The Journal of Nutrition
Community and International Nutrition

Assessing Changes in Adolescents' Sleep Characteristics and Dietary Quality in the START Study, a Natural Experiment on Delayed School Start Time Policies

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ABSTRACT

Background: Sleep duration, quality, and timing may influence dietary quality. In adults, poor dietary quality is a risk factor for numerous chronic diseases. It is unclear how these various sleep domains influence adolescents' diets because prior population-based studies have not effectively manipulated sleep, did not include objective sleep measures, and had short follow-up times.

Objectives: The objectives of this study were to examine *1*) how adolescent sleep characteristics relate to dietary quality; and *2*) how delay in high school start times (which lengthened sleep duration) affects dietary quality over 2 y.

Methods: In the START study, adolescents (grades 9–11, $n = 423$) attending 5 high schools in the Minneapolis, Minnesota metropolitan area were annually assessed in 3 waves (2016–2018). At Baseline, all schools started "early" (07:30 or 07:45). From Follow-up 1 through Follow-up 2, 2 "policy change schools" shifted to later start times (to 08:20 and 08:50). Three "comparison schools" maintained their early start throughout. Sleep characteristics were measured with actigraphy. Mixed-effect regression models were used to examine cross-sectional and longitudinal associations of sleep characteristics with dietary quality, and school start time policy change with dietary quality change.

Results: Cross-sectionally, later sleep midpoint and onset were associated with dietary quality scores 1.6–1.7 lower (both $P < 0.05$). However, no prospective associations were observed between sleep characteristics and dietary quality in longitudinal models. Shifting to later school start time tended to be associated with a 2.4-point increase in dietary quality score ($P = 0.09$) at Follow-up 1, but was not associated with change in dietary quality scores at Follow-up 2 ($P = 0.35$).

Conclusions: High school students attending delayed-start schools maintained better dietary quality than students in comparison schools; however, differences were not statistically significant. Overall study findings highlight the complexity of the relation between sleep behavior and diet in adolescence. *J Nutr* 2021;151:2808–2815.

Keywords: actigraphy, adolescence, diet, sleep timing, school start times, high school

Introduction

Two-thirds of adolescents in the United States sleep less than the recommended 8–10 h/night (1). In addition, over half report regularly experiencing sleep problems, including trouble falling asleep or staying asleep, that may affect the overall quality of their sleep (2). The immediate consequences of poor-quality and/or insufficient sleep during adolescence include poor school performance (3), reduced self-esteem, and dampened mood (4), as well as a greater risk of injury (5–7).

In adulthood, poor sleep has been linked to the development of numerous chronic diseases, including cardiovascular disease and type 2 diabetes (8–10). One potential pathway explaining this link is that poor sleep may lead to increased adiposity and weight gain by altering base metabolic rate, changing hormone regulation, decreasing physical activity, modifying diet through increasing caloric intake, reducing dietary quality, or influencing appetite via central brain pathways (11–14). The relation between poor sleep and diet has been less studied in the adolescent population. In laboratory studies among adolescents, sleep restriction led to excessive caloric intake and to changes in food preferences, resulting in greater consumption of high-sugar snacks and desserts (15, 16). Ideally, a long-term experimental

Manuscript received March 19, 2021. Revision accepted May 5, 2021.
First published online June 4, 2021; doi: https://doi.org/10.1093/jn/nxab169.

trial outside of the laboratory setting would be needed to best understand the nature of a link between poor sleep and diet in adolescents (11, 14). However, implementing such a population-based study with real-world assessment is likely not feasible because it is difficult to effectively manipulate adolescents' sleep at a community scale for extended periods of time (14).

Adolescents face unique challenges to getting healthy sleep (7, 17). Sleep during this important period of development is challenged by increased homework burden, intense social pressures, more opportunities for caffeine intake, chores, and greater use of mobile devices, all of which can push bedtimes later (7, 17). Moreover, some adolescents have early morning extracurricular activities or other responsibilities that require early wake-ups (17). But the shift that is likely most salient to adolescents' sleep insufficiencies is the bioregulatory changes that occur around the onset of puberty, including circadian timing delay (18), which leads to later evening alertness and later sleep onset (17). Because of this, delaying high school start times to better align school with the neurobiology of adolescents is a powerful policy option that can counteract population-wide adolescent sleep deprivation (17, 19, 20). In fact, evidence demonstrates later start times result in longer sleep durations, improved quality of life, and better academic performance (7, 21–25).

In secondary schools where start time delays have been implemented there is an opportunity to examine the potential impacts of this sleep intervention. This study leverages objectively measured sleep data from the START study, a field-based natural experiment of school start time delay (26). In a previous START study, we found that students in high schools with delayed start times extended their sleep durations over the 2-y study period (27). The goal of this study was to investigate whether sleep influences dietary quality and what dimensions of sleep may be important. Specifically, the objectives of this study were to *1*) examine cross-sectional and prospective associations of sleep characteristics with measures of dietary quality assessed via multiple 24-h recalls, including overall quality and added sugar and sodium intakes; and *2*) prospectively assess if delaying high school start times was associated with subsequent changes in adolescent diet quality. We hypothesized that poor sleep efficiency, insufficient sleep duration, and later sleep timing would be associated with lower dietary quality and that students in the policy change schools would have improved dietary quality relative to students in the comparison schools at 1 and 2 y after start times were delayed.

Methods

Study design

The START study was designed to evaluate a natural experiment where several school districts delayed their high schools' start times (26). In the spring of 2016, START recruited ninth-grade students ($n = 2134$) from 5 suburban Minneapolis, Minnesota schools. At Baseline (2016), all 5 schools started at 07:30 or 07:45. Beginning in Fall 2017, 2 schools delayed their start times by 50 and 65 min, from 07:30 to 08:20 and 07:45 to 08:50 am, respectively. At Follow-up 2 (spring 2018) these 2 "policy change" schools maintained their delayed start times; 3 other schools ("comparison schools") served as a comparison group starting at 07:30 throughout the study period.

