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Multidimensional association of sleep health with dietary habits and physical activity in adolescents

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ABSTRACT

Background: While insufficient sleep is associated with poor lifestyle factors, a multidimensional approach assessing multiple sleep health dimensions via subjective and objective measures has emerged as a more comprehensive method of investigating these relationships. We examine the multidimensional association between sleep health, diet, and physical activity (PA).

Methods: We studied 373 adolescents from the Penn State Child Cohort (16.4 ± 2.3 years; 46.6% female; 20.9% racial/ethnic minority), of whom 234 (63.5%) were evaluated while in-school. Sleep dimensions were assessed via self-reports, actigraphy (ACT), and polysomnography (PSG). PA was assessed via ACT and self-reports, metabolic equivalent of task (MET) via ACT, and diet via self-reports. Stepwise multivariable-adjusted regression models tested the association between sleep dimensions and lifestyle factors.

Results: Later self-reported and ACT-measured bedtime and rising time were associated with more snacking, higher caloric intake, and sedentarism. A later ACT-measured sleep midpoint was associated with higher carbohydrate intake and more snacking. Higher ACT-measured sleep variability was associated with higher sedentarism. Longer self-reported or ACT-measured sleep latency was associated with more snacking and higher PA and METs. Longer ACT-measured time in bed was associated with lower PA. Sleep dimensions were more strongly associated with diet, PA, and sedentarism among adolescents evaluated while in-school, whereas they were more strongly associated with snacking among those on-break. PSG-measured sleep dimensions were not strongly associated with lifestyle factors; although a greater apnea/hypopnea index was associated with lower METs and greater sedentarism, it was not significant after adjusting for BMI.

Conclusions: Evaluating sleep with a multidimensional approach better captures its association with lifestyle factors. Future research should assess downstream effects on cardiovascular outcomes.

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Introduction

Obesity is a complex medical condition, and a fifth of the US children and adolescents are considered “obese” based on body mass index (BMI) percentile criteria.[1] Current evidence shows that obesity during adolescence strongly predicts obesity in adulthood, making this a critical time to implement lifestyle interventions.[2-4] During adolescence, actions geared toward preventing and managing obesity are most effective when targeting both diet, using low-fat nutrient-dense foods, with minimal added sugars, refined starchers, saturated fats, or sodium,[5] and engage for at least 60 minutes in moderate-to-vigorous physical activity (MVPA) daily[6,7]; however, few interventions have incorporated sleep among its therapeutic strategies.[8] Sleep, like diet and PA, occurs within the 24-hour cycle, has a bidirectional relationship with those health behaviors,[9,10] and has been recognized as an important modifiable risk factor for cardiometabolic health.[11]

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What was known

Insufficient sleep in adolescents has been consistently associated with poorer dietary quality and lower physical activity, both of which contribute to increased cardiovascular risk. However, most prior studies have relied on single sleep metrics (e.g., duration) and self-reported measures, limiting our understanding on how multiple sleep dimensions and assessment methods relate to lifestyle behaviors.

What this study adds

This study demonstrates that multiple dimensions of sleep health are differentially associated with diet composition, snacking patterns, sedentary behavior, and physical activity in adolescents. By integrating self-report, actigraphy, and polysomnography measures of sleep, the findings show that sleep timing and regularity dimensions are more strongly linked to lifestyle behaviors than other sleep dimensions, and that these associations vary by whether youth are attending school or are on-break.

Prompted by pubertal changes,[12] sleep undergoes both homeostatic and circadian changes, particularly a delay in the timing of sleep during adolescence[13] that stabilizes in adulthood.[14] As such, adolescents become more "evening-types" compared with their childhood years, showing a preference for later sleep and wake times and experiencing peak alertness and performance in the late afternoon or evening hours (in contrast to morning-types who tend to wake up and feel most alert and productive earlier in the day, with earlier sleep onset and offset times).[15,16] In addition, adolescents face unique challenges that further interfere with their sleep, for example, early school schedules, academic pressures, social needs, and device use.[17–19] These typically result in poor sleep quality, irregular sleep-wake schedules, or social jetlag.[20,21]

Insufficient, disturbed, or misaligned sleep has been linked to increased consumption of sugary and high-fat foods, irregular meal patterns,[22] and a higher likelihood of mid-morning snacking in lieu of breakfast.[23] Furthermore, sleep and circadian preference have been shown to play a pivotal role in regulating PA and sedentary behavior.[24] Morning-type adolescents are more likely to engage in moderate-to-vigorous PA (MVPA) and are less sedentary[25] than evening-type adolescents, who are prone to insufficient sleep, social jetlag, daytime sleepiness, reduced motivation toward exercising, and increased sedentary behavior.[26] Prior research has also shown that high sleep irregularity is associated with increased screen time and sedentarism in adolescents.[25] However, the influence of additional school-related variables on the relationship between sleep and PA in adolescents has yet to be further explored.[27] Adolescents spend most of their year in-school, where they may engage in structured MVPA, but they significantly change their behavior while on-break from school.[28]

Moreover, it has remained elusive which of the multiple dimensions of sleep and circadian health has the greatest impact on adverse health outcomes in adolescents. A recent effort has consisted of defining this multidimensional aspect of sleep health using a 24-hour framework where regularity, satisfaction, timing, alertness, efficiency, and duration (RU-SATED) define good sleep health.[29] Although useful, this framework may require first testing each dimension while employing a multimethod approach, where subjective measures (i.e., self-reported questionnaires, logs) and objective measures (i.e., actigraphy [ACT], polysomnography [PSG]) can be tested to provide a deeper understanding of such multidimensionality of sleep health[29–31] and its association with diet and PA. Furthermore, evaluating adolescents' sleep health requires taking into account the context of evaluation, as they could be in-school or on-break, which may offer valuable insight into how imposed daytime schedules may influence its association with dietary habits or PA.[32] School schedules generally impose early rising times that conflict not only with solar time,[33] but with adolescents' circadian preference and endogenous rhythm, leading to insufficient sleep.[34] Conversely, weekends and school breaks typically allow for more flexible sleep schedules, catch-up sleep, or longer sleep duration[35] that may not necessarily be optimal or healthy in relationship to diet or activity levels. However, few studies have used a multidimensional approach to study the association of sleep health with dietary habits and PA in adolescents or even adults.[36,37]

Given that unhealthy dietary habits and PA are risk factors for the development of obesity,[38] identifying the association between sleep health with nutrition choices, PA, and metabolic expenditure is crucial for primordial prevention. Prior research has examined the role of sleep health in dietary patterns, sedentarism, and PA[39–42]; however, most studies evaluated sleep with single dimensions or methods, typically self-reports,[39–41] rather than examining sleep health as a multidimensional phenomenon that can be assessed via multiple methods of measurement (i.e., multidimensional-multimethod). This latter approach is particularly relevant in adolescents, as puberty is associated with a shift toward a cascade of delayed, irregular, and insufficient sleep.[43] This cascade requires a deeper evaluation able to capture the behavioral and physiological aspects at-play. To the best of our knowledge, only four studies have evaluated the association of multiple sleep dimensions and methods with diet or PA regardless of age.[39–42] As a result, the association of sleep health dimensions with lifestyle factors during the critical stage of adolescence has yet to be fully understood.

Our overarching aim is to assess whether specific sleep dimensions, as measured by distinct methods, will be differentially associated with dietary patterns and PA in adolescents, and whether schooling modifies the strength of these associations. We hypothesize that sleep timing would be most associated with dietary patterns, particularly during the school year. Thus, using a multidimensional-multimethod approach, we studied the association of multiple sleep health dimensions, assessed by subjective and objective methods, with diet and PA in adolescents. We also explored the impact of being evaluated while in-school or while on-break on these associations. Our approach in this paper allows for a comprehensive evaluation of sleep health and its associations with health-related behaviors while considering the period of the academic school year.

Methods

Participants

We analyzed data from 373 adolescents from the Penn State Child Cohort (PSCC). The design, recruitment, and assessments of this cohort study have been described in detail elsewhere.[44–46] The adolescent visit of the PSCC took place between 2010 and 2013, and 421 subjects participated (60.1% response rate). No significant differences in baseline demographic characteristics were found with the 279 participants who did not return for follow-up. The PSCC is unique as it includes a deep multidimensional-multimethod phenotyping of sleep (self-reported, ACT-measured, and PSG-measured) and other health outcomes in youth from the general population. Their ages ranged from 12-23 years (90% 12-19 years old), with 47.5% identifying as female and 21.5% as a racial/ethnic minority. In-lab assessments were conducted at the Clinical Research Center (CRC) at

the Penn State College of Medicine. The study protocol was approved by Penn State Institutional Review Board. Written informed consent from the parent or legal guardian and from participants 18 years or older, and assent from those younger than 18 years, were all obtained.

