Earlier Bedtime and Its Effect on Adolescent Sleep Duration

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abstract

BACKGROUND AND OBJECTIVES: Sleep duration decreases by ~10 minutes per year throughout adolescence. A circadian phase delay and changes in homeostatic sleep regulation enable adolescents to stay up later. We determine if teens are able to increase sleep duration by advancing bedtime and whether this ability changes with age.

METHODS: A younger cohort of 77 participants ranging in age from 9.9 to 16.2 years were studied annually for 3 years. An older cohort of 67 participants ranging in age from 15.0 to 20.6 years was studied only once. Annually, participants kept each of 3 different time in bed (TIB) schedules (7, 8.5, and 10 hours) for 4 consecutive nights. Participants kept their habitual weekday rise times; TIB was altered by advancing bedtimes. We report polysomnography-measured sleep durations from the fourth night of the TIB schedule.

RESULTS: Despite increases in sleep onset latency and wake after sleep onset, sleep duration increased with TIB as bedtime was advanced. Average (SE) sleep duration increased from 402.8 (1.6) minutes with 7 hours to 470.6 (2.1) minutes with 8.5 hours to 527.5 (3.0) minutes with 10 hours TIB. Sleep duration decreased with age (1.55 [0.48] minutes/year), but the TIB effect on sleep duration did not (TIB by age interaction, $P = .42$).

CONCLUSIONS: Adolescents can substantially increase sleep duration by advancing bedtime, and this ability does not change between ages 10 and 21 years. Additional research is needed to determine how to translate these findings from experiment-controlled sleep schedules to real-world sleep duration increases.

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Dr Campbell designed the study, collected and analyzed data, wrote parts of the initial draft of the manuscript, and revised the manuscript; Mr Cruz-Basilio recruited study participants, collected and analyzed data, and edited the manuscript; Ms Figueroa collected and analyzed data, wrote the first draft of the results, and edited the manuscript; Mr Bottom collected and analyzed data and edited the manuscript; and all authors approved the final manuscript as submitted and agree to be accountable for all aspects of this work.

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WHAT'S KNOWN ON THIS SUBJECT: Sleep duration decreases steeply throughout adolescence. This decrease is associated with a circadian phase delay that enables older adolescents to stay up later. Increasing sleep duration may reduce negative outcomes associated with adolescent sleep loss.

WHAT THIS STUDY ADDS: Adolescents and young adults (aged 10–21 years) were able to overcome their circadian phase delay and increase polysomnography-measured sleep duration by 41 minutes per hour of advanced bedtime. The results hold promise for new approaches to improve adolescent sleep.

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In industrialized nations across the world, sleep duration decreases dramatically throughout adolescence.[1–5] Weeknight sleep duration decreases of 10 to 12 minutes per year[6,7] are associated with delayed bedtimes accompanied by constant or earlier rise times.[8] Reduced sleep duration and daytime sleepiness are associated with negative scholastic, behavioral, and mental health consequences. Adolescents with later bedtimes, shorter sleep duration, and greater daytime sleepiness report lower school enjoyment, increased absences and tardiness, and lower academic performance.[4,9] Late bedtimes and shorter sleep duration are associated with increased anxiety and depression, suicidal thoughts, an elevated likelihood of engaging in risky behavior, and an increased risk of traffic crashes.[10–14] In addition, interventions to improve adolescent sleep reduce these negative mental health effects.[15,16]

Homeostatic and circadian processes contribute to sleep propensity.[17] Both processes change during adolescence. With pubertal development, there is a decreased rate of sleep need accumulation,[18] and the circadian phase is delayed, as demonstrated by later melatonin release.[19,20] These 2 factors combine to make it easier for adolescents to stay up later. The recognition of adolescent sleep habits has prompted advocacy to delay high school start times in an effort to increase sleep duration.[21]