Data for the present analysis are from a subsample of START participants (START substudy; $n = 455$) who took part in longitudinal actigraphy sleep assessments and 24-h dietary recalls (**Figure 1**). To arrive at this subsample, we selected START participants randomly, proportional to school size. E-mail invitations and consent materials were sent to parents of these selected students. If the parent/guardian consented and their child assented to the research procedures, the student was enrolled in the substudy. After Baseline, all substudy participants were invited to participate in the subsequent waves of substudy data collection (Follow-ups 1 and 2). From the stratified random invitation list generated at Baseline, additional students were recruited to the substudy at Follow-up 1. At each of the 3 waves of data collection, participants received $85 if they completed all substudy measures. To account for seasonality, all 3 waves of data collection were completed in the spring of each school year (from mid-March through May). At each wave, participants completed sleep assessments and dietary recalls in the same week. START substudy data were collected from 284 participants at Baseline, 305 participants at Follow-up 1, and 184 participants at Follow-up 2. All START procedures were in accordance with the ethical standards of and approved by the University of Minnesota Institutional Review Board.

Sleep characteristics

We asked substudy participants to wear an ActiGraph (wGT3X-BT Monitor, Actigraph) triaxial accelerometer on their nondominant wrist for 24 h/d over a 7-d period, removing it only for contact sports, swimming, or bathing. Across the 3 waves of data collection, a total of 455 students provided $\geq$1 wk of valid actigraphy. Among the 455 students with valid data, 230, 132, and 93 provided 1, 2, and 3 valid weeks of actigraphy, respectively. Participants concurrently completed a sleep log to self-report times in and out of bed for the nighttime sleep period and for napping. Wrist actigraphy has been shown to provide valid estimates of sleep characteristics in adolescents as compared with polysomnography (28).

Actigraphy data were processed by the Brigham Sleep Reading Center in Boston, Massachusetts. Using ActiLife version 6.13 (ActiGraph Corp), a trained sleep coder defined the main sleep period for each night by reviewing the reported in-bed and out-of-bed time from the sleep journal and visually reviewing the accelerometer activity counts. The validated Cole–Kripke (29) algorithm was applied to the identified sleep periods, and each 60-s epoch of the sleep period was classified as "sleep" or "wake." We removed all weekday sleep periods where nonstandard school schedules were followed (e.g., weather-related school cancelations). Because 1 school started instruction 30 min later for staff professional development on Wednesdays, all data from Tuesday nights for the full sample were excluded.

We created 6 sleep measures: sleep duration, short sleep duration, sleep efficiency, sleep fragmentation, sleep midpoint, and sleep onset. Sleep duration was defined as the total minutes classified as sleep in the main sleep period (min/night). This total minutes of sleep duration does not include minutes awake that occurred during the sleep period. Owing to a small number of participants in our sample meeting sleep duration recommendations of 8 h/night, we created a dichotomous variable for short sleep duration, with <7 h on average per night representing short sleep (1/0). Sleep efficiency was defined as the proportion of the main sleep period, from lights out to wake, spent sleeping. Sleep fragmentation index was defined as the proportion of the sleep period characterized by movement (based on activity counts and periods of immobility) (30). Sleep midpoint, considered a valid marker of habitual sleep chronotype or circadian timing (31), was defined as the halfway point in time between sleep onset and morning awakening. Sleep onset was the time of sleep initiation defined by the Cole–Kripke algorithm

Supported by NIH Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) grant R01 HD088176 (to RW), National Heart, Lung, and Blood Institute training grant T32 HL007779 (to KMF), and NICHD training grant T32 HD095134 (to KMB).

Author disclosures: The authors report no conflicts of interest.

Supplemental Table 1 is available from the "Supplementary data" link in the online posting of the article and from the same link in the online table of contents at https://academic.oup.com/jn/.

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Abbreviations used: ASA24, Automated Self-Administered 24-Hour; DGA, Dietary Guidelines for Americans; GLMM, generalized linear mixed-effect regression model; HEI-2015, Healthy Eating Index 2015.

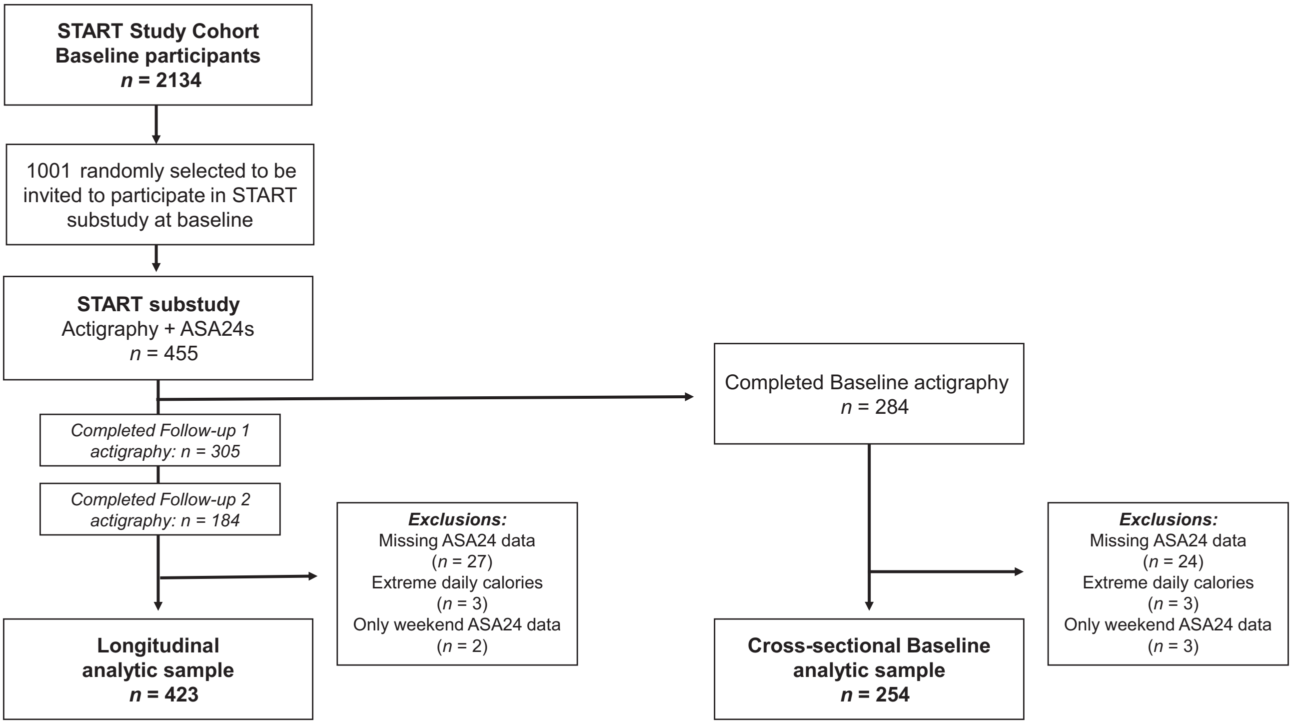

FIGURE 1 START substudy participant flowchart. ASA24, Automated Self-Administered 24-Hour.