Please see the Supplementary Methods for specifics on questions used, measures' reliability, actigraphy algorithm, sleep scoring, and parameters' definitions, among many other details.

Sleep health variables

Self-reported

Based on a self-report version of the Pediatric Sleep Questionnaire (PSQ), we derive habitual [(weekdays *5 + weekends * 2) / 7] bedtimes and rising times, insomnia symptoms, and excessive daytime sleepiness measures.[47,48] Insomnia symptoms were considered present if participants reported difficulty falling or staying asleep on the PSQ.[47] A complaint of excessive daytime sleepiness (EDS) was considered present if participants reported feeling sleepy and tired during the day, while observed EDS if a teacher or supervisor had observed them sleepy during the day.[49] Circadian preference was assessed using the Morningness-Eveningness Questionnaire.[15] Subjective sleep measures were independent variables in the regression models.

Actigraphy

Starting at the CRC visit, participants wore an ActiGraph GT3X configured to record data using 60-second epochs, on their hip while awake, and nondominant wrist during sleep, for up to 7 additional consecutive nights at-home following the CRC visit. Simultaneously, participants completed sleep logs to record nonwear time, bedtimes, and rising times. All recordings were scored with ActiLife v6.0.0. (ActiGraph LLC, Pensacola, FL).[50] A minimum of 3 valid nights were required to be included in the analyses. We extracted mean and standard deviations of timing, regularity, duration, and efficiency dimensions of sleep health. These indices included: bedtime, rising time, and sleep midpoint,[45,46] sleep (*midpoint*) irregularity, social jetlag,[21,45,51] total sleep time (TST), sleep (*TST*) variability, and weekends' catch-up sleep,[44,46,51] sleep onset latency (SOL), number of awakenings, wake after sleep onset (WASO), time in bed (TIB), TIB variability, and sleep efficiency (SE). "Habitual" parameters were calculated with the total amount of recorded nights (3-7 nights), "weekdays" with nights between Sunday night and Thursday night (2-5 nights), and "weekends" with nights between Friday night and Saturday night (1-2 nights). These ACT-measured sleep measures were independent variables in the regression models.

Polysomnography

Physiologic sleep was assessed in a sound-attenuated, light, and temperature-controlled sleep laboratory using 16-channel PSG, including electroencephalography, electrooculography, and electromyography. Respiration was monitored with nasal pressure, thermocouple, and thoracic and abdominal strain gauges. Hemoglobin oxygen saturation was obtained from the finger. All participants were continuously monitored over a 9-hour time-in-bed window ("lights out" ranging from 21:00-23:00 and "lights on" from 06:00-08:00), based on participants' habitual sleep schedule as reported and observed in-school. Sleep recordings were scored according to standard criteria.[52,53] We extracted SOL, TST, WASO, TIB, SE, and apnea/hypopnea index (AHI).[53] These in-lab sleep measures were independent variables in the regression models.

Nutrition variables

Food intake

Participants reported their food intake on the Youth/Adolescent Food Frequency Questionnaire,[54] a self-reported measure of frequency consumption of 152 items over the past year, which allows scoring for nutrients representing daily intake.[44] Dietary intake lower than 500 kcal or greater than 5000 kcal was not included in the analysis.[55,56] Dietary intake indices were dependent variables in the regression models.

Snacks intake

We also extracted from the Youth/Adolescent Food Frequency Questionnaire participants' snack-intake behavior in the past year, including number (none—4 or more), period (school year and vacations, including weekends), and timing (mid-morning, mid-afternoon, and late-evening), as reported elsewhere.[44] Snacking behavior were dependent variables in the regression models.

Physical activity variables

Actigraphy-derived physical activity and energy expenditure

PA variables derived from ACT included the time in sedentary behavior, time spent in light PA (LPA), and in MVPA. PA indices were dependent variables in the regression models.

Self-reported physical activity

Using the Active Where Adolescent Survey—Physical Activity and the Active Where Adolescent Survey—Sedentary Behavior questionnaires,[57] we extracted indices such as total sedentary behavior score, sedentary behavior on weekdays and on weekends, and the number of days (0-7) performing at least 60 minutes of exercise. These self-reported PA and sedentary behavior indices were dependent variables in the regression models.

Other covariables

Subjects' demographic information was collected via a self-reported questionnaire at offset of the CRC visit (see Supplementary Methods).

Statistical analysis

Among 421 subjects who completed the adolescent examination, 48 of them were excluded from the analysis due to insufficient nights of at-home sleep data (< 3 nights, n = 44), unavailable PA and sedentary behavior data from ACT (n = 1), or implausible daily total caloric intake data (n = 3). Thus, the effective sample size for this report is N = 373; no significant differences in demographic characteristics were observed between study participants and the 48 excluded.

First, univariate associations between multiple sleep dimensions with diet, snacking, PA, and energy expenditure were explored with Pearson correlations (see Supplementary Tables S1-S4) to avoid multivariable-adjusted spurious associations and reduce the likelihood of type I error. Second, based on such correlation matrices, linear regression models were built by initially replicating the univariate association (model 1) and, thereafter, adjusting for age, sex, race/ethnicity, SES, schooling, and BMI percentile (model 2). Third, all sleep dimensions remaining significant in model 2 were included in a competitive model with backward elimination (model 3), where multicollinearity was assessed using Durbin-Watson, tolerance, and variance inflation factor indices. If multicollinearity was observed, models were tested forcing each variable in and out of the model, opting for the most valuable dimensions representing adolescents' sleep health (e.g., choosing habitual bedtime vs. weekends' bedtime, and opting for ACT-measured over self-reported variables). This approach solves Heinze-Wallisch-Dunkler concerns on backward elimination.[58] In addition, model 3 was further adjusted for externalizing behaviors and smoking (model 4) and, thereafter, internalizing symptoms (model 5). Models were also fitted separately

among those in-school and those on-break to test the effect of entrainment conditions that participants were evaluated under. Finally, we explored interaction effects between sex and sleep dimensions on outcomes. No major violations of statistical assumptions were found in the analyses. All analyses were performed using SPSS version 29.0 (IBM Corp). A two-sided p-value of $< .05$ was used to determine statistical significance.

Results

Sample characteristics

Sociodemographic, sleep, nutrition, and PA data of the study population are summarized in Table 1. In brief, the mean age was 16.4 years, with 174 identifying as females, 78 as a racial/ethnic minority, and 127 belonging to higher SES households. Their habitual sleep showed average bedtimes and rising times at 23:30 and 8:00, respectively. Adolescents went to bed on average 30 minutes later and delayed their rising time by up to 2.5 hours on weekends, with a 1-hour delay in sleep midpoint. Participants slept on average 18 minutes longer and extended their TIB by 25 minutes on weekends. Participants ate on average 1774.8 kcal and about 1.5 snacks in the late-evening, per day. Participants spent on average 4286.9 minutes per week (71 hours and 30 minutes) sedentary, 377.5 minutes per week (6 hours and 15 minutes) in MVPA, and spent 1.5 METs per hour. Participants reported 3.7 days with at least 60 minutes of exercise.

A total of 234 participants were evaluated while in-school (62.5%). As shown in Table 1, these participants were not significantly different in terms of sex, race/ethnicity, BMI percentile, self-reported chronotype, EDS or insomnia symptoms, diet, snacking, and self-reported or ACT-measured PA and METs. Participants evaluated while in-school were 7 months younger and spent on average 9 hours less per week being sedentary than those studied while on-break. Participants evaluated while in-school had earlier bedtimes and rising times, a sleep midpoint 1.25 hours earlier, spent 30 minutes less TIB, had a 30-minute average social jetlag, and almost 1 hour of catch-up sleep compared with those evaluated while on-break (Table 1).

Please see Supplementary Results for greater level of detail on all the associations found below, which we present here in a concise manner.

Multivariable association of sleep dimensions with dietary habits and physical activity

Food intake and snacking

Aligned with our study hypothesis, a later ACT-measured rising time and sleep midpoint were associated with higher caloric and carbohydrates intake in model 2, while only a later rising time was associated with higher fat intake (Table 2, see Supplementary Results).

ACT-measured physical activity

A later self-reported bedtime was associated with greater sedentarism and LPA in model 2 (Table 4, see Supplementary Results). However, a later ACT-measured rising time, more awakenings, longer sleep onset latency, and greater variability were associated with more sedentarism and LPA (Table 4).

Self-reported physical activity

Except habitual and weekdays rising time, all self-reported sleep variables were associated with habitual and weekdays sedentary behavior scores in model 2 (Table 5, see Supplementary Results).

