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Wearable and mobile technology to characterize daily patterns of sleep, stress, presleep worry, and mood in adolescent insomnia

Luca Menghini, PhD[a], Dilara Yuksel, PhD[b], Devin Prouty, PhD[b], Fiona C. Baker, PhD[b,c], Christopher King, PhD[d], Massimiliano de Zambotti, PhD[b*]

[a] Department of General Psychology, University of Padova, Padova, Italy
[b] Center for Health Sciences, SRI International, Menlo Park, California, USA
[c] Brain Function Research Group, School of Physiology, University of the Witwatersrand, Johannesburg, South Africa
[d] Department of Pediatrics, University of Cincinnati College of Medicine; Division of Behavioral Medicine and Clinical Psychology, Pediatric Pain Research Center (PPRC), Cincinnati Children's Hospital Medical Center, Cincinnati, Ohio, USA

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ABSTRACT

Objectives: Characterizing daily patterns of sleep, stress, presleep worry, and mood in adolescents with and without insomnia symptomatology.
Design: Two months of continuous wearable tracking and daily diary ratings.
Setting: Free-living conditions.
Participants: Ninety-three adolescents (59 girls; 16-19 years old) with (N = 47; 26 with clinical and 21 with sub-clinical) and without (N = 46; control) DSM-5 insomnia symptomatology.
Measurements: Fitbit Charge 3 tracked sleep, heart rate, and steps. Evening electronic diaries collected ratings of daily stress, presleep worry, and mood.
Results: While sleep duration (control: 6.88 ± 1.41 hours; insomnia: 6.92 ± 1.28 hours), architecture, timing, and night-to-night variability were similar between groups, the insomnia group reported higher levels of stress and worry, being mainly related to "school". At the intraindividual level, stress and worry predicted shorter sleep duration and earlier wake up times, which, in turn, predicted higher stress the following day. Moreover, higher-than-usual stress predicted higher sleep-time heart rate, with a more consistent effect in adolescents with insomnia. Results were overall consistent after controlling for covariates and several robustness checks.
Conclusions: There is a bidirectional relationship between daily stress and sleep, with daily stress negatively impacting sleep, which in turn leads to more stress in adolescents with and without insomnia symptoms. Findings also highlight the complexity of insomnia in adolescence, in which the core clinical features (perceived sleep difficulties) and the critical factors (stress/worry) implicated in the pathophysiology of the disorder are not necessarily reflected in objective sleep indicators.

Introduction

Adolescence is characterized by profound changes in sleep habits due to the interplay between several co-occurring biopsychosocial factors.[1] Neurodevelopment across adolescence is accompanied by changes in sleep architecture (sleep/wake patterns and sleep stages), timing (bedtime, wake-up time), and variability (night-to-night intraindividual variation).[2-4] Moreover, psychosocial stressors, including increased pressure from school, family, and peers, and the associated psychological states such as stress, worry, and negative mood, can impact adolescents' sleep at both inter-[5] and intraindividual level,[6–9] in a reciprocal fashion.[6,8,9]

Insomnia frequently emerges during this vulnerable period, being particularly common in older girls, and typically showing a chronic course.[10,11] Despite its high prevalence, the manifestation and pathophysiology of adolescent insomnia are still poorly understood, challenging accurate detection and diagnosis.[11,12] At the subjective level, a distinct clinical profile of older adolescents with insomnia has been recently identified across a range of characteristics related to sleep cognitions, mood, reactivity, and coping, with some characteristics (eg, presleep cognitive activity) being amplified in girls.[13] Some studies also provided evidence of objective sleep alterations such as reduced sleep duration, delayed onset, and hyperarousal (eg, elevated cortical, neuroendocrine, inflammatory, and autonomic

*Corresponding author: Massimiliano de Zambotti, PhD, SRI International, 333 Ravenswood Avenue, Menlo Park, CA, 94025, USA, Tel: 650-859-2714; Fax: 650-859-2743.
E-mail addresses: massimiliano.dezambotti@sri.com, maxdeze@gmail.com (M. de Zambotti).

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markers) in adolescent insomnia,[14,15] in line with some adult literature.[16,17] However, most studies used cross-sectional designs and single-night assessments, providing limited ability to capture the complexity of insomnia and its interplay with time-varying psychosocial factors.

Recently, ecological momentary assessment (EMA) using electronic diaries and wearable sensors has been increasingly employed to investigate adolescents' sleep.[6,8,9] Particularly, the use of multi-sensor wearable sleep technology, capable of passive longitudinal tracking of sleep, physical activity, and autonomic indices, may ultimately capture the complexity of adolescent sleep and influential factors.[18,19] Yet, while a few studies investigated the cooccurrence between objective poor sleep indicators and daily reports of insomnia symptoms in healthy adolescents,[20] to our knowledge no previous EMA studies investigated objective sleep disturbances in adolescents diagnosed with insomnia, or their transient relationships with self-reported well-being. Moreover, most studies used EMA protocols lasting only 1-to-2 weeks, which might be poorly representative of adolescents' sleep.

The use of intensive longitudinal designs combining electronic diaries and passive data collection from wearable-sensing technology enables a finer characterization of the daily experience, behavior, and physiology of adolescent insomnia.[18] This allows the evaluation of how factors like daily stress and other affective states implicated in the pathophysiology of insomnia disorder[17] might interact with other modifiable behavioral factors such as bedtime and physical activity, to ultimately unveil potential new target for the diagnosis and treatment of a frequently overlooked, highly common and detrimental disorder in adolescents.[12,13,11]

In this study, we used a 2-month EMA to characterize the daily patterns of, and the reciprocal relationships between, objective sleep measures (architecture, timing, night-to-night variability, and autonomic activity) and subjective ratings of stress, worry, and mood in a sample of 93 adolescents with and without DSM-5[21] insomnia symptomatology. At the interindividual level, we hypothesized (H1) greater sleep disturbances (ie, disrupted sleep, elevated night-to-night variability, and increased nocturnal heart rate [HR]) and (H2) higher perceived stress, worry, and negative mood in adolescents with insomnia compared to controls. At the intraindividual level, we hypothesized that (H3) higher-than-usual stress, presleep worry, and negative mood would predict more disturbed sleep, and that (H4) disturbed sleep would be, in turn, associated with greater next-day perceived stress, worry, and negative mood, with (H5) stronger associations in adolescents with insomnia symptoms (greater vulnerability to stress-induced psychophysiological activation). The role of demographics (eg, sex) and other behavioral covariates (eg, physical activity) was also explored.