The alternative approach, advancing bedtime, may effectively increase adolescent sleep duration. Compared with adolescents allowed to set their own sleep schedule, those with a parent-set bedtime have earlier bedtimes and longer time in bed (TIB),[22] and adolescents with earlier parental set bedtimes have longer self-reported sleep duration.[10] In a study that advanced bedtime, actigraphy-measured sleep was ~2.5 hours greater on an extended (10-hour) versus a restricted (6.5-hour) sleep schedule.[23]

Our current within-subjects study with 3 TIB conditions (7, 8.5, and 10 hours) builds on these previous studies in 2 ways: (1) we use at-home polysomnography to precisely assess how advancing bedtime for 4 consecutive nights affects total sleep duration, non-rapid eye movement (NREM) and rapid eye movement (REM) durations, sleep onset latency, and wake after sleep onset (WASO), and (2) we determine if the ability to extend sleep duration changes with age. Publications on TIB restriction effects on the EEG and performance from the first phase of this study (10–16 years of age) note the sleep duration increase with longer TIB.[24–26] We now add an older cohort to the data set and evaluate the ability to increase sleep duration across adolescence and into early adulthood (10 to 21 years).

METHODS

Study Participants

Two pools of subjects participated in this study. One cohort (n = 77, 35 female, 42 male) entered the study between ages 9.9 and 14.0 years (mean [SD] = 12.2 [1.2] years) and was studied annually for 3 years. Of the 77 participants that completed the first year, 76 returned for year 2, and 64 participated in year 3. This cohort's recruitment process and racial/ethnic composition were previously documented.[27] The other cohort (n = 73, 41 female, 32 male) entered the study between ages 15.0 and 20.6 years (mean = 18.0 [1.6] years). For the older cohort, we report only data from year 1, before the study was paused for the coronavirus disease 2019 pandemic. Six older cohort participants completed only 1 TIB condition and were not included in the analyses, leaving 67 subjects (39 female, 28 male, mean age = 18.1 years). The older cohort was recruited via flyers, emails, and announcements in high school and college classrooms. The older cohort's race/ethnicity composition was 33% Latino, 32% Asian, 27% non-Latino white, 1% Black, and 7% multiracial.

Parents of minor participants provided informed consent with minors' assent. Adult participants provided informed consent. The consent interview assessed the following exclusion criteria: doctor's diagnosis of psychiatric or behavioral disorder, head injury causing loss of consciousness and symptoms lasting >24 hours, current use of medication affecting the central nervous system, visual impairment or manual dexterity problems that would interfere with daytime performance tests, and a Sleep Disturbance Scale for Children[28] t-score >70. The UC Davis Institutional Review Board approved all study procedures.

Experiment Design

Subjects participated in 3 recording weeks per year, keeping each of 3 different TIB schedules: 7, 8.5, and 10 hours in bed for 4 consecutive nights (Fig 1). Three nights of 8.5 hours in bed preceded each of the 4-night schedules so that participants had the same sleep history for at least 3 nights before the assigned TIB schedules. Participants maintained their habitual weekday rise time; TIB was adjusted by altering bedtime. Participants were instructed to go to bed at their assigned bedtime with lights off and to try to fall asleep. If they were initially unable to fall asleep or if they woke up before their assigned rise time, they were to stay in bed with lights off and try to fall asleep. Because the TIB schedules could conflict with scholastic, extracurricular, work, and social demands, we did not randomly assign the order in which subjects completed the 3 schedules. Instead, we suggested a TIB assignment but allowed participant input. In doing so, we were able to balance the order in which participants completed the TIB schedules, with 35% of subject-years beginning with 7 hours, 33% with 8.5 hours, and 32% with 10 hours TIB. Wrist actigraphy and EEG recordings (see below) confirmed compliance with the assigned schedule. Participants were instructed not to nap and to abstain from caffeine, alcohol, and illicit drugs during the