(29). To obtain weekly averages, estimates of each sleep characteristic were averaged across all of the valid nights of wear for each participant.

Measures of dietary quality

The primary outcome for this analysis was overall dietary quality estimated by the Healthy Eating Index 2015 (HEI-2015) (32). To assess dietary intake, all subsample participants were asked to complete two 24-h dietary recalls at Baseline and 3 recalls at Follow-ups 1 and 2. Participants' dietary intake data for a 24-h period were collected and analyzed using the Automated Self-Administered 24-Hour (ASA24) Dietary Assessment Tool (2016, developed by the National Cancer Institute; https://epi.grants.cancer.gov/asa24/) (33). Self-reported measures of dietary intake are known to suffer from issues with misreporting; however, the ASA24 tool has been shown to assist with reporting and provide valid estimates of dietary meal intake (34). Data from the ASA24 recalls were used to calculate dietary quality as defined by the HEI-2015 (32). The HEI-2015 is based on the Dietary Guidelines for Americans (DGA) for 2015–2020 (32). Comprised of 13 subcomponents (9 "adequacy" and 4 "moderation" components), total HEI-2015 scores represent overall dietary quality, with the maximum score of 100 representing complete alignment with the DGA. Of the moderation subcomponents (foods to limit), we focused on 2 separately (added sugars and sodium intakes) based on previous evidence of sleep restriction and changes in dietary preference (15, 16). A score of 10 for added sugars intake represents alignment with meeting the DGA recommendation of limiting sugar intake to <10% of daily calories from sugar; a score of 10 for sodium intake represents alignment with the recommendation of limiting sodium intake to <2300 mg/d. Owing to a small number of participants in our sample meeting the DGA sugar and sodium recommendations, we dichotomized at a score ≥8 for added sugar and ≥9 for sodium to represent intake close to this DGA recommendation. For participants with multiple ASA24 recalls in a school year, we calculated mean HEI-2015 scores across all recalls. Participants were excluded if they were missing ASA24 data altogether (cross-sectional Baseline sample, $n = 24$; longitudinal sample, $n = 27$), if they reported extreme daily calorie intakes that suggested a validity issue for that day's reporting (<500 or ≥5000 kcal; cross-sectional Baseline sample, $n = 3$; longitudinal sample, $n = 3$), or if they only had ASA24 recalls from weekend days (cross-sectional Baseline sample, $n = 3$; longitudinal sample, $n = 2$). Across the 3 waves of data collection, a total of 423 students provided ≥1 valid weekday dietary recall. Among these 423 students with valid dietary recall data, 195 students provided valid dietary recall data at 1 time point; 140 and 88 provided valid ASA24s at 2 and 3 time points, respectively.

Covariates

All START participants completed a survey and self-reported information on biological sex (male; female; prefer not to answer), race (Native American; Asian, Hawaiian, or Pacific Islander; black; white; multiple; unknown or not reported), free or reduced-price meal eligibility (yes; no; don't know), and each parent or guardian's highest obtained education. Race was recategorized as white or nonwhite as a crude proxy measure of exposure to racism in these predominantly white communities. Parent education was recoded as having ≥1 parent or guardian who completed college.

Statistical analyses

The present analysis includes 2 analytic samples. The analytic sample for the cross-sectional Baseline analysis includes the 254 students at Baseline who had valid actigraphy data, completed ≥1 weekday 24-h dietary recall, and had complete covariate information. The analytic sample for the longitudinal analyses included 423 students from the subsample who had valid actigraphy data and ≥1 valid weekday 24-h dietary recall from the same week at any wave.

For the cross-sectional analytic sample, we described and compared Baseline participant characteristics according to quartiles of mean sleep duration. For the longitudinal analytic sample, we compared participant characteristics across school start time policy groups (policy change as opposed to comparison). Chi-square tests and 1-factor ANOVAs were used to compare participant characteristics across sleep duration quartiles.

A series of adjusted generalized linear mixed-effect regression models (GLMMs) and linear mixed-effect regression models were run to test the cross-sectional and prospective associations between objectively measured sleep characteristics and measures of dietary quality. First, cross-sectional linear mixed-effect models estimated associations of sleep characteristics with overall dietary quality scores (HEI-2015) at Baseline. Next, cross-sectional GLMMs were run to estimate the

TABLE 1 Baseline participant characteristics by accelerometer-measured weekday sleep duration; START study[1]