Participants and methods

Participants

Ninety-three postpubertal adolescents (59 girls) aged on average (±SD) 17.9 ± 0.9 years (body mass index, BMI = 21.8 ± 3.2 kg m^{-2}), recruited from the San Francisco Bay Area local high schools and community, participated in the study. This study is part of a larger study evaluating insomnia, sleep, and cardiovascular health in adolescence (R01HL139652), including multi-nights in-lab polysomnographic assessments and daily wearable-based sleep and stress assessments under free-living conditions. All adults consented to participate, with minors providing written assent and consent from a legal guardian. The study was approved by the Advarra Institutional Review Board. Participants received $150 compensation. Full details about sample and recruitment are provided in.[13]

Forty-seven adolescents (31 girls) presented DSM-5[22] insomnia symptomatology, as determined by a semi-structured clinical interview with a CA-licensed clinical psychologist (DP), and were assigned to the insomnia group. Among them, 26 (20 girls) met full criteria, whereas 21 (11 girls) met all criteria except for weekly frequency (ie, they reported experiencing insomnia symptoms less than 3 times/week). Forty-six participants (28 girls) reported no sleep difficulties and were assigned to the control group.

Exclusion criteria for both groups included past/current medical (eg, diabetes) or mental conditions (eg, depression), medications affecting sleep or cardiovascular functions (eg, antihypertensives), breathing/movement-related sleep disorders, past month time-zones traveling, pregnancy, and breast-feeding. Seven girls in the control and 9 in the insomnia group reported taking hormonal birth control. Participants were required to have a smartphone with Android 7.0+ or iOS 12.2+.

Procedure

The study consisted of a 2-month EMA (see Fig. 1) conducted between January 2019 and April 2021. Instructions and devices were given via in-lab appointments at SRI International and/or online calls. Participants were instructed to install the Fitbit App on their mobile phones using ad-hoc e-mail addresses without personal information, wear a Fitbit Charge 3 (FC3; Fitbit, LLC., San Francisco, CA) 24/7 on

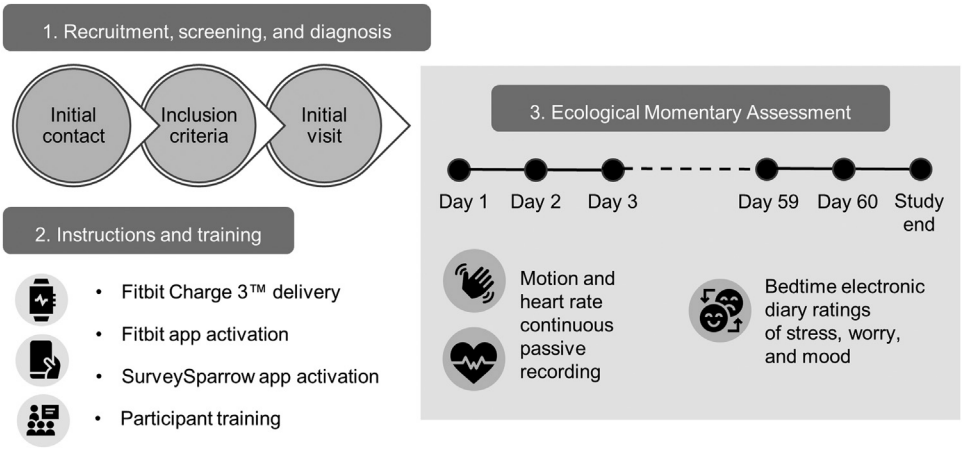

Fig. 1. Preliminary phases and structure of the ecological momentary assessment (EMA) protocol. Icons were made by Freepik from www.flaticon.com and licensed by the Creative Commons 3.0

their nondominant wrist for 2 months, and synch the device with the Fitbit App every morning. Notifications and data feedback were deactivated, and participants were instructed to not run any update or change settings in the Fitbit App. To collect daily stress, worry, and mood data, participants were also instructed to fill out a mobile-based electronic diary each evening before bedtime. Diaries were administered using SurveySparrow (SurveySparrow Inc, Palo Alto, CA) at 8 PM, accepting responses until the following morning.

Measures

Objective assessment of night-time sleep, heart rate, and physical activity

The multi-sensor (photoplethysmography + accelerometry) FC3 device was used to measure sleep, HR, and physical activity. The FC3 and other Fitbit models have been repeatedly tested against reference methods, showing similar/better performance than standard actigraphy,[22] and the FC3 performance has been recently evaluated in 42% of the current sample who underwent concurrent in-lab polysomnography.[23] Firmware versions used were 1.49.45 and the following 4 updates (1.49.46-1.49.49, each used by 1-to-36 participants).

FC3 devices were connected to the Fitabase platform (Small Steps Labs LLC., San Diego, CA), from which we exported sleep, HR, and steps count data, and we implemented a preprocessing pipeline for accurately represent night-time sleep and filtering atypical/unreliable cases (Appendix B). Then, we used the preprocessed 30-second epoch-by-epoch sleep classifications for computing the study outcomes (see[24]) for each night-time sleep period (ie, inactivity period starting between 6 PM and 6 AM and with a sleep duration $\geq$3 hours) (see details in Appendix B), including time in bed (TIB, minute), total sleep time (TST, minute), wake after sleep onset (WASO, minute), sleep efficiency (SE, %), and the percentage of time in "light," "deep," and rapid-eye-movement (REM) sleep over TST, in addition to the number of hours between midnight and sleep onset (SO) and wake-up time, respectively. For core sleep architecture (TIB, TST, WASO) and timing (SO, wake-up time), we computed night-to-night variability as the squared differences between the value of each variable on a given night and the value of the same variable on the previous night, as high variability has been reported in adult insomnia.[25] Minute-level HR was used for computing non-REM sleep (NREM-HR) and REM sleep-related (REM-HR) mean HR (bpm). Finally, the total number of steps per day was computed as an index of physical activity. For all variables, we also recorded whether the measurement was taken on a night before a weekday (Sunday-to-Thursday) or on a night before a weekend day (Friday-to-Saturday).