Competing association between sleep dimensions with dietary habits and physical activity

Food intake and snacking

Competitive models showed that a later ACT-measured weekdays' rising time was independently associated with greater caloric and fat intake, while a longer habitual time in bed and a later sleep midpoint were independently associated with greater carbohydrates intake in model 3 (Table 2). Further adjusting for externalizing behaviors, smoking, and internalizing symptoms did not meaningfully change the associations found (models 4 and 5 in Table 2).

ACT-measured physical activity

A later self-reported bedtime was independently associated with more LPA in model 3 (Table 4). A later ACT-measured bedtime and weekends rising time, longer weekdays SOL, and more awakenings were independently associated with more sedentarism. Longer SOL, shorter TST, and greater sleep variability were independently associated with more LPA. Longer SOL and shorter TIB were independently associated with more MVPA. Longer SOL was independently associated with more METs in model 3 (Table 4). Further adjusting for externalizing behaviors, smoking, and internalizing symptoms did not meaningfully change the associations found in models 4 and 5 (Table 4, see Supplementary Results).

Self-reported physical activity

A later self-reported bedtime on weekends and greater ACT-measured sleep variability were independently associated with higher habitual and weekdays sedentary behavior scores. A later ACT-measured bedtime was independently associated with more sedentary behavior scores on weekends in model 3 (Table 5). Further adjusting for externalizing behaviors, smoking, and internalizing symptoms, did not meaningfully change the associations found (models 4 and 5 in Table 5).

Exploring the effect of schooling in the association of sleep dimensions with dietary habits and physical activity

Among participants evaluated while in-school, a later ACT-measured rising time and sleep midpoint were independently associated with greater caloric and carbohydrates intake and more late-evening snacking (see Supplementary Results). Among participants evaluated while on-break, a later self-reported rising time was independently associated with more mid-morning snacking (see Supplementary Results).

Exploring the interaction of sex with sleep dimensions on dietary habits and physical activity

There were significant interactions between male sex and later ACT-measured sleep midpoint on greater carbohydrates intake (model 6 in Table 2) and later ACT-measured weekends rising time on greater sedentarism (model 6 in Table 4). There were significant interactions between female sex and later self-reported weekdays bedtime on greater late-evening snacking during school days (model 6 in Table 3), later self-reported weekends rising time on greater mid-afternoon snacking and weekdays rising time or weekends bedtime on greater late-evening snacking during vacation (model 6 in Table 3), and longer ACT-measured sleep onset latency on greater MVPA and METs (model 6 in Table 4). No other significant interactions between sex and sleep dimensions on dietary and PA outcomes were found (Table 5).

Table 1
Characteristics of the sample

	Overall (N = 373)	In-school (n = 234)	On-break (n = 139)	*p*-value
Demographics				
Age, y	16.4 (2.3)	16.1 (2.2)	16.7 (2.4)	**.045**
Female sex, n (%)	174 (46.6)	104 (44.4)	70 (50.4)	.284
Racial/ethnic minority, n (%)	78 (20.9)	48 (20.5)	30 (21.6)	.794
Tanner stage, score	4.2 (0.8)	4.1 (0.8)	4.2 (0.8)	**.045**
Higher SES, n (%)	127 (34.0)	78 (33.3)	49 (35.3)	.735
In-school, n (%)	234 (62.5)	—	—	
Anthropometrics				
BMI, percentile	65.7 (28.3)	63.8 (29.4)	68.9 (26.0)	.156
Self-reported sleep				
Habitual				
Bedtime, hh:mm	23:18 (1:31)	23:10 (1:35)	23:31 (1:25)	**.018**
Rising time, hh:mm	8:05 (1:45)	7:51 (1:51)	8:28 (1:33)	**<.001**
Sleep onset latency, min	23.6 (19.8)	24.5 (20.4)	22.0 (18.6)	.152
Insomnia symptoms, n (%)	142 (38.1)	95 (40.6)	47 (33.8)	.225
Sleepiness, score	0.9 (0.8)	1.0 (0.8)	0.8 (0.8)	.101
None, n (%)	133 (35.7)	74 (31.6)	59 (42.4)	.117
Complaint, n (%)	140 (37.5)	92 (39.3)	48 (34.5)	
Observed, n (%)	100 (26.8)	68 (29.1)	32 (23.0)	
Circadian preference, score	25.9 (5.1)	26.0 (5.1)	25.8 (5.3)	.732
Morning-type, n (%)	121 (32.4)	73 (31.3)	48 (34.5)	.444
Intermediate-type, n (%)	133 (35.7)	89 (38.0)	44 (31.7)	
Evening-type, n (%)	118 (31.6)	71 (30.5)	47 (33.8)	
Weekdays				
Bedtime, hh:mm	22:55 (1:33)	22:46 (1:36)	23:11 (1:27)	**.008**
Rising time, hh:mm	7:22 (2:00)	7:04 (2:03)	7:52 (1:48)	**<.001**
Weekends				
Bedtime, hh:mm	00:13 (1:43)	00:08 (1:49)	00:21 (1:32)	.149
Rising time, hh:mm	9:50 (1:56)	9:45 (2:06)	9:58 (1:36)	**.034**
Actigraphy sleep				
Habitual				
Bedtime, hh:mm	23:37 (1:22)	23:15 (1:19)	00:14 (1:13)	**<.001**
Rising time, hh:mm	8:12 (1:34)	7:42 (1:33)	9:01 (1:14)	**<.001**
Sleep onset latency, min	8.5 (8.3)	7.8 (8.0)	9.5 (8.8)	.086
Awakenings, num	18.5 (7.6)	17.8 (7.0)	19.7 (8.3)	**.023**
Wakes after sleep onset, min	71.6 (33.7)	66.4 (30.8)	80.2 (36.6)	**<.001**
Total sleep time, h	7.2 (0.9)	7.1 (0.9)	7.3 (1.0)	.157
Sleep variability, h	1.3 (0.5)	1.3 (0.6)	1.4 (0.8)	.148
Time in bed, h	8.5 (1.0)	8.3 (0.9)	8.8 (1.2)	**<.001**
Time-in-bed variability, h	1.4 (0.7)	1.3 (0.7)	1.5 (0.7)	**.039**
Sleep efficiency, %	84.7%	85.4%	83.3%	**<.001**
Sleep midpoint, hh:mm	4:00 (1:33)	3:34 (1:33)	4:44 (1:14)	**<.001**
Sleep irregularity, hh:mm	0:56 (0:40)	0:56 (0:34)	0:57 (0:48)	.897
Weekdays				
Bedtime, hh:mm	23:29 (1:28)	23:04 (1:25)	00:10 (1:17)	**<.001**
Rising time, hh:mm	7:58 (1:49)	7:20 (1:47)	9:00 (1:22)	**<.001**
Sleep onset latency, min	8.6 (9.5)	8.3 (9.5)	9.2 (9.5)	.479
Awakenings, num	18.8 (7.9)	17.9 (7.1)	20.1 (9.0)	**.020**
Wakes after sleep onset, min	71.3 (36.4)	65.5 (31.6)	81.1 (41.5)	**<.001**
Total sleep time, h	7.1 (1.0)	6.9 (0.9)	7.3 (1.0)	**<.001**
Sleep variability, h	1.1 (0.7)	1.0 (0.6)	1.3 (0.8)	**<.001**
Time in bed, h	8.4 (1.1)	8.1 (1.0)	8.8 (1.2)	**<.001**
Sleep efficiency, %	84.5%	85.3%	83.3%	**.010**
Sleep midpoint, hh:mm	3:19 (2:04)	2:55 (2:21)	3:58 (1:13)	**<.001**
Sleep irregularity, hh:mm	0:50 (0:46)	0:45 (0:51)	0:57 (0:36)	**<.001**
Weekends				
Bedtime, hh:mm	23:57 (1:30)	23:41 (1:28)	00:25 (1:26)	**<.001**
Rising time, hh:mm	8:47 (1:31)	8:37 (1:34)	9:04 (1:25)	**<.001**
Sleep onset latency, min	8.1 (13.2)	6.7 (11.5)	10.4 (15.5)	**.007**
Awakenings, num	17.9 (10.2)	17.4 (10.2)	18.8 (10.2)	.158
Wakes after sleep onset, min	72.4 (48.0)	68.9 (46.5)	78.3 (50.1)	.075
Total sleep time, h	7.4 (1.5)	7.6 (1.4)	7.1 (1.5)	**<.001**
Time in bed, h	8.8 (1.5)	8.9 (1.5)	8.6 (1.6)	.085
Sleep efficiency, %	85.0%	85.9%	83.5%	**.006**
Sleep midpoint, hh:mm	3:56 (1:58)	3:48 (2:17)	4:09 (1:15)	**<.001**
Weekends-weekdays				
Social jetlag, h	1.1 (1.0)	1.3 (1.1)	0.9 (0.7)	**<.001**
Catch-up sleep, min	23.4 (90.0)	44.6 (84.4)	-12.3 (87.3)	**<.001**
Polysomnography sleep				
In-lab				
Sleep onset latency, min	25.7 (24.2)	23.2 (20.3)	30.0 (29.2)	**<.001**
Wakes after sleep onset, min	70.0 (43.9)	65.5 (41.7)	77.6 (46.5)	**.004**
Total sleep time, h	7.5 (0.9)	7.5 (0.9)	7.2 (1.0)	**<.001**
Time in bed, min	9.0 (0.1)	9.0 (0.1)	9.0 (0.1)	.245
Sleep efficiency, %	82.6%	84.0%	80.4%	**<.001**
AHI, events/h	2.6 (5.7)	2.2 (2.7)	3.2 (8.5)	.609
Diet				
Habitual				
Caloric intake, kcal	1774.8 (676.4)	1777.8 (714.5)	1769.8 (609.4)	.650
Carbohydrates, gm	233.9 (91.8)	232.7 (94.8)	235.9 (86.6)	.511
Total sugars, gm	112.2 (52.3)	111.5 (53.3)	113.4 (50.7)	.616