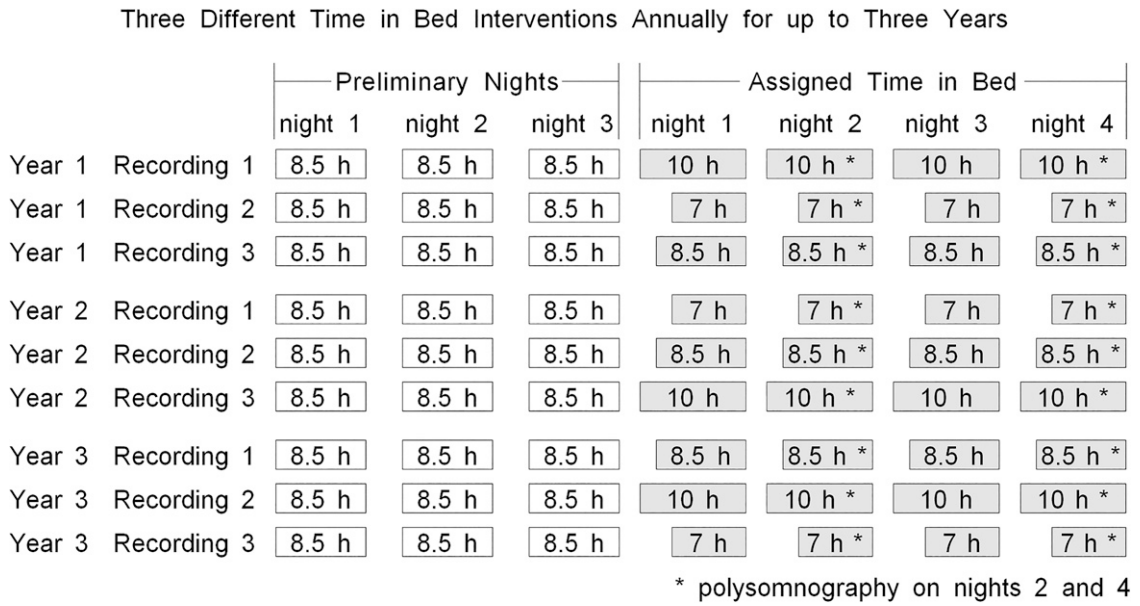

FIGURE 1

Intervention schematic. Annually, participants kept each of 3 different TIB schedules: 7, 8.5, and 10 hours for 4 consecutive nights (filled rectangles) preceded by three 8.5-hour TIB preliminary nights (open rectangles). We balanced the order in which participants completed the TIB schedules.

assigned sleep schedule. If the participant's TIB deviated by >60 minutes from the assigned schedule, if they napped during sleep schedule days, or if a urine test was positive for drugs or caffeine, we asked the participant to repeat that schedule. If the deviation was discovered after it was practical to reschedule, data from that recording were dropped (<1% of recordings).

EEG Recording and Sleep Duration Measures

On the second and fourth nights of the assigned 4-night TIB schedule, we recorded all-night sleep EEG in the participants' homes (ie, their habitual sleep environment). EEG electrodes were applied at F3, F4, C3, C4, P3, P4, O1, O2, A1, and A2, with reference and ground electrodes on the scalp and forehead. Electrooculogram and submental electromyogram were also recorded. Grass Aura 24 ambulatory recorders were used to record all-night EEG, electrooculogram, and chin electromyogram. Sleep laboratory employees did not monitor the all-night recordings. Participants marked bedtime by blinking 10 times when they turned off lights, settled in bed, and began to try to fall asleep.

Trained research associates scored all night records using modified[27] AASM 2007 criteria.[29] A second research associate checked the scoring, and a senior laboratory scientist (IGC) resolved discrepancies. The following measures were determined for each night: total sleep time (TST = NREM + REM), stage REM duration, stage N1 duration, stage N2 duration, stage N3 duration, stage NREM duration (N2 + N3), and WASO. For nights when participants complied with the eye blink instruction, sleep onset latency (SL) was calculated as the time between eye blinks and the first epoch of sleep sustained for at least 5 minutes. SL was excluded for 5 recordings in which the participant dosed off before waking up and blinking, yielding a negative SL.