Subjective assessment of stress, worry, and mood

Daily stress ("How stressful was your day?") and presleep worry ("How worried do you feel right now?") (1="Not at all stressful/worried," 2="Not so stressful/worried," 3="Somehow stressful/worried," 4="Very stressful/worried," 5="Extremely stressful/worried") and mood ("How is your mood right now?") (1="Very bad," 2="Somehow bad," 3="Neither bad nor good," 4="Somehow good," 5="Very good") were rated via the electronic diaries using Likert scales (see Appendix A). All participants were requested to complete the diary at bedtime. In cases of missed data entries (eg, participants forgot to complete the diary), they were instructed to complete the diary as soon as possible on the following morning, referring their ratings to the previous evening (eg, "How worried were you feeling yesterday, at bedtime?"). When rated with a score higher than 1, stress and worry items triggered multiple-choice questions on contextual sources of stress/worry, namely "school," "family," "health," "peers," "COVID-19," and "others." To improve the psychometric qualities of the ratings, we also computed an aggregate "global distress" score, whose multilevel confirmatory factor analysis showed satisfactory fit indices ($\chi^2(1)$ = 3.92, RMSEA = 0.024, CFI = 0.999, SRMR-within < 0.001, SRMR-between = 0.026) and reliability (ω-between = 0.92, ω-within = 0.67) (see Appendix C).

Statistical analyses

Analyses were conducted with R 4.2.0,[26] using generalized linear mixed-effects regression (GLMER) with the maximum likelihood estimator. GLMER is appropriate for multilevel datasets, with daily observations (level-1) nested within participants (level-2), unbalanced observations, and deviations from normality.[27,28] For each outcome, a hierarchical regression was conducted by including the predictors one-by-one to a baseline model. Level-1 continuous predictors were person-mean-centered, whereas level-2 predictors were grand mean-centered before fitting any model. At each step, models were evaluated and compared based on the likelihood ratio test (significant level set at $p < .05$, Benjamini-Hochberg-corrected for multiple comparisons within each set of models) and the weight of the Akaike Information Criterion (Aw).[29] We interpreted significant likelihood ratios, higher Aw than all previous models, and high coefficient/standard error ratios as signs of substantial effects.

Several robustness checks were conducted accounting for the arbitrariness of data processing and analytical choices: selection of participants with "full-clinical" (n = 26) vs. "sub-clinical" (n = 21) DSM-5 insomnia disorder; inclusion of COVID-19-related data collection period (n = 39) as a further covariate; exclusion of participants with less than 2 weeks of observations in any data type (n = 7); removal of daily steps from the models; exclusion of diary forms filled in the morning (n = 1010, 20.5%); and use of alternative GLMER distribution families.

Results

Based on Fitbit data, a total of 5,121 sleep periods were identified (average compliance: 88.5 ±20.8%), of which 85.9% included valid sleep stages data, 84.5% with sleep-related HR, 84.2% with steps, and 84.6% with diary data (compliance with the diary protocol: 87.2 ±15.5%) (see Table 1).

Daily patterns of sleep, stress, worry, and mood

Table 1 shows the descriptive statistics of the main variables for the insomnia and control groups. As a whole group, adolescents went to sleep at 00:31 AM (±1.63 hours) and woke up at 8:14 AM (±1.62 hours), with an average TIB of 7.81 (±1.54) hours, of which 6.90 (±1.35) classified as sleep. Ratings of "very/extreme" stress and worry and "somehow/very bad" mood were recorded on 12.3%, 12.6%, and 14.5% of the days, respectively. "School" was the most frequently reported source of stress (43.4%) and worry (45.4%), with 31-to-52.3% diary entries being associated with multiple sources (see Fig. 2).

First, we specified a set of baseline GLMER models (M1) predicting sleep outcomes by several covariates (ie, SO, prior-day step counts, weekend/weeknights differences, participants' age and BMI). Then, the group factor (ie, controls vs. insomnia) (M2) was included as an additional predictor to the baseline models M1 (hypothesis H1), followed by participants' sex (M3), and the insomnia-by-sex interaction (M4). The results did not support the incremental contribution of group differences in predicting any sleep architecture and sleep timing outcome ($\chi^2(1)$ ranging from 0.01 to 2.37, p = .37-.90, Aw = 0.27-0.45) over the set of included covariates. Some differences only emerged for night-to-night variability outcomes (modeled with Gamma distribution and log link function), with the insomnia group showing substantially (although not significantly after correction for multiple comparisons) lower variability in TIB ($\chi^2(1)$ = 4.49, p = .10, Aw = 0.79, exp(B) = 0.77 (standard

Table 1
Descriptive statistics and zero-order Pearson correlations between the main continuous variables