	Overall	Accelerometer-measured sleep duration quartiles, min/night			
	Overall ($n = 254$)	Q1 (<377) ($n = 64$)	Q2 (377 to <411) ($n = 62$)	Q3 (411–439) ($n = 65$)	Q4 (>439) ($n = 63$)
Demographics					
Age, y	15.2 ± 0.3	15.1 ± 0.3	15.1 ± 0.3	15.3 ± 0.3	15.2 ± 0.3
Sex					
Female	118 (46.5)	28 (43.8)	28 (45.2)	34 (52.3)	28 (44.4)
Male	136 (53.5)	36 (56.2)	34 (54.8)	30 (47.7)	35 (55.6)
Race					
Nonwhite	33 (13.0)	7 (10.9)	7 (11.3)	13 (20.0)	6 (9.5)
White	221 (87.0)	57 (89.1)	55 (88.7)	52 (80.0)	57 (90.5)
Free or reduced-price meal eligibility	15 (5.9)	5 (7.8)	2 (3.2)	4 (6.2)	4 (6.3)
≥1 Parent completed college	211 (83.1)	52 (81.2)	57 (90.5)	53 (82.8)	49 (77.8)
Dietary measures					
Total energy, kcal/d	2040 ± 814	2060 ± 924	2080 ± 788	2140 ± 845	1870 ± 669
Total HEI-2015 score	47.9 ± 12.2	46.0 ± 13.0	48.9 ± 12.9	48.3 ± 11.1	48.5 ± 12.0
HEI-2015 added sugars score (0–10)	6.4 ± 2.8	6.2 ± 3.0	6.6 ± 2.6	6.2 ± 2.9	6.5 ± 2.7
HEI-2015 sodium intake score (0–10)	4.6 ± 2.9	4.3 ± 3.1	4.8 ± 2.7	4.6 ± 3.0	4.6 ± 2.8
Actigraphy-measured sleep characteristics					
Weekday sleep duration, min	406 ± 52.1	339 ± 34.8	395 ± 10.4	424 ± 8.1	466 ± 29.3
Sleep efficiency, %	85.4 ± 4.5	83.5 ± 4.7	84.4 ± 4.9	86.2 ± 3.7	87.4 ± 3.3
Sleep fragmentation index	30.1 ± 7.7	30.8 ± 9.0	30.4 ± 7.1	29.3 ± 6.9	29.9 ± 7.7
Time of sleep midpoint (SD in min)	02:21 (35.3)	02:42 (32.0)	02:19 (27.9)	02:16 (25.6)	02:07 (43.9)
Time of sleep onset (SD in min)	22:28 (52.3)	23:20 (48.1)	22:30 (35.2)	22:10 (27.9)	21:50 (38.8)

[1] $n = 254$. Values are mean ± SD or n (%) unless otherwise specified. HEI-2015, Healthy Eating Index 2015; Q, quartile.

predicted probabilities of reporting sugar and sodium intakes close to meeting DGA recommendations (score of ≥8 for added sugar and ≥9 for sodium) for participants at the 25th and 75th percentiles of sleep characteristics. Next, longitudinal linear mixed-effect regression models tested the prospective associations between changes in sleep characteristics and changes in overall dietary quality. These longitudinal mixed models included fixed effects for each sleep characteristic, time, and a sleep characteristic-by-time interaction term. This interaction term represents the prospective changes in sleep on changes in overall dietary quality over the 2-y study period. All models were adjusted for demographic characteristics that could mark a factor such as exposure to racism or other social disadvantage, or covariates that might confound the exposure–outcome relations of interest (biological sex, nonwhite race, free or reduced-price meal eligibility, and parent education). All models included a random effect for school to account for clustering of students within schools, and all longitudinal models included an additional random effect for student to account for repeated measurement.

Last, linear mixed-effects models tested the effect of the school start time policy on participant dietary quality over the 2-y study period. Models included school condition (policy change compared with comparison school), time (Baseline, Follow-up 1, Follow-up 2), and an interaction term (school condition-by-time) as fixed effects. The main effect of interest is the condition-by-time interaction term, which represents the longitudinal policy effects on the overall dietary quality outcome at Follow-up 1 and Follow-up 2. A random effect for participant within school was included to account for repeated-measure variation within participant and for clustering at the school level. These models also included adjustment for biological sex, nonwhite race, free or reduced-price meal eligibility, and parent education.

All statistical analyses were performed with R software version 3.6.3 (R Project for Statistical Computing) (35).

Results

Table 1 presents characteristics of the 254 participants in the cross-sectional Baseline analytic sample by mean sleep duration quartile. At Baseline, the mean age of START participants was 15.2 y, just under half of the participants were female (46.5%), and the majority were white (87%). Those in the shortest sleep duration quartile (<375 min/night) were more likely to be male, had the lowest mean HEI-2015 score, and the lowest sleep efficiency percentages as compared with participants in the other quartiles.

Study participants from the comparison schools were more likely to be male and white and less likely to have a parent or guardian who completed college than the students in the policy change schools. At Baseline, sleep measures were comparable between policy change and comparison schools (sleep duration $P = 0.7$; sleep efficiency $P = 0.6$), whereas average HEI-2015 score was higher in the policy change schools ($P = 0.06$) (**Supplemental Table 1**).

Over the 2-y study period, the mean dietary quality scores of the participants decreased slightly from Baseline (HEI: 48.0) to Follow-up 2 (HEI: 47.5; $P = 0.7$; data not shown). Participants' average weekday sleep duration increased from Baseline to Follow-up 2 (Baseline: 405.8 min; Follow-up 2: 422.5 min; $P < 0.01$), and timing of sleep onset was pushed on average 13 min later [Baseline: 22:28; Follow-up 2: 22:41; $P < 0.01$; data previously published (27)].

Sleep characteristics and measures of dietary quality

Cross-sectionally at Baseline, later sleep midpoint and later sleep onset were associated with lower dietary quality scores (HEI-2015) in both crude and adjusted models (Table 2). Although not statistically significant, the association between sleep duration and dietary quality was in the hypothesized direction, with shorter sleep durations associated with lower HEI-2015 scores ($P = 0.29$). After adjustment for demographic characteristics, a 1-SD (35.0 min) later sleep midpoint was associated with a 1.6 lower HEI-2015 score ($P = 0.03$). In addition, a 1-SD (52.3 min) later sleep onset was associated

TABLE 2 Baseline cross-sectional associations of sleep characteristics with total Healthy Eating Index 2015 score; START study[1]

	β Coefficient ± SE	*P*-trend
Weekday sleep duration, min (per 1 SD)		
Crude	0.58 ± 0.77	0.45
Adjusted[2]	0.79 ± 0.75	0.29
<7 h of sleep duration		
Crude	− 0.09 ± 1.55	0.95
Adjusted[2]	− 0.60 ± 1.52	0.69
Sleep efficiency, % (per 1 SD)		
Crude	0.25 ± 0.77	0.75
Adjusted[2]	− 0.33 ± 0.77	0.67
Sleep fragmentation index (per 1 SD)		
Crude	0.25 ± 0.77	0.74
Adjusted[2]	0.80 ± 0.76	0.29
Sleep midpoint, min (per 1 SD)		
Crude	− 1.60 ± 0.75	0.03[3]
Adjusted[2]	− 1.64 ± 0.73	0.03[3]
Sleep onset, min (per 1 SD)		
Crude	− 1.39 ± 0.76	0.07
Adjusted[2]	− 1.69 ± 0.75	0.02[3]

[1] $n = 254$. Models used baseline data only. 1 SD of sleep duration = 52.1 min; 1 SD of sleep efficiency = 4.5%; 1 SD of sleep fragmentation = 7.7 awakenings; 1 SD of sleep midpoint = 35.0 min; 1 SD of sleep onset = 52.3 min.
[2] Model adjusted for biological sex, nonwhite race, free or reduced-price meal eligibility, and parent education with a random effect for school.
[3] Indicates $P < 0.05$.

with a 1.7 lower HEI-2015 score ($P = 0.02$). Although not statistically significant, greater weekday sleep duration was associated with a higher HEI-2015 score (0.8 points, $P = 0.29$) per SD of sleep time (52.1 min) in adjusted models.