(*continued on next page*)

Table 1 (*continued*)

	Overall (N = 373)	In-school (n = 234)	On-break (n = 139)	*p*-value
Added sugars, gm	59.4 (31.7)	59.6 (33.0)	59.1 (29.4)	.714
Natural sugars	52.8 (28.3)	51.9 (27.7)	54.3 (29.3)	.489
Fat, gm	63.9 (27.0)	64.7 (28.6)	62.6 (24.0)	.752
Saturated fat, gm	22.9 (10.5)	23.1 (11.0)	22.5 (9.6)	.829
Polyunsaturated fat, gm	13.2 (5.6)	13.3 (5.9)	12.8 (4.9)	.833
Proteins, gm	70.8 (27.9)	71.3 (29.4)	70.0 (25.4)	.941
Animal protein, gm	48.6 (20.8)	49.1 (21.6)	47.8 (19.4)	.836
Vegetable protein, gm	22.2 (9.7)	22.2 (10.4)	22.3 (8.6)	.344
Snacking	(N = 309)	(n = 193)	(n = 116)	
During the school year				
Mid-morning, num	0.5 (0.9)	0.5 (0.9)	0.5 (0.9)	.405
Mid-afternoon, num	1.5 (1.0)	1.5 (1.0)	1.4 (1.0)	.349
Late-evening, num	1.4 (1.0)	1.4 (1.1)	1.3 (1.0)	.540
During vacations				
Mid-morning, num	1.0 (1.0)	1.0 (1.1)	0.9 (0.9)	.949
Mid-afternoon, num	1.7 (1.0)	1.7 (1.1)	1.6 (1.0)	.332
Late-evening, num	1.6 (1.0)	1.6 (1.1)	1.6 (1.0)	.943
Self-reported physical activity				
Habitual				
Total sedentary, T-score	28.5 (8.9)	27.7 (8.5)	29.8 (9.4)	**.038**
Sedentary on weekdays, T-score	27.8 (9.4)	26.8 (9.1)	29.3 (9.8)	**.016**
Sedentary on weekends, T-score	29.9 (9.1)	29.1 (8.5)	31.3 (10.0)	**.041**
PA > 60 min, days/week	3.7 (2.0)	3.6 (2.0)	3.8 (1.9)	.294
Actigraphy physical activity	(N = 341)	(n = 230)	(n = 111)	
Habitual				
Sedentary, min/week	4286.9 (1884.0)	4080.8 (1628.1)	4620.9 (2203.6)	**.025**
Light PA, min/week	692.0 (270.7)	706.3 (263.9)	667.9 (281.2)	.262
MVPA, min/week	377.5 (313.3)	388.7 (324.7)	359.4 (294.3)	.189
METs, kcal/kg/h	1.5 (0.2)	1.5 (0.3)	1.5 (0.2)	.601

Abbreviations: METs, metabolic equivalent of task; MVPA, moderate-to-vigorous physical activity; PA, physical activity; SES, socioeconomic status.
Data are mean and (standard deviation) for continuous variables and n (%) for categorical variables. Bold *p*-values indicate a statistically significant difference between groups at $p < .05$. Apnea/hypopnea index (AHI) measured via 9-h in-lab polysomnography (PSG). Social jetlag = absolute difference between weekends sleep midpoint and weekdays sleep midpoint, indicating that the sleep midpoint is 1.1 (1.0) hours later on weekends than on weekdays.

Table 2
Linear regression models between multiple sleep dimensions with food intake

	Model	Calories	Carbs	Fat
Actigraphy				
Habitual				
Rising time	1	90.5 (34.8) **0.010**	12.5 (4.7) **0.008**	3.2 (1.4) **0.021**
	2	115.2 (39.3) **0.004**	15.3 (5.3) **0.004**	4.4 (1.6) **0.005**
	3	NS	NS	NS
Time in bed	1	75.6 (34.9) **0.031**	11.6 (4.7) **0.015**	—
	2	80.1 (35.8) **0.026**	11.5 (4.9) **0.018**	
	3	NS	9.8 (4.9) **0.046**	
	4		11.53 (4.8) **0.018**	
	5		11.6 (4.8) **0.017**	
	6		0.947	
Sleep midpoint	1	76.4 (34.9) **0.029**	10.9 (4.7) **0.022**	—
	2	99.2 (39.5) **0.013**	13.6 (5.4) **0.012**	
	3	NS	11.8 (5.4) **0.030**	
	4		11.2 (5.5) **0.041**	
	5		11.3 (5.4) **0.040**	
	6		**0.004**	
Weekdays				
Rising time	1	90.6 (34.8) **0.010**	12.2 (4.7) **0.010**	3.4 (1.4) **0.016**
	2	120.8 (40.1) **0.013**	15.6 (5.5) **0.005**	4.9 (1.6) **0.002**
	3	119.4 (40.4) **0.003**	NS	4.9 (1.6) **0.002**
	4	105.4 (40.4) **0.009**		3.8 (1.7) **0.025**
	5	106.2 (40.4) **0.009**		3.8 (1.7) **0.024**
	6	0.578		0.398
Time in bed	1	—	9.35 (4.7) **0.049**	—
	2		NS	
	3			

Abbreviations: NS, not statistically significant after adjustments in each model. —, not entered in the models based on univariate analyses.
Data are regression coefficients (standard error) *p*-value for each standard deviation increase (z-scores) associated with each independent variable (e.g., risetime, time in bed, and sleep midpoint). Model 1 = unadjusted. Model 2 = adjusted for sex, age, race/ethnicity, BMI, SES, and schooling. Model 3 = model 2 + all other significant sleep dimensions (sleep dimensions with Backward/elimination method, and demographics with Enter/forced-entry method). Model 4 = model 3 + externalizing behaviors, including tobacco use (with Enter/forced-entry method). Model 5 = model 4 + internalizing symptoms (with Enter/forced-entry method). Model 6 = *p*-value for the sex by sleep dimension interaction. Bold *p*-values indicate a statistically significant association at $p < .05$.

Discussion

This cohort study showed that sleep timing, efficiency, and duration evaluated through distinct methods were associated with poorer dietary choices and PA in adolescents, suggesting that circadian misalignment may be involved in adolescent's dietary intake and timing. Specifically, a delayed sleep timing, such as a later bedtime or sleep midpoint, was associated with consuming high-caloric diets, replacing breakfast for snacking, and being more sedentary. In addition, lower sleep efficiency was associated with

Table 3
Linear regression models between multiple sleep dimensions with self-reported snacking during the prior year while attending school and while on-breaks from school