	No. obs.	Controls mean (SD)	Insomnia mean (SD)	ICC	Correlation coefficients														
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Fitbit-based outcomes																			
1. TIB (min)	5,121	466.09 (96.68)	470.82 (87.7)	0.18		*0.97*	*0.56*	-0.13	-0.01	-0.09	0.10	*-0.46*	*0.62*	-0.01	-0.07	0.02	-0.06	-0.09	0.00
2. TST (min)	5,121	413.04 (84.71)	415.43 (77.07)	0.17	*0.97*		*0.36*	0.11	-0.04	-0.08	0.14	*-0.44*	*0.61*	-0.01	-0.07	0.03	-0.06	-0.09	0.00
3. WASO (min)	5,121	46.98 (22.66)	49.33 (25.09)	0.20	*0.54*	*0.32*		*-0.81*	0.14	-0.06	-0.14	-0.28	*0.34*	0.02	-0.02	0.01	-0.03	-0.03	0.01
4. SE (%)	5,121	88.74 (3.77)	88.38 (4.29)	0.22	-0.29	-0.03	*-0.90*		-0.19	0.02	0.24	0.06	-0.06	0.00	0.01	0.02	-0.01	0.00	0.00
5. "Light" sleep (%)	4,401	57.70 (8.01)	59.90 (8.33)	0.31	0.25	0.15	*0.42*	*-0.40*		*-0.71*	*-0.74*	-0.01	-0.01	-0.02	0.02	-0.03	-0.02	-0.01	0.01
6. "Deep" sleep (%)	4,401	20.08 (5.15)	19.51 (5.33)	0.24	-0.22	-0.22	-0.10	0.05	*-0.51*		0.05	0.07	-0.03	0.04	-0.02	0.02	0.01	0.01	-0.01
7. REM sleep (%)	4,401	22.22 (6.32)	20.60 (5.90)	0.41	-0.14	-0.03	*-0.41*	*0.43*	*-0.82*	-0.07		-0.06	0.05	-0.01	-0.01	0.03	0.01	0.00	0.00
8. SO (hh from 00:00)	5,121	0.51 (1.68)	0.54 (1.58)	0.47	*-0.56*	*-0.53*	*-0.37*	0.20	-0.11	0.12	0.05		*0.41*	-0.01	0.03	-0.02	-0.07	-0.06	-0.08
9. Wake-up time (hr from 00:00)	5,121	8.17 (1.63)	8.28 (1.61)	0.31	0.02	0.04	-0.06	0.05	0.04	-0.01	-0.03	*0.82*		-0.01	-0.04	0.01	-0.13	-0.14	-0.07
10. NREM-HR (bpm)	4,327	61.43 (8.6)	58.58 (6.70)	0.76	0.15	0.17	-0.01	0.05	-0.29	0.00	*0.34*	-0.24	-0.19		*0.81*	0.17	0.04	-0.01	-0.02
11. REM-HR (bpm)	4,325	63.48 (8.50)	60.57 (6.46)	0.74	0.12	0.14	-0.03	0.06	-0.28	-0.09	*0.38*	-0.16	-0.11	*0.95*		0.14	0.05	-0.02	-0.02
12. Daily steps (No.)[a]	4,664	8.89 (5.61)	7.45 (4.60)	0.42	-0.09	-0.10	0.05	-0.06	0.01	0.06	-0.06	-0.17	-0.25	-0.12	-0.18		-0.05	-0.06	-0.10
Mobile diary ratings																			
13. Stress (1-5)	4,932	2.16 (1.02)	2.27 (1.13)	0.26	-0.09	-0.07	-0.14	0.09	-0.08	0.08	0.04	0.03	-0.03	-0.07	-0.05	0.15		*0.38*	*0.36*
14. Worry (1-5)	4,932	2.21 (1.04)	2.27 (1.13)	0.33	-0.12	-0.10	-0.10	0.06	-0.13	0.12	0.07	0.13	0.08	-0.14	-0.10	0.06	*0.88*		*0.45*
15. Bad mood (1-5)	4,932	2.49 (0.98)	2.30 (1.07)	0.25	-0.09	-0.11	-0.04	-0.03	-0.15	0.05	0.14	0.11	0.05	0.04	0.03	0.05	*0.49*	*0.55*	
Demographics																			
16. Age (years)[b]	93	18.14 (0.94)	17.7 (0.92)		0.04	-0.01	0.18	-0.19	0.03	-0.08	0.02	-0.21	-0.22	0.27	0.19	*0.43*	-0.11	-0.21	0.08
17. BMI (kg m^{-2})	93	22.34 (3.70)	21.30 (2.58)		-0.02	0.01	-0.06	0.11	-0.23	0.11	0.20	-0.26	*-0.32*	0.28	0.22	0.04	-0.04	-0.06	0.06

ICC, intraclass correlation coefficient; TIB, Time in bed; TST, Total sleep time; SE, sleep efficiency; WASO, wake after sleep onset; REM, rapid-eye-movement; SO, sleep onset; HR, heart rate; NREM, non-REM sleep; BMI, body mass index.
Descriptive statistics in the 2 groups are reported as mean (standard deviation). Correlations between individuals (level 2) are shown below the diagonal, whereas within-individual correlations are shown above the diagonal. Italic text highlights correlations ≥ .30.
[a] Daily steps are reported as thousands of steps per day for better comparability with other measures
[b] Age and BMI correlated at $r = 0.06$.

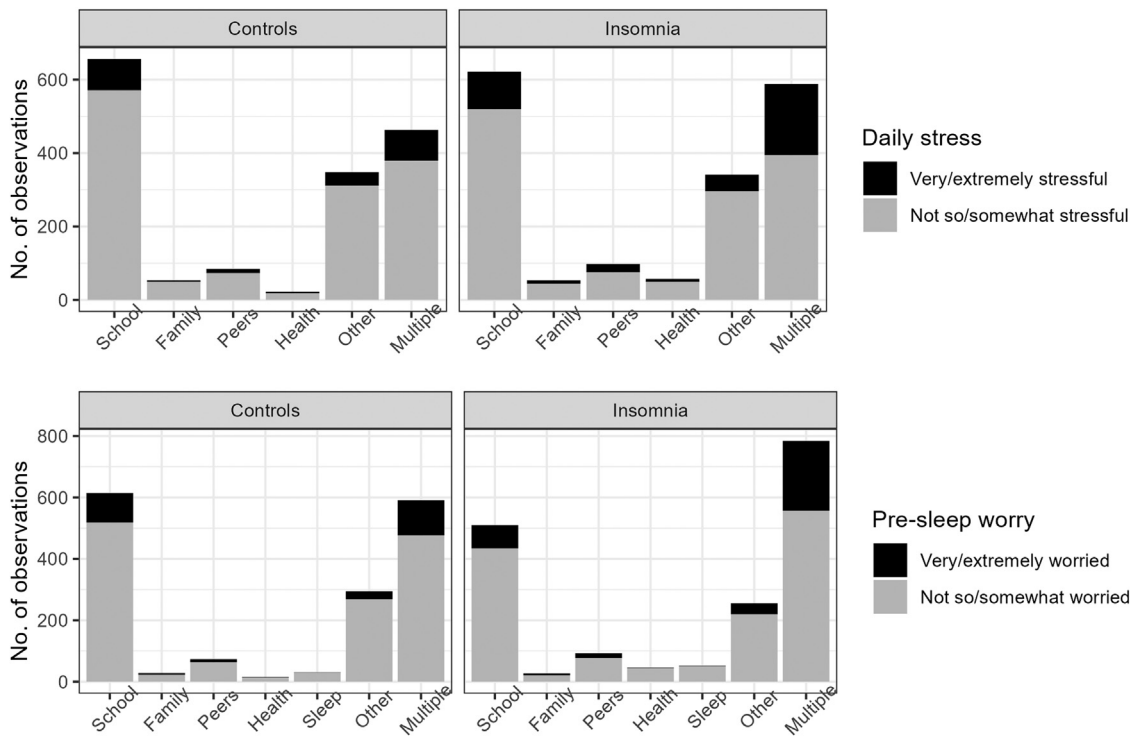

Fig. 2. Number of diary entries by reported source and level of daily stress and presleep worry in the 2 groups of adolescents ("Multiple" sources identify the number of cases in which 2 or more response options were selected)