Table 3 presents the predicted probabilities from the cross-sectional GLMMs of having sugar and sodium intakes close to the DGA recommendations. Participants with later sleep midpoints (02:40) had a higher probability of having a sugar intake close to the recommended DGA level (score of ≥8 for added sugar) than those with earlier sleep midpoints (02:00; 25.2%; 95% CI: 17.4%, 29.1% compared with 16.8%; 95% CI: 11.0%, 19.4%; $P < 0.01$). A similar association was observed for participants with later sleep onset (23:00; 24.8%; 95% CI: 17.1%, 29.3%) compared with earlier onset (22:00; 18.5%; 95% CI: 12.2%, 21.8%; $P = 0.02$). With sodium intake, participants with earlier sleep midpoints (02:00) had a higher probability of having a sodium intake close to the recommended DGA level (score of ≥9) (28.9%; 95% CI: 24.5%, 40.5%) than those with later sleep midpoints (02:40; 17.7%; 95% CI: 14.2%, 25.7%; $P < 0.01$). Again, a similar association was observed for earlier sleep onset: those who went to sleep at 22:00 had a predicted probability of 27.0% (95% CI: 22.0%, 38.3%) of having a sodium intake close to the recommended DGA level as compared with a 20.0% probability (95% CI: 15.7%, 29.0%) for those who went to sleep at 23:00 ($P < 0.01$).

In our prospective analyses, no longitudinal associations were found between sleep characteristics and overall dietary quality (Table 4). Participants who slept <7 h on average had lower HEI-2015 scores (−0.2 points, $P = 0.79$) over the 2-y period and those with later sleep midpoints and sleep onsets had higher HEI-2015 scores (0.5 points, $P = 0.23$; 0.6 points, $P = 0.19$, respectively).

School start time policy and dietary quality

At each time point, the HEI-2015 score was higher in the policy change schools than in the comparison schools, although differences were not statistically significant (Follow-up 1: $P = 0.06$; Follow-up 2: $P = 0.55$). Figure 2 presents the mixed-effect model–based estimates of total HEI-2015 score at each time point over the 2-y study period, adjusting for Baseline demographics and nesting of participants within schools. After adjustment, students at policy change schools had higher dietary quality scores than students in comparison schools over the 2-y study period, but the differences were not statistically significant (Follow-up 1: 2.4 HEI points, $P = 0.09$; Follow-up 2: 1.5 HEI points, $P = 0.35$).

Discussion

In this study, the average sleep duration of high school students increased whereas the average dietary quality scores decreased over the 2-y study period as participants moved from 9th through 11th grade. In cross-sectional analyses, we observed an association between measures of later sleep timing and poorer

TABLE 3 Predicted probabilities of sugar and sodium intakes close to meeting the 2015–2020 Dietary Guidelines for Americans recommendations at the 25th and 75th percentiles of sleep characteristics at baseline; START study[1]

		<10% of daily calories from added sugar		<2300 mg Na/d	
Sleep characteristic	25th and 75th percentiles[2]	Predicted probability, % (95% CI)	*P*-trend	Predicted probability, % (95% CI)	*P*-trend
Weekday sleep duration	6 h	22.0 (15.4, 24.6)	0.86	22.7 (18.3, 32.5)	0.57
	8 h	21.0 (14.6, 23.5)		26.2 (21.5, 37.0)	
Sleep efficiency	82%	21.0 (14.5, 23.4)	0.74	22.1 (18.3, 31.5)	0.39
	89%	22.4 (15.6, 25.0)		25.7 (21.6, 36.1)	
Sleep fragmentation index	25 awakenings	21.4 (14.9, 23.6)	0.87	23.4 (18.8, 33.6)	0.70
	35 awakenings	21.9 (15.4, 24.3)		24.7 (20.0, 35.4)	
Sleep midpoint	02:00	16.8 (11.0, 19.4)	<0.01[3]	28.9 (24.5, 40.5)	<0.01[3]
	02:40	25.2 (17.4, 29.1)		17.7 (14.2, 25.7)	
Sleep onset	22:00	18.5 (12.2, 21.8)	0.02[3]	27.0 (22.0, 38.3)	<0.01[3]
	23:00	24.8 (17.1, 29.3)		20.0 (15.7, 29.0)	

[1] $n = 254$. Models used baseline data only. Predicted probabilities estimated with adjusted generalized linear mixed-effect regression models. Models adjusted for biological sex, nonwhite race, free or reduced-price meal eligibility, and parent education with a random effect for school.
[2] 25th and 75th percentiles were approximated to aid in easy interpretation.
[3] Indicates $P < 0.05$.

TABLE 4 Prospective associations of sleep characteristics with total Healthy Eating Index 2015 score, START study[1]

	β Coefficient ± SE	*P*-trend
Weekday sleep duration, min (per 1 SD)		
Crude	−0.17 ± 0.42	0.69
Adjusted[2]	−0.28 ± 0.44	0.53
<7 h of sleep duration		
Crude	−0.58 ± 0.88	0.51
Adjusted[2]	−0.23 ± 0.88	0.79
Sleep efficiency, % (per 1 SD)		
Crude	0.38 ± 0.44	0.38
Adjusted[2]	0.32 ± 0.44	0.47
Sleep fragmentation index (per 1 SD)		
Crude	−0.37 ± 0.44	0.41
Adjusted[2]	−0.42 ± 0.45	0.35
Sleep midpoint, min (per 1 SD)		
Crude	0.43 ± 0.45	0.34
Adjusted[2]	0.54 ± 0.45	0.23
Sleep onset, min (per 1 SD)		
Crude	0.48 ± 0.43	0.27
Adjusted[2]	0.58 ± 0.44	0.19

[1] $n = 423$. Models used data from all time points. 1 SD of sleep duration = 50.6 min; 1 SD of sleep efficiency = 4.5%; 1 SD of sleep fragmentation = 7.6 awakenings; 1 SD of sleep midpoint = 40.3 min; 1 SD of sleep onset = 55.4 min.
[2] Model adjusted for biological sex, nonwhite race, free or reduced-price meal eligibility, and parent education with a random effect for school.

overall dietary quality. Our longitudinal analyses showed that school start time policy change was associated with a small reduction in the decline in dietary quality over the 2-y period. However, the evidence for this relation was dampened by the facts that this finding was not statistically significant and that there was no apparent longitudinal association between sleep changes and change in dietary quality.