		During the school year			During vacation		
	Model	Mid-morning	Mid-afternoon	Late-evening	Mid-morning	Mid-afternoon	Late-evening
Self-report							
Habitual							
Bedtime	1	0.14 (0.5) **0.008**	—	0.16 (0.06) **0.007**	0.19 (0.06) **0.001**	0.14 (0.06) **0.019**	0.16 (0.06) **0.007**
	2	NS		0.19 (0.07) **0.005**	0.25 (0.07) **< 0.001**	0.20 (0.07) **0.002**	0.19 (0.07) **0.004**
	3			NS	NS	NS	NS
Rising time	1	0.15 (0.05) **0.004**	—	0.13 (0.06) **0.035**	0.15 (0.06) **0.013**	—	0.19 (0.06) 0.001
	2	0.12 (0.06) **0.035**		0.13 (0.06) **0.041**	0.18 (0.06) **0.005**		0.22 (0.06) < 0.001
	3	0.12 (0.06) **0.035**		NS	NS		NS
	4	NS					
	5						
	6	0.391					
Sleep onset latency	1	—	—	—	0.13 (0.07) **0.049**	—	0.16 (0.07) **0.012**
	2				0.18 (0.07) **0.006**		0.20 (0.07) **0.003**
	3				0.17 (0.07) **0.044**		0.15 (0.06) **0.018**
	4				NS		0.15 (0.07) **0.035**
	5				NS		0.14 (0.07) **0.037**
	6				0.436		0.330
Eveningness	1	—	—	0.15 (0.06) **0.013**	—	—	0.16 (0.06) **0.008**
	2			0.15 (0.06) **0.012**			0.16 (0.06) **0.008**
	3			NS			NS
Weekdays							
Bedtime	1	0.14 (0.05) **0.008**	—	0.16 (0.06) **0.009**	0.18 (0.06) **0.002**	0.14 (0.06) **0.020**	0.15 (0.06) **0.012**
	2	NS		0.18 (0.07) **0.008**	0.24 (0.07) **< 0.001**	0.20 (0.07) **0.002**	0.18 (0.07) **0.006**
	3			0.18 (0.07) **0.007**	NS	0.19 (0.07) **0.005**	NS
	4			0.17 (0.07) **0.014**		0.19 (0.07) **0.005**	
	5			0.17 (0.07) **0.017**		0.19 (0.07) **0.004**	
	6			**0.047**		0.153	
Rising time	1	0.14 (0.05) **0.005**	—	—	0.13 (0.06) **0.033**	—	0.18 (0.06) **0.003**
	2	0.11 (0.06) **0.048**			0.16 (0.06) **0.010**		0.21 (0.06) **< 0.001**
	3	NS			0.13 (0.06) **0.044**		0.19 (0.06) **0.004**
	4				NS		0.18 (0.06) **0.006**
	5				NS		0.18 (0.06) **0.006**
	6				0.169		**0.003**
Weekends							
Bedtime	1	0.12 (0.05) **0.020**	—	0.15 (0.06) **0.013**	0.19 (0.06) **0.001**	0.12 (0.06) **0.041**	0.15 (0.06) **0.010**
	2	NS		0.15 (0.06) **0.013**	0.22 (0.06) **< 0.001**	0.16 (0.06) **0.015**	0.15 (0.06) **0.010**
	3			NS	0.21 (0.07) **0.002**	NS	0.15 (0.06) **0.018**
	4				0.18 (0.06) **0.004**		0.15 (0.06) **0.022**
	5				0.18 (0.06) **0.004**		0.14 (0.06) **0.032**
	6				0.255		**0.0003**
Rising time	1	0.11 (0.05) **0.037**	—	0.14 (0.06) **0.022**	0.15 (0.06) **0.013**	0.14 (0.06) **0.014**	0.16 (0.06) **0.006**
	2	NS		0.12 (0.06) **0.044**	0.14 (0.06) **0.018**	0.14 (0.06) **0.014**	0.15 (0.06) **0.011**
	3			NS	NS	0.13 (0.06) **0.029**	NS
	4					0.13 (0.06) **0.030**	
	5					0.13 (0.06) **0.029**	
	6					**0.048**	
Actigraphy							
Habitual							
Bedtime	1	0.13 (0.05) **0.014**	—	—	—	—	—
	2	NS					
	3						
Rising time	1	—	—	—	—	—	0.13 (0.06) **0.029**
	2						0.15 (0.07) **0.026**
	3						NS
Sleep onset latency	1	—	—	—	—	—	0.12 (0.06) **0.035**
	2						0.14 (0.06) **0.021**
	3						0.16 (0.06) **0.007**
	4						0.14 (0.06) **0.016**
	5						0.14 (0.06) **0.016**
	6						0.194
Awakenings	1	-0.12 (0.06) **0.035**	—	—	—	—	
	2	NS					
	3						
Sleep variability	1	0.13 (0.05) **0.012**	—	—	—	—	0.13 (0.06) **0.030**
	2	NS					NS
	3						
Sleep midpoint	1	—	—	0.12 (0.06) **0.043**	—	—	0.13 (0.06) **0.023**
	2			0.15 (0.07) **0.027**			0.14 (0.07) **0.029**
	3			0.14 (0.07) **0.029**			NS
	4			0.14 (0.07) **0.047**			
	5			0.14 (0.07) **0.042**			
	6			0.176			
Weekdays							
Bedtime	1	0.13 (0.5) **0.017**	—	—	—	—	—
	2	NS					
	3						
Rising time	1	—	—	—	—	—	0.13 (0.06) **0.026**
	2						0.16 (0.07) **0.018**
	3						NS

(*continued on next page*)

Table 3 (*continued*)

		During the school year			During vacation		
	Model	Mid-morning	Mid-afternoon	Late-evening	Mid-morning	Mid-afternoon	Late-evening
Sleep onset latency	1	—	—	0.15 (0.06) **0.009**	—	—	0.15 (0.06) **0.010**
	2			0.17 (0.06) **0.004**			0.16 (0.06) **0.006**
	3			0.17 (0.06) **0.004**			NS
	4			0.17 (0.06) **0.003**			
	5			0.17 (0.06) **0.003**			
	6			0.342			
Sleep variability	1	—	—	—	—	—	0.16 (0.06) **0.007**
	2						0.16 (0.06) **0.011**
	3						NS
Sleep midpoint	1	0.15 (0.08) **0.048**	—	—	—	—	0.20 (0.09) **0.022**
	2	NS					0.27 (0.11) **0.014**
	3						NS
Weekends							
Bedtime	1	0.12 (0.05) **0.032**	—	—	—	—	—
	2	NS					
	3						
Rising time	1	—	—	0.13 (0.06) **0.033**	—	—	—
	2			0.12 (0.06) **0.047**			
	3			NS			
Total sleep time	1	—	—	—	-0.13 (0.06) **0.043**	—	—
	2				NS		
	3						
Weekends-weekdays							
Catch-up sleep	1	—	—	—	-0.13 (0.06) **0.040**	—	—
	2				-0.16 (0.07) **0.015**		
	3				NS		

Abbreviations: NS, not statistically significant after adjustments in each model. —, not entered in the models based on univariate analyses.
Data are regression coefficients (standard error) *p*-value for each standard deviation increase (z-scores) associated with each independent variable (e.g., risetime, time in bed, and sleep midpoint). Model 1 = unadjusted. Model 2 = adjusted for sex, age, race/ethnicity, BMI, SES, and schooling. Model 3 = model 2 + all other significant sleep dimensions (sleep dimensions with Backward/elimination method, and demographics with Enter/forced-entry method). Model 4 = model 3 + externalizing behaviors, including tobacco use (with Enter/forced-entry method). Model 5 = model 4 + internalizing symptoms (with Enter/forced-entry method). Model 6 = *p*-value for the sex by sleep dimension interaction. Bold *p*-values indicate a statistically significant association at $p < .05$.

consuming more sugar and nightly snacks, yet with spending more time in LPA. Finally, insufficient sleep, such as shorter and highly variable sleep duration, was associated with consuming more morning snacks and being more sedentary. Adjusting for externalizing behaviors, smoking, and internalizing symptoms did not meaningfully change the associations found, except for some self-reported sleep timing measures and mid-morning snacking. Interestingly, the association of sleep dimensions with diet composition, physical activity, and sedentarism was stronger among adolescents evaluated while attending school, whereas their association with snacking was stronger among adolescents evaluated while on-break from school. Having to adapt to morning school schedules and extracurricular activities, combined with the challenges adolescents face in achieving adequate sleep, may influence the strength of association with health behaviors: while on-break, there may be greater flexibility, which may weaken these associations.

While PSG-derived sleep dimensions have been widely linked to cardiometabolic health outcomes, our results showed that objective and subjective measures of habitual sleep timing at-home, and not those captured via in-lab PSG, overlapped in their association with lifestyle factors. The strength of the association was weaker for subjective measures of habitual sleep. Therefore, at-home objective measures like ACT, rather than PSG, may be preferable when assessing the relationship between sleep health, diet, and PA, as it more accurately captures habitual sleep patterns in real-world contexts and in connection with co-occurring daytime behaviors (e.g., eating, being sedentary). While self-reported data include the individual's perception of sleep quality and routine, which can be closely tied to daily habits and decision-making, ACT provides objective behavioral data over multiple days in a noninvasive way, monitoring fluctuations and consistency in sleep that may influence or be influenced by lifestyle behaviors such as diet and PA. Our findings can inform on strategies targeting adolescents' sleep by focusing on regularity, timing, and duration in the home environment when aiming to prevent or manage health behaviors, such as diet and PA, known to be associated with long-term adverse health outcomes.