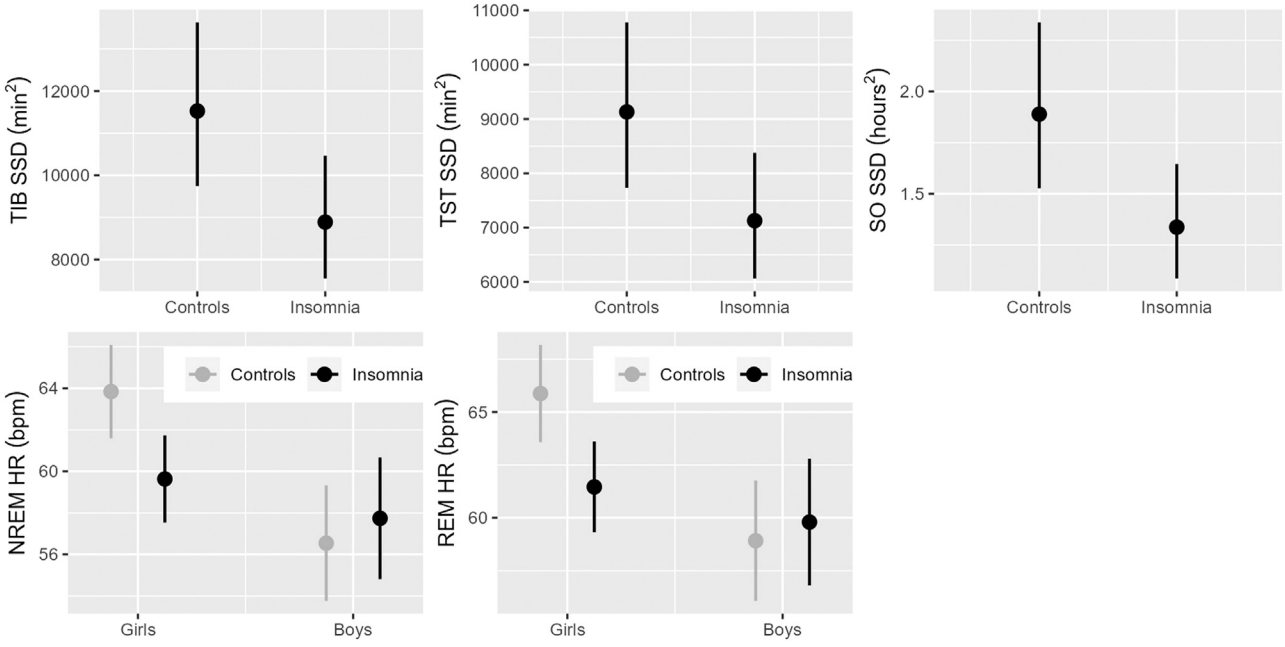

Figure 3. Parameters (dots) and 95% confidence intervals (error bars) estimated by models M2 for group differences in time in bed (TIB), total sleep time (TST) and sleep onset (SO) squared successive differences (SSD), and by model M4 for group-by-sex differences in mean nonrapid-eye-movement (NREM)- and REM-related mean heart rate (HR)

error = 0.09)) and TST ($\chi^2(1) = 4.18$, $p = .12$, Aw = 0.75, exp(B) = 0.78 (0.09)), and significantly lower variability in SO ($\chi^2(1) = 6.88$, $p = .03$, Aw = 0.92, exp(B) = 0.67 (0.10)), compared to the control group (see Fig. 3). Results were overall consistent, although robustness checks highlighted that group differences in sleep variability were driven by participants meeting "full-clinical" DSM-5 criteria, whereas no subgroup differences were found for sleep architecture and timing outcomes (see details in Appendix C).

As shown in Fig. 3, night-time HR was predicted by the interaction between sex and insomnia (M4), with substantially (but not significantly after correction for multiple comparisons) lower NREM- ($\chi^2(1) = 4.35$, $p = .055$, Aw = 0.76, B = -4.21 (1.60) bpm) and REM-HR ($\chi^2(1) = 4.01$, $p = .07$, Aw = 0.72, B = -54.41 (1.64) bpm) in girls with insomnia symptomatology compared to girls without insomnia symptoms, and no differences among boys (NREM-HR: interaction's B=5.40 (2.56) bpm; REM-HR: interaction's B = 5.30 (2.62) bpm). Overall, girls showed higher NREM- (B = 7.30 (1.83) bpm) and REM-HR (B = 6.96 (1.87) bpm) compared to boys.

Similar models were specified for predicting diary ratings (hypothesis H2), only including daily steps and weekends as covariates in the baseline models M1. No substantial group differences (M2) were found in terms of stress, worry, mood ($\chi^2(1) = 0.01$-3.50, $p = .14$-$.91$), and the aggregate "global distress" score (see Appendix C). However, considering "full clinical" and "sub-clinical" DSM-5 insomnia as separate groups led to substantially higher stress ($\chi^2(2) = 10.00$, $p = .007$, Aw = 0.95; odds ratio (OR)[1]=2.35 (0.67)) and worry ($\chi^2(2) = 8.44$, $p = .015$, Aw = 0.90; OR = 2.26 (0.78)) in the "full clinical" compared to the control group, and no differences between the latter and the "sub-clinical" group.