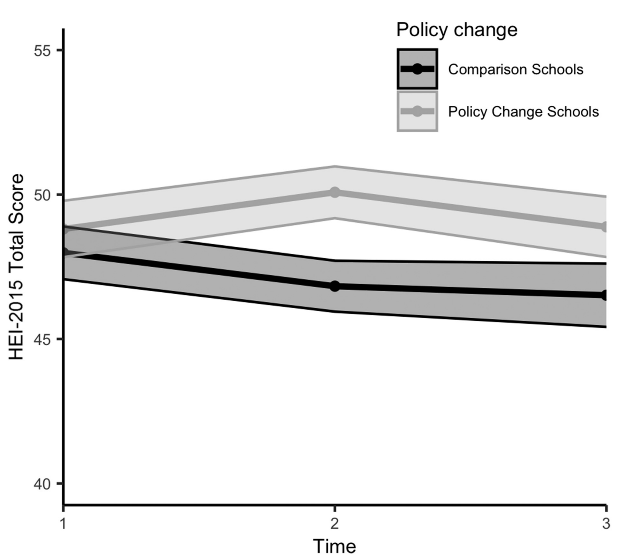

FIGURE 2 Differences in mean total HEI-2015 scores between policy change and comparison schools over time after adjustment. Results of a mixed-effect regression model estimating effect of policy change on dietary quality over a 2-y study period. Model adjusted for biological sex, nonwhite race, free or reduced-price meal eligibility, and parent education with a random effect for student nested within school. HEI-2015 overall dietary quality score ranged from 0 to 100. Time: 1: Baseline; 2: Follow-up 1; 3: Follow-up 2. HEI-2015, Healthy Eating Index 2015.

Getting sufficient sleep duration and quality at times that are aligned with teenagers' natural circadian wiring is a challenge faced by adolescents in the United States (7, 17). Similar to prior findings (1, 2, 7, 17, 36), the majority of START participants were not meeting the National Sleep Foundation recommendations that adolescents sleep between 8 and 10 h/night (37). Similarly, with a median sleep onset time of 22:35 that was pushed later throughout the study period, START participants also had delayed sleep timing consistent with estimates from population-based studies (2, 36).

Previous population-based studies examining associations between sleep and diet among adolescents have used cross-sectional designs and focused primarily on sleep duration as the exposure (38–42). This may be in part due to the reliance of epidemiologic studies on self-reported measures of sleep (14). The majority of these studies have found that adolescents with shorter sleep durations report poorer dietary habits (39, 42) and greater consumption of energy-dense foods (38, 40, 41). In our cross-sectional analysis, high school students with later sleep onsets and later sleep midpoints were more likely to report lower dietary quality scores. These findings are consistent with previous cross-sectional studies among adolescents (43–46). An advantage of our study is that it is one of the first to include actigraphy measures of sleep timing, allowing for the assessment of sleep onset, a more precise measure than self-reported bedtime, as well as sleep midpoint which can be used as a marker of chronotype or circadian timing (47). Our cross-sectional results also suggested that later sleep times and later chronotypes may be associated with a higher probability of high sodium intake, which may be an indicator of adolescents who get inadequate sleep having cravings for less healthy foods, as prior studies have suggested (15, 16, 38, 48).

Systematic reviews provide consistent evidence of an association of sleep characteristics with dietary patterns, including meal timing, dietary quality, types of foods consumed, and total caloric intake, in adults (14, 49). However, contrary to our hypothesis and our cross-sectional results, we found no association between changes in any sleep characteristics and overall dietary quality over the 2-y study period in high school adolescents. Our results may be explained by the fact that once dietary habits are established in adolescents, they are hard to change over relatively short time intervals. Given our cross-sectional results and the well-documented link between later chronotype and incident chronic cardiometabolic conditions in adult populations (50–52), further investigation in adolescent populations is warranted to identify potential early opportunities for intervention.

To evaluate sleep and dietary quality in adolescents we leveraged a rich resource from an evaluation of a community-based natural experiment in school start time policy modification. START's strengths include objective measurement of sleep characteristics and multiple-day 24-h dietary recall measures at 3 times over 2 y in a population-based adolescent cohort. Compared with FFQs, 24-h diet recalls are known for providing a more accurate assessment of actual diet (34), especially when repeated several times over a week. Wrist actigraphy is the gold standard for community-based objective assessment of sleep characteristics (53), and this is one of few studies to have repeated measures of wrist actigraphy in a cohort of high school students. Further, the school start time policy change created changes in sleep in the START sample (27), and this policy change was likely not caused by an underlying factor that would also cause diet change, allowing for a rigorous evaluation of a natural experiment. Despite these strengths, one weakness of our study was attrition of the START substudy sample. The differences we are examining in our analyses may be too small to detect with the size of this subsample. In addition, if adolescents with overall better sleep and diet profiles were more likely to remain in the study sample, selection bias may be present. Further, the schools in our study were all very similar, increasing the internal validity of our study, but the START study sample overall had little racial or geographic diversity, potentially limiting the generalizability of our results.

To our knowledge, this is one of the first studies to test the effect of a school start time policy on changes in dietary quality among high school students, and the first to use objective measures of adolescent sleep. Our research shows the importance of examining various dimensions of adolescent sleep when exploring the link between sleep, diet, and weight gain. Although our study does not provide strong evidence for later school start times having an influence on overall dietary quality, given the many potential risks associated with poor sleep during adolescence, it is still important we consider effective ways to enhance sleep during this critical period of development. We also encourage further exploration of how sleep might affect dietary quality in adolescents in other populations, given these prefatory findings.