Statistical Analyses

TIB and age effects and their interaction on sleep measures were evaluated with mixed effects analysis,[30] with age as a continuous variable and TIB as a class variable. TIB condition order was dropped from models after initial analyses found that order effects were not significant. Night (2 vs 4) and sex were also included in initial analyses.

The structure of the data set was complicated by having 3 years of data for the younger cohort and only 1 year for the older cohort. We analyzed the data in 2 ways. First, we included all data from both cohorts. Second, we created a purely cross-sectional data set for age by semi-randomly selecting a single year of data for each subject in the younger cohort. We selected years such that subjects were evenly distributed (12 or 13 subjects per year) across the 6 years of age (10–15).

Age was a continuous measure for statistical analyses, but recordings were separated into age quartiles for the figures.

RESULTS

TIB Effects on Sleep Measures

Although sleep duration (TST) on night 2 was significantly (F_{1142}= 21.9, $P < .0001$) shorter (5.8 [1.2] minutes, mixed effect estimate [SE]) than on night 4, the TIB effect did not

TABLE 1 Effect of TIB and Age on Sleep Stage Measures, All Recordings

	TIB Mean (SE) (Min)			TIB Stats		Age			Age × TIB	
Measure	7 h	8.5 h	10 h	F	*P*	Slope (min/y)	F	*P*	F	*P*
TST	402.8 (1.6)	470.6 (2.1)	527.5 (3.0)	1793	<.001[a]	−1.55 (0.48)	10.4	.0013[a]	0.88	.42
REM	96.8 (1.7)	120.5 (1.9)	137.8 (2.1)	283	<.001[a]	+2.96 (0.41)	53.2	<.001[a]	1.70	.18
NREM	305.9 (2.1)	350.1 (2.2)	389.6 (2.9)	947	<.001[a]	−4.32 (0.50)	73.8	<.001[a]	0.83	.43
N3	103.2 (2.2)	99.9 (2.3)	99.0 (2.2)	3.65	.027[a]	−3.58 (0.49)	53.9	<.001[a]	0.98	.38
N2	202.8 (1.9)	250.2 (2.4)	290.7 (2.5)	704	<.001[a]	−0.30 (0.58)	0.28	.60	0.42	.66
N1	4.17 (0.36)	5.39 (0.32)	8.87 (0.54)	74.3	<.001[a]	+0.09 (0.09)	0.96	.33	1.30	.27
SL	7.38 (0.57)	13.56 (1.13)	23.79 (1.46)	111	<.001[a]	+1.09 (0.24)	20.8	<.001[a]	0.57	.56
WASO	13.8 (0.8)	18.5 (0.9)	31.4 (2.1)	66.0	<.001[a]	−0.11 (0.29)	0.15	.70	6.88	.0011[a]

Statistics results are for mixed effects analyses with TIB as a class measure and age as a continuous measure. Age slope is the estimate (SE) from mixed effects analysis.
[a] Significant effect ($\alpha = 0.05$).

differ between nights (TIB × night $F_{2234} = 0.79$, $P = .45$). In addition, TST did not differ between males and females ($F_{1142} = 2.28$, $P = .13$), nor was there a significant sex by TIB interaction ($F_{2254} = 0.32$, $P = .72$). Therefore, further analyses are limited to sleep recorded on night 4 and do not include a sex factor.

Sleep duration increased nearly linearly with TIB (Table 1). Average TST increased 68 minutes from 7 to 8.5 hours TIB and increased another 57 minutes with 10 hours TIB. Reanalyzing with TIB as a continuous measure revealed a 41.5 (0.7) minute increase in TST for each additional hour in bed. The TST increase was composed of significant increases (Table 1) in both stage REM and NREM. The NREM increase was entirely a stage N2 increase; stage N3 decreased slightly but significantly with increasing TIB.

Stage N1, WASO, and SL increased with TIB but did not do so linearly (Table 1). The 8.5-hour TIB SL average was 6.2 minutes longer than the 7-hour TIB average, and the 10-hour TIB average was 10.2 minutes longer than the 8.5-hour TIB average. The WASO average for 10 hours TIB exceeded by 12.9 minutes the 8.5-hour TIB average, which was 4.7 minutes greater than the 7-hour TIB average.