Several outcomes were significantly predicted by the included covariates consistently over models M1-M4 (see examples in Table 2 and Table 3, and details in Appendix C), with later SO showing the strongest and most consistent effects, predicting later wake-up times, shorter TIB, TST, and WASO, higher SE and time in "deep" sleep, lower time in REM sleep and WASO variability, and higher REM-HR. Weekends were associated with longer TIB, TST, and WASO, later SO and wake-up time, higher night-to-night sleep variability, and lower stress, worry, and negative mood than weekdays. On those days associated with more steps than usual, participants showed earlier SO, higher nocturnal HR, and lower stress and bad mood. Higher BMI was associated with earlier wake-up times, and with higher night-time HR and night-to-night variability in TIB and TST, whereas older age predicted longer WASO and lower SE. In both groups, boys were characterized by later SO and shorter TST than girls.

Reciprocal relationships between adolescents' sleep and stress, worry, and mood

The intraindividual relationships between adolescents' sleep and diary ratings (hypothesis H3) were evaluated by including prior-day ratings (M5) as further predictors in addition to those listed above (ie, for each outcome, we only retained those predictors showing substantial effects from models M1-M4). Then, we added the relationship between sleep and the corresponding next-day diary ratings (M6, hypothesis H4), followed by the interaction between prior-day ratings and insomnia (M7, hypothesis H5). Considering the medium-to-strong correlations among diary measures (see Table 1), the 3 ratings were included in separate models to reduce multicollinearity.

Model comparisons indicated substantial additional contributions of worry and stress (M5) in predicting shorter TIB and TST, and earlier SO and wake-up time (see Table 2 and Table 3), with earlier SO being also predicted by negative mood ($\chi^2(1) = 17.82$, $p < .001$, Aw = 0.99, B = -0.09 (0.02) hours), whereas WASO was only negatively related with prior-day worry (see Table 2). Higher-than-usual stress was also positively associated with higher REM-related HR (see Table 4).

Some sleep outcomes were bidirectionally associated with stress ratings. As shown in Table 3, model M6 including next-day stress was selected for TIB, TST, and wake-up time, showing substantial relationships in the same directions of the direct effects reported above, whereas WASO was substantially related to next-day but not to prior-day stress ratings. Similarly, next-day but not prior-day negative mood was positively related to NREM-HR and REM-HR (although only the former relationship was significant; see Table 4). These

[1] Diary items were binarily recoded (ie, 0 = item rated as 3 or lower, 1 = item rated as 4 or 5) in models M1-M3, and modeled using logistic GLMER.

Table 2
Unstandardized parameters estimated by the selected models M5 of the relationships between sleep architecture and timing and presleep worry controlling for level-1 and level-2 covariates (N = 4333 obs. from 93 participants)

	TIB (min)		TST (min)		WASO		SO (h from 00:00)		Wake-up time (h from 00:00)	
Predictors	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*
Intercept	451.33 (4.45)	442.50, 460.13	406.24 (4.55)	397.22, 415.23	46.39 (1.15)	44.04, 48.52	0.47 (0.11)	0.24, 0.69	8.00 (0.09)	7.81, 8.18
SO (h from 00:00)	-35.28 (0.91)	-37.07, -33.49	-30.21 (0.82)	-31.81, -28.61	-5.36 (0.26)	-5.87, -4.84			0.41 (0.02)	0.38, 0.45
Week time (weekend)	49.41 (2.39)	44.71, 54.10	43.88 (2.14)	39.69, 48.07	6.15 (0.68)	4.80, 7.49	0.43 (0.04)	0.35, 0.51	0.83 (0.04)	0.76, 0.91
Sex (boys)			-20.37 (7.51)							
Age (years)					2.34 (1.18)	0.01, 4.67				
BMI (kg m^{-2})							-0.09 (0.04)	-0.16, -0.02	-0.10 (0.03)	-0.16, -0.04
Prior-day worry (1-5)	-8.11 (1.18)	-10.43, -5.79	-7.22 (1.06)	-9.29, -5.15	-0.73 (0.34)	-1.39, -0.06	-0.06 (0.02)	-0.10, -0.02	-0.13 (0.02)	-0.17, -0.09
SD (intercept)	40.93		33.29		10.32				0.88	
$\chi^2(1)$	50.54***		47.66***		7.34*		8.18*		48.19***	
Aw	0.99		0.99		0.93		0.96		0.99	

TIB, time in bed; TST, total sleep time; WASO, wake after sleep onset; SO, sleep onset; BMI, body mass index; B, unstandardized regression coefficient; SE, standard error; CI, profile-likelihood confidence intervals.
Worry ratings and SO were person-mean-centered, and BMI was grand-mean-centered before fitting the models. The table also shows the result of the likelihood ratio test and the Akaike weight (Aw) associated with the inclusion of prior-day presleep worry in each model.
* $p < .05$.
*** $p < .001$.

results were overall consistent across the robustness checks, whereas sleep stages and night-to-night sleep variability outcomes showed mostly unsubstantial and inconsistent results (see Appendix C).

Finally, a substantial and consistent (but not statistically significant after correction for multiple comparisons) interaction between diary ratings and insomnia (M7) was only highlighted for NREM-HR, such that the positive relationship between stress and NREM-HR was substantial in the insomnia but not in the control group (see Table 4).