Acknowledgments

We thank asethe adolescents participating in the START study who attended schools in the Wayzata, Elk River, and Buffalo-Montrose-Hanover school districts in Minnesota, these three school districts that welcomed us to do research in their schools, the START data collectors who were employed by the University of Minnesota, and Bill baker for his work to manage the data. The authors also gratefully acknowledge support from the Minnesota Population Center (grant P2C HD041023), which is funded by NICHD. The authors' responsibilities were as follows—MNL, DE, CI, and RW: designed the research; ATB, MNL, DE, KML, SR, and RW: conducted the research; KMF: analyzed the data and had primary responsibility for the final content; KMF, RW, MNL, ATB, SR, and KMB: wrote the manuscript; and all authors: read and approved the final manuscript.

References

1. Eaton DK, McKnight-Eily LR, Lowry R, Perry GS, Presley-Cantrell L, Croft JB. Prevalence of insufficient, borderline, and optimal hours of sleep among high school students - United States, 2007. J Adolesc Health 2010;46(4):399–401.
2. National Sleep Foundation. Sleep in America Poll: teens and sleep [Internet]. Washington (DC): National Sleep Foundation; 2006 [cited 10 August, 2020]. Available from: https://www.sleepfoundation.org/wp-content/uploads/2018/10/2006_summary_of_findings.pdf?x26987.
3. Roberts RE, Roberts CR, Xing Y. Restricted sleep among adolescents: prevalence, incidence, persistence, and associated factors. Behav Sleep Med 2011;9(1):18–30.
4. Fredriksen K, Rhodes J, Reddy R, Way N. Sleepless in Chicago: tracking the effects of adolescent sleep loss during the middle school years. Child Dev 2004;75(1):84–95.
5. Paiva T, Gaspar T, Matos MG. Sleep deprivation in adolescents: correlations with health complaints and health-related quality of life. Sleep Med 2015;16(4):521–7.
6. Roberts RE, Duong HT. The prospective association between sleep deprivation and depression among adolescents. Sleep 2014;37(2):239–44.
7. Owens J, Adolescent Sleep Working Group, Committee on Adolescence. Insufficient sleep in adolescents and young adults: an update on causes and consequences. Pediatrics 2014;134(3):e921–32.
8. Cappuccio FP, D'Elia L, Strazzullo P, Miller MA. Quantity and quality of sleep and incidence of type 2 diabetes: a systematic review and meta-analysis. Diabetes Care 2010;33(2):414–20.
9. Cappuccio FP, Cooper D, D'Elia L, Strazzullo P, Miller MA. Sleep duration predicts cardiovascular outcomes: a systematic review and meta-analysis of prospective studies. Eur Heart J 2011;32(12):1484–92.
10. St-Onge M-P, Grandner MA, Brown D, Conry MB, Jean-Louis G, Coons M, Bhatt DL. Sleep duration and quality: impact on lifestyle behaviors and cardiometabolic health: a scientific statement from the American Heart Association. Circulation 2016;134(18):e367–86.
11. Hart CN, Cairns A, Jelalian E. Sleep and obesity in children and adolescents. Pediatr Clin North Am 2011;58(3):715–33.
12. Taheri S. The link between short sleep duration and obesity: we should recommend more sleep to prevent obesity. Arch Dis Child 2006;91(11):881–4.
13. Chaput J-P, Dutil C. Lack of sleep as a contributor to obesity in adolescents: impacts on eating and activity behaviors. Int J Behav Nutr Phys Act 2016;13(1):103.
14. Chaput J-P. Sleep patterns, diet quality and energy balance. Physiol Behav 2014;134:86–91.
15. Beebe DW, Simon S, Summer S, Hemmer S, Strotman D, Dolan LM. Dietary intake following experimentally restricted sleep in adolescents. Sleep 2013;36(6):827–34.
16. Simon SL, Field J, Miller LE, DiFrancesco M, Beebe DW. Sweet/dessert foods are more appealing to adolescents after sleep restriction. PLoS One 2015;10(2):e0115434.
17. Crowley SJ, Wolfson AR, Tarokh L, Carskadon MA. An update on adolescent sleep: new evidence informing the perfect storm model. J Adolesc 2018;67:55–65.
18. Carskadon MA, Acebo C, Jenni OG. Regulation of adolescent sleep: implications for behavior. Ann N Y Acad Sci 2004;1021:276–91.
19. Troxel WM, Wolfson AR. The intersection between sleep science and policy: introduction to the special issue on school start times. Sleep Health 2017;3(6):419–22.
20. Adolescent Sleep Working Group; Committee on Adolescence; Council on School Health. School start times for adolescents. Pediatrics 2014;134(3):642–9.
21. Owens JA, Belon K, Moss P. Impact of delaying school start time on adolescent sleep, mood, and behavior. Arch Pediatr Adolesc Med 2010;164(7):608–14.
22. Wahlstrom KL. Changing times: findings from the first longitudinal study of later high school start times. NASSP Bull 2002;86(633):3–21.
23. Wahlstrom KL. Later start time for teens improves grades, mood, and safety. Phi Delta Kappan 2016;98(4):8–14.
24. Bowers JM, Moyer A. Effects of school start time on students' sleep duration, daytime sleepiness, and attendance: a meta-analysis. Sleep Health 2017;3(6):423–31.
25. Minges KE, Redeker NS. Delayed school start times and adolescent sleep: a systematic review of the experimental evidence. Sleep Med Rev 2016;28:86–95.
26. Widome R, Wahlstrom KL, Laska MN, Erickson DJ, Berger A, Iber C, Kilian G. The START study: an evaluation to study the impact of a natural experiment in high school start times on adolescent weight and related behaviors. Obs Stud 2020;6:66–86.
27. Widome R, Berger AT, Iber C, Wahlstrom KL, Laska MN, Kilian G, Redline S, Erickson DJ. Association of delaying school start time with sleep duration, timing, and quality among adolescents. JAMA Pediatr 2020;174(7):697–704.
28. Weiss AR, Johnson NL, Berger NA, Redline S. Validity of activity-based devices to estimate sleep. J Clin Sleep Med 2010;6(4):336–42.
29. Cole RJ, Kripke DF, Gruen W, Mullaney DJ, Gillin JC. Automatic sleep/wake identification from wrist activity. Sleep 1992;15(5):461–9.
30. Haba-Rubio J, Ibanez V, Sforza E. An alternative measure of sleep fragmentation in clinical practice: the sleep fragmentation index. Sleep Med 2004;5(6):577–81.
31. Roenneberg T, Wirz-Justice A, Merrow M. Life between clocks: daily temporal patterns of human chronotypes. J Biol Rhythms 2003;18(1):80–90.