Previous studies have described an association between eveningness or later bedtimes with frequent intake of high-energy-dense and nutrient-poor foods, later meal timing,[23,37,40,59,60] or lower intake of vegetables and fruits.[61] Prior studies have reported that greater sleep variability is associated with more calories and snacking.[44] Moreover, an experimental sleep-manipulation trial among adolescents showed that restricting sleep led to later last-meal timing, lengthened feeding windows, and greater total caloric exposure.[62] Lastly, a longitudinal study reported that adolescents whose caloric intake was misaligned with their chronotype showed increased fat mass index over time.[63] However, few studies accounted for the period of the year during which adolescents were evaluated. Based on our novel findings stratified by entrainment to the academic school schedule, a delayed sleep timing is associated with eating more calories, fat, carbs, and mid-afternoon/late-evening snacks when evaluated while attending school. Our data showed that a delayed sleep timing and lower sleep efficiency were associated with more snacking in those evaluated while on-break. Thus, sleep timing, and to a lesser extent its efficiency, are the sleep health dimensions most strongly associated with nutrients and late-snacking, which suggest that circadian misalignment is involved in adolescent's dietary intake and timing.

Our overall findings also show that a delayed sleep timing, high sleep irregularity, and a greater AHI are associated with more sedentarism. The latter did not hold significant after adjusting for BMI. Furthermore, stratified analysis indicated that those with greater sleep variability evaluated while attending school had higher self-reported weekdays sedentary behavior scores, while those evaluated while on-break had lower LPA. Previous studies have described positive associations between greater sleep variability and higher

Table 4
Linear regression models between multiple sleep dimensions with objective physical activity in adolescents

	Model	Sedentary	LPA	MVPA	METs
Self-report					
Habitual					
Bedtime	1	415.9 (101.0) **< 0.001**	-52.7 (14.1) **< 0.001**	—	-0.05 (0.01) **< 0.001**
	2	327.5 (115.4) **0.005**	-34.3 (16.3) **0.035**		NS
	3	NS	-35.9 (15.3) **0.019**		
	4		-38.9 (16.5) **0.019**		
	5		-38.5 (16.5) **0.020**		
	6		0.585		
Rising time	1	326.7 (102.1) **0.002**	-44.4 (14.2) **0.002**	—	-0.03 (0.01) **0.012**
	2	NS	NS		NS
	3				
Eveningness	1	—	-30.6 (14.2) **0.032**	—	—
	2		NS		
	3				
Weekdays					
Bedtime	1	460.3 (99.6) **< 0.001**	-54.9 (13.9) **< 0.001**	—	-0.06 (0.01) **< 0.001**
	2	380.5 (114.5) **< 0.001**	-36.5 (16.1) **0.024**		NS
	3	NS	NS		
Rising time	1	308.9 (101.5) **0.003**	-43.1 (14.2) **0.003**	—	-0.04 (0.01) **0.005**
	2	NS	NS		NS
	3				
Weekends					
Bedtime	1	250.3 (101.7) **0.014**	-38.6 (14.2) **0.007**	—	-0.03 (0.01) **0.025**
	2	NS	NS		NS
	3				
Rising time	1	223.4 (102.3) **0.030**	-28.5 (14.1) **0.044**	—	—
	2	NS	NS		
	3				
Actigraphy					
Habitual					
Bedtime	1	537.9 (98.3) **< 0.001**	-46.9 (14.0) **< 0.001**	—	-0.04 (0.01) **0.025**
	2	454.8 (115.9) **< 0.001**	NS		NS
	3	253.4 (121.6) **0.038**			
	4	461.9 (116.3) **< 0.001**			
	5	468.2 (116.2) **< 0.001**			
	6	0.134			
Rising time	1	419.3 (98.0) **< 0.001**	-66.1 (13.8) **< 0.001**	-37.3 (16.6) **0.025**	-0.04 (0.01) **0.006**
	2	312.5 (112.3) **0.006**	-60.8 (15.8) **< 0.001**	NS	NS
	3	NS	NS		
Sleep onset latency	1	-325.7 (99.2) **0.001**	64.5 (13.7) **< 0.001**	78.0 (16.2) **< 0.001**	0.08 (0.01) **< 0.001**
	2	-310.9 (101.7) **0.002**	60.7 (14.0) **< 0.001**	79.8 (16.9) **< 0.001**	0.06 (0.01) **< 0.001**
	3	NS	48.8 (13.3) **< 0.001**	91.53 (16.9) **< 0.001**	0.06 (0.01) **< 0.001**
	4		62.8 (14.0) **< 0.001**	82.1 (16.7) **< 0.001**	0.06 (0.01) **< 0.001**
	5		63.1 (14.0) **< 0.001**	80.6 (16.4) **< 0.001**	0.06 (0.01) **< 0.001**
	6		0.387	**0.032**	**0.007**
Awakenings	1	-278.7 (101.1) **0.006**	63.9 (13.8) **< 0.001**	—	—
	2	-268.1 (103.4) **0.010**	58.1 (14.2) **< 0.001**		
	3	NS	NS		
Wakes after sleep onset	1	—	45.9 (14.2) **0.001**	—	—
	2		45.5 (14.8) **0.002**		
	3		NS		
Total sleep time	1	—	-80.2 (13.6) **< 0.001**	-52.4 (16.9) **0.002**	—
	2		-86.6 (13.5) **< 0.001**	-55.1 (17.1) **0.001**	
	3		-84.4 (13.4) **< 0.001**	NS	
	4		-86.2 (13.6) **< 0.001**		
	5		-86.2 (13.6) **< 0.001**		
	6		0.304		
Sleep variability	1	329.9 (100.8) **0.001**	-50.1 (14.0) **< 0.001**	—	—
	2	265.7 (102.5) **0.010**	-42.7 (14.1) **0.003**		
	3	NS	-29.8 (13.4) **0.027**		
	4		-47.4 (14.4) **0.001**		
	5		-47.4 (14.4) **0.001**		
	6		0.528		
Time in bed	1	—	-34.9 (14.3) **0.015**	-35.1 (17.3) **0.044**	—
	2		-44.6 (14.6) **0.002**	-40.5 (18.0) **0.025**	
	3		NS	-54.7 (17.8) **0.002**	
	4			-40.2 (17.9) **0.025**	
	5			-39.5 (17.6) **0.025**	
	6			**0.344**	
Sleep efficiency	1	—	-66.6 (13.8) **< 0.001**	-36.1 (17.1) **0.036**	-0.04 (0.01) **0.001**
	2		-66.7 (14.1) **< 0.001**	-36.8 (17.9) **0.041**	-0.03 (0.01) **0.020**
	3		NS	NS	NS
Sleep midpoint	1	422.9 (97.9) **< 0.001**	-50.1 (13.9) **< 0.001**	—	-0.03 (0.01) **0.015**
	2	314.5 (112.0) **0.005**	-38.0 (15.9) **0.018**		NS
	3	NS	NS		
Weekdays					
Bedtime	1	478.6 (99.4) **< 0.001**	-47.0 (13.9) **< 0.001**	—	-0.04 (0.01) **< 0.001**
	2	374.3 (117.6) **0.002**	NS		NS
	3	NS			

(*continued on next page*)

Table 4 (*continued*)