Discussion

In this study, we used a 2-month EMA to characterize and explore the interplay between sleep, stress, worry, and mood in adolescents with and without insomnia. Contrarily to hypothesis H1, we did not find an overall pattern of disturbed sleep in the insomnia group compared to controls, and this null result was consistently reproduced across a number of robustness checks, including the separate

Table 3
Parameters estimated by the selected models M5-M6 of the relationships between sleep architecture and timing and daily stress controlling for level-1 and level-2 covariates (N = 3,798 obs. from 92 participants)

	TIB (min)		TST (min)		WASO (min)		SO (h since 00:00)		Wake-up (h since 00:00)	
Predictors	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*
Intercept	459.02 (5.46)	448.18, 469.81	406.12 (4.61)	396.96, 415.21	46.47 (1.15)	44.20, 48.74	0.49 (0.11)	0.27, 0.71	8.03 (0.09)	7.85, 8.21
SO (h from 00:00)	-37.21 (0.99)	-39.14, -35.28	-32.03 (0.88)	-33.76, -30.30	-5.49 (0.28)	-6.04, -4.94			0.37 (0.02)	0.34, 0.41
Week time (weekend)	51.31 (2.52)	46.36, 56.25	45.92 (2.26)	41.49, 50.35	5.77 (0.72)	4.35, 7.18	0.45 (0.04)	0.37, 0.53	0.86 (0.04)	0.78, 0.94
Sex (boys)	-19.66 (9.13)	-37.71, -1.55	-18.55 (7.69)	-33.77, -3.28						
Age (years)					2.16 (1.19)	-0.19, 4.53				
BMI (kg m-2)							-0.09 (0.03)	-0.15, -0.02	-0.09 (0.03)	-0.15, -0.03
Prior-day stress (1-5)	-5.17 (1.23)	-7.57, -2.76	-4.71 (1.10)	-6.87, -2.53	-0.63 (0.35)	-1.32, 0.06	-0.06 (0.02)	-0.10, -0.02	-0.09 (0.02)	-0.13, -0.05
Next-day stress (1-5)	-7.18 (1.24)	-9.60, -4.76	-6.28 (1.11)	-8.45, -4.11	-1.12 (0.35)	-1.81, -0.43			-0.12 (0.02)	-0.16, -0.08
$\chi^2(1)$	33.64***		32.03***		10.04**		9.46**		35.41***	
Aw	0.99		0.99		0.98		0.98		0.99	

TIB, time in bed; TST, total sleep time; WASO, wake after sleep onset; SO, sleep onset; BMI, body mass index; B, unstandardized regression coefficient; SE, standard error, CI, profile-likelihood confidence intervals.
When used as predictors, SO and stress ratings were person-mean-centered, while BMI and age were grand-mean-centered before the analyses. The table also shows the result of the likelihood ratio test and the Akaike weight (Aw) associated with the inclusion of prior- (M5; only selected for predicting SO) or next-day (M6) daily stress in each model.
** $p < .01$;
*** $p < .001$.

Table 4
Parameters estimated by the selected models M5-M7 of the relationships between sleep autonomic functioning and, respectively, stress and mood ratings

	NREM HR (bpm)				REM HR (bpm)			
	By stress (M7)		By mood (M6)		By stress (M5)		By mood (M6)	
Predictors	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*	*B (SE)*	*95% CI*
(Intercept)	63.15 (1.04)	61.09, 65.21	61.53 (0.81)	59.92, 63.14	63.67 (0.84)	62.00, 65.33	63.53 (0.84)	61.87, 65.20
SO (h from 00:00)					0.18 (0.06)	0.05, 0.30	0.19 (0.07)	0.06, 0.33
Daily steps (No.)[a]	0.16 (0.02)	0.12, 0.19	0.15 (0.02)	0.11, 0.19	0.14 (0.02)	0.10, 0.17	0.13 (0.02)	0.09, 0.17
Week time (weekend)	0.36 (0.17)	0.03, 0.70	0.36 (0.17)	0.02, 0.69				
Sex (boys)	-4.42 (1.34)	-7.08, -1.76	-4.26 (1.38)	-6.99, -1.52	-4.41 (1.40)	-7.19, -1.63	-4.18 (1.43)	-7.02, -1.34
BMI (kg m-2)	0.47 (0.20)	0.07, 0.86	0.55 (0.20)	0.15, 0.95				
Insomnia (yes)	-3.07 (1.29)	-5.63, -0.51						
Prior-day stress (1-5)	-0.01 (0.12)	-0.24, 0.22			0.21 (0.08)	0.05, 0.36		
Next-day stress (1-5)	-0.05 (0.08)	-0.21, 0.11						
Prior-day stress (1-5) × Insomnia (yes)	0.35 (0.16)	0.03, 0.66						
Prior-day negative mood (1-5)			-0.05 (0.09)	-0.22, 0.12			-0.10 (0.09)	-0.28, 0.07
Next-day negative mood (1-5)			0.20 (0.09)	0.03, 0.37			0.19 (0.09)	0.02, 0.36
SD (Intercept)	5.96		6.15		6.39		6.39	
No. participants (days)	90 (2773)		90 (2773)		92 (3177)		90 (2789)	
$\chi^2(1)$	4.72		5.53*		6.25*		4.78	
Aw	0.69		0.62		0.89		0.60	

REM, rapid-eye-movement sleep; NREM, non-REM sleep; HR, heart rate; SO, sleep onset; BMI, body mass index; B, unstandardized regression coefficient; SE, standard error, CI, profile-likelihood confidence intervals.

[a] Daily steps were operationalized as thousands of steps per day for better comparability with other measures. SO, daily steps, and diary ratings were person-mean-centered, and BMI was grand-mean-centered before the analyses. The table also shows the result of the likelihood ratio test and the Akaike weight (Aw) associated with the inclusion of prior- (M5) or next-day (M6) diary ratings, or the interaction between diary ratings and insomnia (M7), in each model.

* $p < .05$.

consideration of participants with "full-clinical" and "partial-clinical" symptomatology. While these findings contrast with some previous actigraphic studies conducted with adults,[30] they are coherent with some recent adolescence studies that failed at least partially to objectively characterize adolescent insomnia.[31,32] For instance, Fernandez-Mendoza and colleagues[15,31] identified specific phenotypes of adolescent insomnia based on the presence/absence of objective "short" (≤7 hours) sleep duration, reporting worse outcomes (depression, systemic inflammation) for those showing both self-reported sleep difficulties and objectively "short" sleep.

Several factors might have contributed to the lack of evidence of objective sleep alterations in the insomnia group, a result common to previous literature that rarely reported objective sleep disturbances in insomnia as pronounced as subjective complaints.[32] For instance, it might be that the objective correlates of sleep perception differed between insomnia and controls. Indeed, paradoxical insomnia, characterized by subjective report of insomnia but healthy objective sleep profile (ie, sleep discrepancy), is a common subtype of insomnia.[33] In addition, the lack of group differences in this age group might be partially explained by a common persistent regime of "sleep restriction" due to a biological push for later bedtime coupled with a social push for early wake-up time.[1,2] Such a chronic sleep restriction might mask some sleep variance especially in the insomnia group, which may only become unmasked during times of adequate sleep opportunities (eg, vacation time). Future studies should investigate the overlooked day-to-day relationship between objective and subjective insomnia symptoms (eg,[20]) in adolescents with insomnia diagnoses. Indeed, while prevalence studies indicated a disproportion between the rate of adolescents reporting daily insomnia symptoms and that of those meeting diagnostic criteria for insomnia,[34] only the latter self-reports (ie, interview-based) were considered in our study.