32. Krebs-Smith SM, Pannucci TE, Subar AF, Kirkpatrick SI, Lerman JL, Tooze JA, Wilson MM, Reedy J. Update of the Healthy Eating Index: HEI-2015. J Acad Nutr Diet 2018;118(9):1591–602.

33. Subar AF, Kirkpatrick SI, Mittl B, Zimmerman TP, Thompson FE, Bingley C, Willis G, Islam NG, Baranowski T, McNutt S, et al. The Automated Self-Administered 24-hour dietary recall (ASA24): a resource for researchers, clinicians, and educators from the National Cancer Institute. J Acad Nutr Diet 2012;112(8):1134–7.

34. Kirkpatrick SI, Subar AF, Douglass D, Zimmerman TP, Thompson FE, Kahle LL, George SM, Dodd KW, Potischman N. Performance of the Automated Self-Administered 24-hour Recall relative to a measure of true intakes and to an interviewer-administered 24-h recall. Am J Clin Nutr 2014;100(1):233–40.

35. R Core Team. R: a language and environment for statistical computing [Internet]. Vienna, Austria: R Project for Statistical Computing; 2013. Available from: http://www.r-project.org/.

36. Crowley SJ, Van Reen E, Lebourgeois MK, Acebo C, Tarokh L, Seifer R, Barker DH, Carskadon MN. A longitudinal assessment of sleep timing, circadian phase, and phase angle of entrainment across human adolescence. PLoS One 2014;9(11):e112199.

37. Hirshkowitz M, Whiton K, Albert SM, Alessi C, Bruni O, DonCarlos L, Hazen N, Herman J, Katz ES, Kheirandish-Gozal L, et al. National Sleep Foundation's sleep time duration recommendations: methodology and results summary. Sleep Health 2015;1(1):40–3.

38. Weiss A, Xu F, Storfer-Isser A, Thomas A, Ievers-Landis CE, Redline S. The association of sleep duration with adolescents' fat and carbohydrate consumption. Sleep 2010;33(9):1201–9.

39. Bel S, Michels N, De Vriendt T, Patterson E, Cuenca-Garcia M, Diethelm K, Gutin B, Grammatikaki E, Manios Y, Leclercq C. Association between self-reported sleep duration and dietary quality in European adolescents. Br J Nutr 2013;110(5):949–59.

40. Westerlund L, Ray C, Roos E. Associations between sleeping habits and food consumption patterns among 10–11-year-old children in Finland. Br J Nutr 2009;102(10):1531–7.

41. Landis AM, Parker KP, Dunbar SB. Sleep, hunger, satiety, food cravings, and caloric intake in adolescents. J Nurs Scholarsh 2009;41(2): 115–23.

42. Garaulet M, Ortega FB, Ruiz JR, Rey-López JP, Béghin L, Manios Y, Cuenca-García M, Plada M, Diethelm K, Kafatos A, et al. Short sleep duration is associated with increased obesity markers in European adolescents: effect of physical activity and dietary habits. The HELENA study. Int J Obes 2011;35(10):1308–17.

43. Golley RK, Maher CA, Matricciani L, Olds TS. Sleep duration or bedtime? Exploring the association between sleep timing behaviour, diet and BMI in children and adolescents. Int J Obes 2013;37(4):546–51.

44. Agostini A, Lushington K, Kohler M, Dorrian J. Associations between self-reported sleep measures and dietary behaviours in a large sample of Australian school students (n = 28,010). J Sleep Res 2018;27(5):e12682.

45. Fleig D, Randler C. Association between chronotype and diet in adolescents based on food logs. Eat Behav 2009;10(2):115–18.

46. Arora T, Taheri S. Associations among late chronotype, body mass index and dietary behaviors in young adolescents. Int J Obes 2015;39(1):39–44.

47. Ancoli-Israel S, Martin JL, Blackwell T, Buenaver L, Liu L, Meltzer LJ, Sadeh A, Spira AP, Taylor DJ. The SBSM guide to actigraphy monitoring: clinical and research applications. Behav Sleep Med 2015;13(sup1):S4–S38.

48. Grummon AH, Sokol RL, Lytle LA. Is late bedtime an overlooked sleep behaviour? Investigating associations between sleep timing, sleep duration and eating behaviours in adolescence and adulthood. Public Health Nutr 2021;24(7):1671–7.

49. Mazri FH, Manaf ZA, Shahar S, Mat Ludin AF. The association between chronotype and dietary pattern among adults: a scoping review. Int J Environ Res Public Health 2019;17(1):68.

50. Merikanto I, Lahti T, Puolijoki H, Vanhala M, Peltonen M, Laatikainen T, Vartiainen E, Salomaa V, Kronholm E, Partonen T. Associations of chronotype and sleep with cardiovascular diseases and type 2 diabetes. Chronobiol Int 2013;30(4):470–7.

51. Yu JH, Yun C-H, Ahn JH, Suh S, Cho HJ, Lee SK, Yoo HJ, Seo JA, Kim SG, Choi KM, et al. Evening chronotype is associated with metabolic disorders and body composition in middle-aged adults. J Clin Endocrinol Metab 2015;100(4):1494–502.

52. Adams CD, Neuhausen SL. Evaluating causal associations between chronotype and fatty acids and between fatty acids and type 2 diabetes: a Mendelian randomization study. Nutr Metab Cardiovasc Dis 2019;29(11):1176–84.

53. Ancoli-Israel S, Cole R, Alessi C, Chambers M, Moorcroft W, Pollak CP. The role of actigraphy in the study of sleep and circadian rhythms. Sleep 2003;26(3):342–92.