	Model	Sedentary	LPA	MVPA	METs
Rising time	1	378.7 (99.0) **< 0.001**	-60.4 (13.8) **< 0.001**	-33.3 (16.7) **0.047**	-0.03 (0.01) **0.013**
	2	255.5 (115.7) **0.028**	-53.6 (16.2) **0.001**	NS	NS
	3	NS	NS		
Sleep onset latency	1	-385.6 (99.3) **< 0.001**	69.0 (13.7) **< 0.001**	69.5 (16.5) **< 0.001**	0.07 (0.01) **< 0.001**
	2	-358.5 (100.4) **< 0.001**	64.8 (13.7) **< 0.001**	68.5 (16.9) **< 0.001**	0.06 (0.01) **< 0.001**
	3	-325.6 (98.2) **0.001**	NS	NS	NS
	4	-363.9 (100.5) **< 0.001**			
	5	-361.7 (100.5) **< 0.001**			
	6	0.198			
Awakenings	1		50.5 (13.9) **< 0.001**	—	—
	2		45.6 (14.2) **0.001**		
	3		NS		
Wakes after sleep onset	1		34.0 (13.4) **0.019**	—	—
	2		33.3 (14.9) **0.026**		
	3		NS		
Total sleep time	1	—	-75.0 (13.7) **< 0.001**	-48.8 (16.8) **0.004**	—
	2		-78.8 (14.0) **< 0.001**	-51.4 (17.5) **0.004**	
	3		NS	NS	
Sleep variability	1	217.5 (103.8) **0.037**	-38.6 (14.2) **0.007**	—	—
	2	NS	NS		
	3				
Time in bed	1	—	-35.0 (14.3) **0.015**	-36.1 (17.3) **0.038**	—
	2		-40.1 (14.9) **0.007**	-39.6 (18.3) **0.032**	
	3		NS	NS	
Sleep efficiency	1		-60.8 (13.9) **< 0.001**		-0.04 (0.01) **0.007**
	2		-60.1 (14.2) **< 0.001**		NS
	3		NS		
Sleep midpoint	1	406.8 (114.8) **< 0.001**	-35.7 (14.0) **0.011**	—	-0.03 (0.01) **0.022**
	2	282.1 (124.2) **0.024**	NS		NS
	3	NS			
Weekends					
Bedtime	1	548.5 (97.9) **< 0.001**	-32.3 (14.1) **0.022**	—	-0.04 (0.01) **0.002**
	2	461.6 (107.1) **< 0.001**	NS		NS
	3	NS			
Rising time	1	389.2 (99.4) **< 0.001**	-61.1 (13.8) **< 0.001**	-36.6 (16.7) **0.029**	-0.03 (0.01) **0.010**
	2	322.2 (101.2) **0.002**	-55.3 (14.0) **< 0.001**	NS	NS
	3	297.4 (103.6) **0.004**	NS		
	4	321.7 (101.7) **0.002**			
	5	327.9 (101.7) **0.001**			
	6	**0.025**			
Sleep onset latency	1	—	—	50.8 (16.4) **0.002**	0.04 (0.01) **< 0.001**
	2			52.3 (16.9) **0.002**	0.03 (0.01) **0.007**
	3			NS	NS
Awakenings	1	-362.1 (102.1) **< 0.001**	65.9 (14.0) **< 0.001**	—	—
	2	-328.6 (104.8) **0.002**	58.2 (14.0) **< 0.001**		
	3	-293.4 (103.9) **0.005**	NS		
	4	-336.8 (105.4) **0.002**			
	5	-348.9 (105.5) **0.001**			
	6	0.579			
Wakes after sleep onset	1	-229.9 (101.2) **0.024**	47.0 (14.2) **< 0.001**	—	0.03 (0.01) **0.029**
	2	-213.6 (102.5) **0.038**	44.5 (14.3) **0.002**		NS
	3	NS	NS		
Total sleep time	1	—	-54.8 (14.0) **< 0.001**	-35.9 (16.9) **0.034**	—
	2		-70.0 (14.0) **< 0.001**	NS	
	3		NS		
Sleep efficiency	1	398.2 (97.7) **< 0.001**	-49.5 (14.0) **< 0.001**	—	-0.04 (0.01) **0.003**
	2	342.1 (99.1) **< 0.001**	-48.8 (14.1) **< 0.001**		-0.03 (0.01) **0.013**
	3	NS	NS		NS
Sleep midpoint	1		-52.4 (13.8) **< 0.001**	—	-0.04 (0.01) **0.006**
	2		-44.1 (14.0) **0.002**		NS
	3		NS		
Polysomnography					
In-lab					
AHI	1	—	—	—	-0.03 (0.01) **0.025**
	2				NS
	3				

Abbreviations: NS, not statistically significant after adjustments in each model. —, not entered in the models based on univariate analyses.
Data are regression coefficients (standard error) *p*-value for each standard deviation increase (z-scores) associated with each independent variable (e.g., risetime, time in bed, and sleep midpoint). Model 1 = unadjusted. Model 2 = adjusted for sex, age, race/ethnicity, BMI, SES, and schooling. Model 3 = model 2 + all other significant sleep dimensions (sleep dimensions with Backward/elimination method, and demographics with Enter/forced-entry method). Model 4 = model 3 + externalizing behaviors, including tobacco use (with Enter/forced-entry method). Model 5 = model 4 + internalizing symptoms (with Enter/forced-entry method). Model 6 = *p*-value for the sex by sleep dimension interaction. Bold *p*-values indicate a statistically significant association at $p < .05$. Apnea/hypopnea index (AHI) measured via 9-h in-lab polysomnography (PSG).

sedentarism,[26] and the protective effect of school days for the amount of LPA or MVPA performed.[64] Prior studies also described the association of reduced sleep efficiency and greater PA.[65] Therefore, a highly variable sleep duration and later bedtime could contribute to obesity-related lifestyle risk factors.[66] Recent studies, and our own novel findings herein, highlight the importance of ascertaining the degree of association using a multidimensional-multimethod approach of sleep with dietary habits and PA under different real-world entrainment conditions in adolescents. They allow a better identification of the association of sleep health with lifestyle behaviors

Table 5
Linear regression models between multiple sleep dimensions with self-reported physical activity in adolescents

	Model	Habitual sedentary	Weekdays sedentary	Weekends sedentary	Days >60 m PA
Self-report					
Habitual					
Bedtime	1	2.1 (0.5) **<0.001**	2.3 (0.5) **<0.001**	1.8 (0.5) **<0.001**	—
	2	1.4 (0.5) **0.010**	1.5 (0.5) **0.008**	NS	
	3	NS	NS		
Rising time	1	1.3 (0.5) **0.008**	1.6 (0.5) **0.001**	—	—
	2	NS	NS		
	3				
Sleep onset latency	1	1.1 (0.5) **0.024**	1.3 (0.5) **0.011**	1.0 (0.5) **0.031**	—
	2	1.2 (0.5) **0.017**	1.4 (0.5) **0.007**	NS	
	3	NS	NS		
Insomnia	1	2.3 (1.0) **0.020**	2.5 (1.0) **0.015**	—	—
	2	NS	2.1 (1.0) **0.043**		
	3		NS		
Eveningness	1	1.4 (0.5) **0.002**	1.6 (0.5) **<0.001**	—	—
	2	1.0 (0.5) **0.030**	1.2 (0.5) **0.015**		
	3	NS	NS		
Weekdays					
Bedtime	1	2.0 (0.5) **<0.001**	2.2 (0.5) **<0.001**	1.6 (0.5) **<0.001**	—
	2	1.2 (0.5) **0.019**	1.4 (0.6) **0.012**	NS	
	3	NS	NS		
Rising time	1	1.0 (0.5) **0.036**	1.4 (0.5) **0.006**	—	—
	2	NS	NS		
	3				
Weekends					
Bedtime	1	1.9 (0.5) **<0.001**	2.0 (0.5) **<0.001**	1.8 (0.5) **<0.001**	—
	2	1.3 (0.5) **0.011**	1.3 (0.5) **0.016**	1.2 (0.5) **0.016**	
	3	1.5 (0.5) **0.003**	1.5 (0.5) **0.005**	NS	
	4	1.1 (0.5) **0.025**	1.1 (0.5) **0.043**		
	5	1.1 (0.5) **0.023**	1.1 (0.5) **0.037**		
	6	0.699	0.498		
Rising time	1	1.4 (0.5) **0.005**	1.5 (0.5) **0.002**	—	—
	2	0.9 (0.5) **0.046**	1.1 (0.5) **0.027**		
	3	NS	NS		
Actigraphy					
Habitual					
Bedtime	1	2.2 (0.5) **<0.001**	2.3 (0.5) **<0.001**	2.0 (0.5) **<0.001**	—
	2	1.5 (0.5) **0.007**	1.4 (0.6) **0.013**	1.5 (0.5) **0.008**	
	3	NS	NS	1.4 (0.6) **0.012**	
	4			1.5 (0.5) **0.005**	
	5			1.5 (0.5) **0.005**	
	6			0.316	
Rising time	1	1.1 (0.5) **0.024**	1.3 (0.5) **0.011**	—	—
	2	NS	NS		
	3				
Awakenings	1	-1.2 (0.5) **0.011**	-1.4 (0.5) **0.006**	—	—
	2	NS	-1.1 (0.5) **0.034**		
	3		NS		
Total sleep time	1	—	—	-1.0 (0.5) **0.049**	—
	2			-1.0 (0.5) **0.032**	
	3			NS	
Sleep variability	1	2.0 (0.5) **<0.001**	2.2 (0.5) **<0.001**	1.3 (0.5) **0.005**	—
	2	1.6 (0.5) **<0.001**	1.8 (0.5) **<0.001**	NS	
	3	1.6 (0.5) **<0.001**	1.9 (0.5) **<0.001**		
	4	1.6 (0.5) **0.001**	1.7 (0.5) **0.001**		
	5	1.5 (0.5) **0.001**	1.7 (0.5) **0.001**		
	6	0.503	0.456		
Time in bed variability	1	1.4 (0.5) **0.002**	1.5 (0.5) **0.002**	1.2 (0.5) **0.010**	—
	2	1.1 (0.5) **0.023**	1.1 (0.5) **0.026**	NS	
	3	NS	NS		
Sleep midpoint	1	1.1 (0.5) **0.025**	1.3 (0.5) **0.010**	—	—
	2	NS	NS		
	3				
Weekdays					
Bedtime	1	2.1 (0.5) **<0.001**	2.2 (0.5) **<0.001**	1.9 (0.5) **<0.001**	—
	2	1.3 (0.5) **0.014**	1.3 (0.6) **0.024**	1.3 (0.5) **0.017**	
	3	NS	NS	NS	
Rising time	1	1.1 (0.5) **0.024**	1.3 (0.5) **0.009**	—	—
	2	NS	NS		
	3				
Awakenings	1	-1.2 (0.5) **0.012**	-1.3 (0.5) **0.007**	-1.0 (0.5) **0.044**	—
	2	-1.0 (0.5) **0.036**	-1.2 (0.5) **0.020**	NS	
	3	NS	NS		
Sleep variability	1	1.8 (0.5) **<0**.001	2.0 (0.5) **<0.001**	1.3 (0.5) **0.006**	—
	2	1.3 (0.5) **0.009**	1.4 (0.5) **0.005**	NS	
	3	NS	NS		
Sleep midpoint	1	1.3 (0.5) **0.018**	1.4 (0.6) **0.013**	—	—
	2	NS	NS		
	3				

