed effects			Random effects				
	Predictors	*b*	95% CI	*P*	$\sigma 2$	$\tau 00$	N	Obs	Marginal R^2/conditional R^2	*b*	95% CI	*P*	$\sigma 2$	$\tau 00$	N	Obs	Marginal R^2/conditional R^2
Diary	TSTd	0.36	0.05-0.66	**.024**	18.14	66.66 $_{id}$	80 $_{id}$	554	0.234 / N/A	−0.09	−0.27 to 0.10	.348	6.51	9.56 $_{id}$	80 $_{id}$	554	0.164 / N/A
	SEd	0.05	0.00-0.09	**.044**	18.18	66.65 $_{id}$	80 $_{id}$	554	0.233 / N/A	−0.01	−0.03 to 0.02	.594	6.52	9.56 $_{id}$	80 $_{id}$	554	0.164 / N/A
	WASOd	−0.02	−0.04 to 0.00	.116	19.28	66.38 $_{id}$	80 $_{id}$	557	0.220 / N/A	0.02	0.00 to 0.03	**.011**	6.47	9.55 $_{id}$	80 $_{id}$	557	0.168 / N/A
	SOLd	−0.03	−0.05 to −0.01	**.001**	18.92	66.43 $_{id}$	80 $_{id}$	557	0.233 / N/A	<0.01	−0.01 to 0.01	.663	6.55	9.54 $_{id}$	80 $_{id}$	557	0.158 / N/A

TST, total sleep time; SE, sleep efficiency (TST/TIB × 100); WASO, wake-after-sleep-onset; SOL, sleep onset latency; REM, rapid eye movement; SWS, slow wave sleep; NA, negative affect; PA, positive affect; ICC, intraclass correlation coefficient.

Estimate represents *b* or the unstandardized regression weights, and 95% CI represents confidence intervals.

Bold values represent significant effects of PA or NA on sleep outcomes.

Suffixes represent measurement type: p, EEG; a, Actigraphy; d, Diary. All models controlled for the reciprocal affect (eg, controlling for negative affect in models predicting positive affect), gender, age, and day of the week.

Building on Konjarski's review, we replicated actigraphy findings using EEG-determined measures of sleep in daily life, providing a more direct means of assessing sleep and sleep staging. Similar to actigraphy findings in Konjarski's review, EEG sleep was not consistently associated with affect in the current study.

There are several potential explanations for why we did not observe many significant associations between positive affect or negative affect and EEG-determined sleep. Perceptions of sleep may be more important for or influenced by affective states than physiological assessments of sleep. Prior work has shown that subjective assessments of sleep quality are associated with subjective well-being.[55,56] However, findings between actigraphy assessed sleep and subjective well-being are more inconsistent.[23] There is also now consensus that objective, inferred, and self-report measures of sleep may capture equally important yet somewhat distinct domains of sleep, including the physiological transition, behavioral quiescence, and reduction in perceptual awareness, respectively.[22,24,57] Future studies should treat these measures as complementary but not fully overlapping. Each approach may provide unique information with distinct benefits and limitations. Whenever possible, studies should use multiple measures of sleep to capture a broader range and greater depth of information about sleep in relation to other constructs (eg, affect).

Another potential explanation for why previous night's self-reported sleep, but not actigraphy- and EEG-measured sleep, was associated with next-morning affect may be due to measurement error and/or self-report bias. In the current study, previous night's sleep and current morning affect were reported concurrently. Better diary sleep predicted higher positive affect and lower negative affect that morning, but it is possible this is an artifact of reporting these variables simultaneously. Those who are in a better mood in the morning may remember their previous night's sleep more favorably. One reason for including techniques that use biological signals to assess sleep is to decipher whether the self-reported measures replicate actigraphy and EEG measures, or if they reflect some sort of reporting bias and/or different underlying psychophysiological process.

Our null results with actigraphy and EEG measures of sleep also may be attributed to the specific items we used to measure daily positive affect and negative affect. All affect items consisted of high arousal affect; recent work has shown that high and low arousal daily affect may be differentially associated with sleep.[58] For example, moments characterized by feeling calm (ie, a lower arousal facet of positive affect) have been associated with greater diary sleep efficiency on days with higher than average stress. Lower arousal positive affect items may be more strongly associated with sleep than higher arousal positive affect items, particularly under times of heightened perceived stress.[58] Future studies should examine how associations between affect and EEG-determined sleep may be moderated by affective arousal.