In contrast, higher self-reported stress and worry were observed in adolescents with "full-clinical" DSM-5 insomnia disorder, in line with hypothesis H2 and previous laboratory findings of profound clinical differences across several self-reported domains.[13] High stress and worry levels might contribute to a broader dysfunctional psychophysiological activation (hyperarousal) that induces disturbed sleep,[14,15,17,35] which might be particularly prominent in adolescents experiencing insomnia symptoms with higher weekly frequency (ie, "full-clinical disorder"). Consistently, we found higher REM-HR in those days associated with higher stress than usual. The same relationship was found for NREM-HR, but only in the insomnia group, possibly highlighting greater vulnerability to stress-induced psychophysiological activation than controls (hypothesis H5). Moreover, in line with hypothesis H3, we found shorter TIB and TST associated with higher-than-usual ratings of stress and worry, as well as earlier wake-up time, possibly indicative of early awakenings, independently from SO.

While these results may indicate stress-induced sleep disturbances, they might also be explained by spurious relationships due to external contingencies. For instance, considering the relatively high frequency of school-related stress and worry, it might be that

adolescents went to bed and woke up earlier when approaching school-related stressors, spending less TIB than usual (implying shorter TST and WASO), while at the same time experiencing higher stress and worry at bedtime. This might also explain the negative relationship highlighted between WASO and worry, those found between earlier SO and both worry and stress, and the negative relationships highlighted between next-day stress (hypothesis H4) and TIB, TST, WASO, and earlier wake-up time, respectively. Future studies should build from these results by employing event-focused designs to disentangle these 2 interpretations. For instance, future research might sample days/nights around the occurrence of exams and other school-related stressors.

Overall, our results were in line with epidemiological studies (see[36]) indicating that adolescents in the U.S. typically spend less than the minimum recommended 8 hours of sleep per night.[37] Sleep duration was even shorter when adolescents went to sleep later than usual, although this also implied shorter WASO. In contrast, weekend nights were characterized by longer TST (~45 minutes) despite later SO (~25 minutes later) and similar SE compared to weeknights. Consistent with previous studies,[4,38] we found more disrupted and less efficient sleep in older compared to younger adolescents, while girls showed overall earlier SO, longer TST, and higher HR during sleep than boys. Reasons for these sex differences may be related to the higher need for sleep in teenage girls than boys, as recent evidence suggests that adolescent girls are more vulnerable to insufficient sleep.[13,39] In contrast to our predictions, we found HR was not higher in adolescents with insomnia but, rather, we highlighted a nonsignificant trend with lower sleeping HR in girls with insomnia than their healthy peers. Such unexpected findings should be better investigated in larger samples covering the spectrum of clinically relevant insomnia and accounting for other confounders potentially contributing to HR profiles,[40] such as physical fitness levels.

Our results support the importance of intervening on psychosocial (especially school-related) stressors and their cognitive appraisal for promoting healthy adolescent sleep. Based on consistent evidence identifying presleep perseverative cognitions as risk factors for adolescent sleep,[41] the potential sleep loss implied by psychosocial stressors might be reduced by approaching exams and other stressful events with adequate strategies that promote relaxation, including deep breathing and mindfulness.[42] For instance, our results suggest that physical activity might predict lower perceived stress, better presleep mood, and earlier SO, although leading to higher nocturnal HR. At the subjective level, the weekly frequency criterion introduced by the DSM-5[21], which likely characterizes a greater severity of insomnia symptomatology, might be an important condition to be considered, as it might be more predictive of insomnia-related stress and worry.

The limitations of the present study include the selective focus on night-time sleep (ie, day-time naps were not considered), the lack of daily subjective indicators of sleep quality, and the use of single-item measures for the subjective evaluation of stress, worry, and mood. Moreover, whereas our sampling strategy allowed diagnosis-based group comparisons (which is rarely achieved in EMA and other longitudinal studies), it also introduced some selection bias making our findings less generalizable. Indeed, we were only able to recruit a limited number of participants meeting "full" DSM-5 criteria for insomnia disorder and our sample was overall unbalanced by sex, mainly due to the difficulties in recruiting boys with insomnia. While higher prevalence of insomnia symptomatology in girls is in line with the literature,[10,11] the findings concerning sex differences should be interpreted with caution. Finally, despite the increasing accuracy of multi-sensor sleep trackers in objectively measuring sleep,[19,22] their performance in sleep stages classification is still limited (see[23]), a factor that may have affected our findings.

Conclusions

This is one of the first studies analyzing intensive longitudinal data from both wearable and mobile technology to investigate insomnia disorder in adolescence based on clinical diagnosis. Findings summarize how adolescent sleep is influenced by several modifiable behavioral variables, such as sleep timing, physical activity, and subjective well-being indicators. Specifically, this study revealed patterns of direct and reciprocal relationships between adolescents' sleep and their subjective experience of daily stress and presleep worry, indicating a tendency for adolescents with insomnia to have higher levels of these states and greater sensitivity to stress-related autonomic arousal during sleep, despite them not differing from controls on sleep architecture and timing. Findings point to new directions of multifactorial treatment approaches involving effective strategies for coping with presleep emotional arousal as possible key therapeutic targets in adolescent insomnia management. Further studies should better investigate the development of insomnia from adolescence into adulthood, using diaries and wearables to track whether objective alterations in sleep emerge later in time.

Appendices

All Appendices are available from https://github.com/SRI-human-sleep/INSA-home

A: Daily diary form used in the study.
B: Data preprocessing pipeline, R code, and outputs.
C: Data analysis pipeline, R code, and outputs.
D: Datasets used for the analyses.

Disclosures

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