(*continued on next page*)

Table 5 (*continued*)

	Model	Habitual sedentary	Weekdays sedentary	Weekends sedentary	Days >60 m PA
Weekends					
Bedtime	1	1.9 (0.5) **<0.001**	1.9 (0.5) **<0.001**	1.8 (0.5) **<0.001**	—
	2	1.3 (0.5) **0.012**	1.2 (0.5) **0.022**	1.3 (0.5) **0.013**	
	3	NS	NS	NS	
Total sleep time	1	—	—	-1.0 (0.5) **0.035**	—
	2			NS	
	3				
Polysomnography					
In-lab					
Sleep onset latency	1	—	—	—	-0.2 (0.1) **0.016**
	2				-0.2 (0.1) **0.024**
	3				NS
AHI	1	1.1 (0.5) **0.022**	1.4 (0.5) **0.005**	—	—
	2	NS	NS		
	3				

Abbreviations: NS, not statistically significant after adjustments in each model. —, not entered in the models based on univariate analyses.
Data are regression coefficients (standard error) *p*-value for each standard deviation increase (z-scores) associated with each independent variable (e.g., risetime, time in bed, and sleep midpoint). Model 1 = unadjusted. Model 2 = adjusted for sex, age, race/ethnicity, BMI, SES, and schooling. Model 3 = model 2 + all other significant sleep dimensions (sleep dimensions with Backward/elimination method, and demographics with Enter/forced-entry method). Model 4 = model 3 + externalizing behaviors, including tobacco use (with Enter/forced-entry method). Model 5 = model 4 + internalizing symptoms (with Enter/forced-entry method). Model 6 = *p*-value for the sex by sleep dimension interaction. Bold *p*-values indicate a statistically significant association at $p < .05$. Apnea/hypopnea index (AHI) measured via 9-h in-lab polysomnography (PSG).

tightly linked to obesity and other adverse health outcomes.[67] Future observational or interventional studies should examine the potential interplay (moderating effects) between specific sleep dimensions and diet and PA, as sleep timing may have a boosting effect in adolescents who receive an intervention to improve their lifestyle. Also, following PA recommendations in adolescents may be increased by adherence to heart-healthy diets[68] coupled with regular, aligned, and sufficient sleep.

Our exploratory analyses on potential sex differences suggest that the association between specific sleep dimensions with health behaviors may differ between males and females. First, we found that the association between delayed sleep timing with greater carbohydrates intake and sedentarism was stronger in males. A delayed sleep phase may lead males to ingest more carbohydrates and engage in lengthy sedentary behaviors (e.g., electronic device use).[60,69,70] Second, we found that the association between delayed sleep timing with greater snacking in the mid-afternoon and late-evening was stronger in females. A delayed sleep phase may lead females to engage in snacking behaviors during the misaligned presleep period. These findings are commensurate with previous studies linking circadian misalignment with greater intake of energy-dense and savory foods.[71] In addition, we found that the "paradoxical" association between longer SOL with greater MVPA and METs was stronger in females. This finding may suggest a misalignment in the timing of MVPA (e.g., extra-academic sports) in females leading to prolonged sleep latency, rather than difficulty sleeping leading to greater MVPA. Similar findings have been reported in adults, where morning, but not evening, MVPA was associated with shorter SOL regardless of the subject's morning or evening chronotype.[72] All these potential sex differences should be confirmed in future studies with larger sample sizes, as they may have important public health and therapeutic implications.

Finally, the current findings reinforce the critical importance of using objective sleep measures in clinical assessments, particularly at-home ACT when studying the relationship between sleep and health behaviors in adolescents. Interventions aimed at reducing obesity-related risk in adolescents should integrate objective sleep monitoring, ideally using multinight home-based ACT to accurately assess key sleep dimensions of timing, regularity, and efficiency. Our results also highlight that interventions should be tailored to the academic calendar, given that the sleep/health behavior associations varied depending on the academic context. During the school term, when adolescents follow stricter schedules, interventions should focus on advancing bedtime, increasing sleep duration, and reducing variability, as these factors were most strongly linked to high-caloric diets and sedentarism. In contrast, during school breaks, interventions might more effectively target delayed sleep timing, late-night snacking, and declines in physical activity. These context-specific approaches, grounded in objective monitoring, may offer more robust strategies for addressing obesity-related behaviors in adolescents.

The results of our study should be interpreted considering some limitations. First, since we only had two weekend days, we could not calculate sleep variables based on standard deviations and the accuracy of the average weekend estimates should be interpreted cautiously.[73] Second, the study design was cross-sectional, which limits the ability to assess causality on the associations observed, it is also important to acknowledge the possibility of reciprocal associations. Previous research suggests that sleep may both influence and be influenced by dietary behaviors and physical activity, indicating potential transactional dynamics between sleep and health behaviors.[74,75] Third, since participants were evaluated only once, the associations described for in-school and on-break could not be explored within-subjects. Future studies should include repeated-measures designs where all subjects transition for these two periods to properly assess the effect of the entrainment conditions on lifestyle outcomes. Fourth, dietary habits and snacking can be affected by a recall bias on self-reported questionnaires, the misalignment of measurement windows between diet and sleep measures presents a potential limitation, and no study has explicitly compared data collected in-school vs. on-break periods; nevertheless, previous work supports the questionnaire used as a valid tool to assess diet.[54] Typical correlations between food frequency questionnaires and short-term dietary assessments range from 0.3-0.7, and vary depending on age, cultural background, and questionnaire format.[76] We used the same questionnaire format across all subjects and we accounted for sex, age, race/ethnicity, and SES in our models in order to provide improved estimates in this sample. Fifth, beyond the physical activity questionnaire, no detailed data were collected on participation in extracurricular activities or school sports teams, which would have offered greater insight into the types of physical activities reported, particularly relevant for the MVPA findings. Finally, although we maximized sample size as much as possible in our analyses, some outcomes (i.e., self-reported snacking, ACT-measured PA) did have missing observations and estimates and *p*-values should, thus, be interpreted accordingly.

In summary, this study using a multidimensional-multimethod approach found that sleep timing was associated with caloric intake, and mid-afternoon/late-evening snacking, particularly when sleep is ACT-measured at-home. Sleep timing was associated with mid-morning/late-

evening snacking and sedentary behavior, especially among adolescents evaluated while on-break. Sleep efficiency was associated with weekdays' sedentary behavior, late-evening snacking during vacation, and MVPA, especially if evaluated while in-school. Sleep efficiency was associated with late-evening snacking and LPA, especially if evaluated while on-break via self-reports. These associations indicated that a delayed and irregular timing of sleep during school days is associated with unhealthy behaviors, including more calories, snacking, and sedentarism. Such an association may need to receive further attention to drive prevention strategies to reduce obesity risk in adolescents. Future studies are needed to fully understand the upstream determinants and underlying mechanisms of the relationships observed.

Author contributions

The conceptualization of the cohort study was carried out by E.B., D.L., and J.F.-M. Methodology was developed by E.B., D.L., and J.F.-M. The conceptualization of the study analysis herein was carried out by P.B.-N. and J.F.-M. and formal analysis was performed by P.B.-N., while data curation was undertaken by J.L., D.L., and N.M.-G. The original draft of the paper was written by P.B.-N. and J.F.-M. Subsequent review and editing were conducted by N.M.-G., K.L., S.C., A.V., and C.N. Funding for the research was acquired by J.F.-M. and E.B.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request via an institutional data use agreement.

Declaration of conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Given their role as Sleep Health Associate Editor, Julio Fernandez-Mendoza had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor.

Use of generative AI and AI-assisted technologies in the writing process

The authors certify that no generative artificial intelligence (AI) tools (e.g., ChatGPT, Bard, or comparable technologies) were utilized in conceptualization, writing, data analysis, or figure creation. The scientific content, analysis, and conclusions remain entirely the work of the authors.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.sleh.2026.01.008.

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