It may also be that the generally null results with affect and actigraphy and EEG measures are due to specific characteristics of our sample. Our sample was relatively young and healthy, with low average levels of sleep disturbances and negative affect, as well as relatively high average levels of positive affect. This may have resulted in a restriction of range in possible values. Significant associations between positive affect, negative affect, and actigraphy and EEG measures of sleep may be observed in those individuals with more marked disturbances in sleep or affect (eg, those with insomnia and/or depression). For example, in studies that have examined actigraphy-determined sleep and daily affect, only those using experimental designs or clinical populations have found significant associations between sleep and daily affect.[7,9,59,60] Future research may consider using more selective inclusion/exclusion criteria during recruitment to reduce potential noise created by confounding factors.

Limitations and future directions

Although this study did have several unique strengths (eg, 3 measurement modalities to assess sleep; 560 potential measurement occasions; preregistered analyses; within-person, lagged analyses), there are some limitations that warrant future research in addition to those already discussed above. First, although we had 560 possible measurement occasions (80 participants × 7 days), more days of sleep and affect assessments may offer more reliable estimates. It is possible we may have been slightly underpowered (73% power) to detect significant effects. A previous study showed that 1 week is sufficient to achieve adequate stability of mean sleep parameters assessed by sleep diaries and EEG,[61] but it is unknown if these same results hold when examining within-person deviations. Future studies should consider more measurement occasions to assess within-person fluctuations in sleep and affect, but this should always be weighed against participant burden.

One consideration in the interpretation of the results is that we did not exclude individuals with sleep or mood disorders or those taking sleep aids, antidepressants, or other medications that may affect sleep. Future studies should carefully consider how these factors may influence sleep and affect associations. For example, sedative hypnotics, which are commonly used to treat insomnia, may lead to improvements in sleep, but also have downstream implications for positive and negative affect.[62] Similarly, some antidepressants (particularly ones with sedative properties such as trazodone), may be initially prescribed for their mood-enhancing effects, but also lead to improvements in sleep.[63] Our sample also was highly educated, and most participants identified as non-Hispanic White, which limits generalizability to other samples. Studies have shown important racial/ethnic and socioeconomic disparities in sleep,[64,65] which will be essential to examine in future studies on daily affect and sleep.

Third, we did not assess the impact of bed partners on participants' sleep. This is an important consideration for future research to address, as studies have shown as many as 30% of movements recorded during sleep periods may be shared among bed partners.[66] Fourth, we did not assess the impact of naps on participants' daily positive and negative affect because both our actigraphy and EEG protocols did not include scoring of sleep outside of the main sleep interval. However, the average number of minutes people reported napping was low (M = 14.87 minutes, SD = 20.82, range = 0-90.33 minutes). Future research should consider the influence of daytime naps on daily affect, as laboratory studies have shown that a midday nap of 20-30 minutes could potentially provide a boost to daily positive affect.[67]

Fifth, although we did not correct for multiple comparisons, we did preregister all hypotheses in alignment with previous theoretical and empirical work.[68] Given that this was the first paper to examine how affect and EEG sleep are associated in daily life, we felt it was important to examine affect in relation to all facets of EEG sleep (and to replicate previous findings with sleep diaries and actigraphy). Future studies should seek to replicate our results. Finally, we found that day of the week was associated with sleep and affect levels, such that weekends were associated with higher positive affect and longer sleep duration (across all 3 sleep measurement techniques) compared to weekdays, which supports findings from previous research.[69,70] Future studies should systematically examine differences in sleep and affect associations by day of the week.

Conclusion

As sleep continues to be recognized as an important transdiagnostic cause and consequence of affective disturbances, it is imperative that emerging innovations in sleep devices: (1) reduce patient

burden, (2) increase ecological validity of results, and (3) validly and reliably assess sleep. Ambulatory single-channel EEG is a promising tool to address these issues due its portability and potential for high-resolution insights. Given the high comorbidity of sleep problems and affective disorders, it is critical to understand how the associations between these variables unfold in everyday life using rigorous measures. Our results indicate that some self-reported sleep parameters are bidirectionally associated with positive and negative affect, although patterns were more consistent and robust for affect predicting sleep than vice versa. The same relationships were not observed for EEG measures of sleep. Researchers should consider the utility of multiple sleep assessment methods to examine in relation to daily affect in future studies.

All data and R code are available on Open Science Framework at https://osf.io/wku6e/?view_only=11ffa520f77d4cfdb625fd23744baf51

Declaration of conflict of interest

The authors have no conflicts of interest to disclose.

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