For 8.5 hours TIB, the sum of average TST, SL, WASO, and N1 (508 minutes) was close to the assigned 510 minutes TIB. For 7 hours TIB, the 428-minute sum exceeded the 420-minute TIB, indicating that, on average, participants slightly exceeded their assigned TIB. In contrast, the 592-minute sum for 10 hours TIB was slightly shorter than the assigned 600 minutes.

Age and Age by TIB Interaction

TST decreased with age by ~1.5 minutes/year (Table 1). This decrease was entirely an NREM duration decrease of ~4.3 minutes/year, as stage REM duration increased by ~3 minutes/year. SL also increased significantly with age. Neither N1 nor WASO changed significantly with age. Figure 2 reveals the age-related changes in TST, NREM, REM, and Fig 3 reveals the age effects on SL and WASO.

Figure 2 also depicts the absence of age by TIB interactions for sleep durations, with age trends being roughly parallel for the 3 TIB conditions. The TIB effect on TST did not change significantly with age (Table 1) nor did the effect on NREM or stage REM duration. The TIB effect on SL did not change with age (Fig 3), as demonstrated by the consistency of the SL difference between 7 and 10 hours TIB for the 4 age quartiles: 14.6, 17.8, 17.9, and 17.3 minutes. WASO was the only measure to reveal an

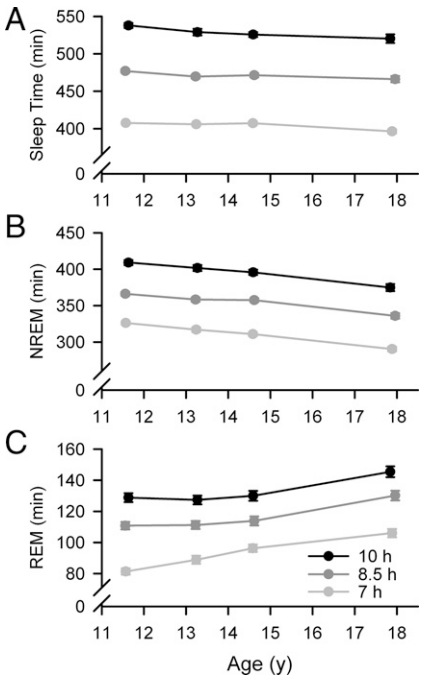

FIGURE 2
Age quartile mean (SE) (A) TST, (B) stage NREM duration, and (C) stage REM duration plotted against age. Durations increased from 7 hours (gray) to 8.5 hours (dark gray) to 10 hours (black) TIB. Neither the age-related TST and NREM declines nor the REM increase differed by TIB.

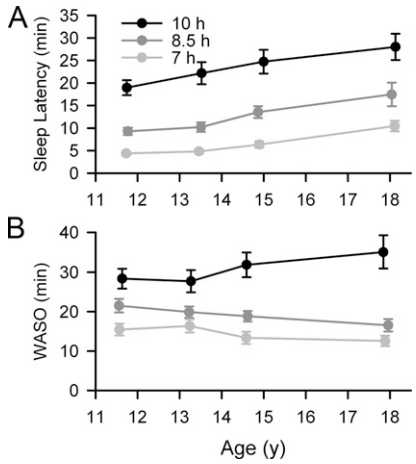

FIGURE 3

Age quartile mean (SE) (A) SL and (B) WASO plotted against age. The SL increase with TIB did not differ by age, but the WASO TIB-related increase was greater for older participants.

age by TIB interaction (Fig 3). The 22-minute average increase in WASO from 7 to 10 hours TIB in the oldest cohort exceeded the 12-minute increase for the youngest cohort.

For SL (Fig 4 A and B) and TST (Fig 4 C and D), we also examined cumulative distribution plots to determine what portion of participants struggled to fall asleep and extend sleep duration, particularly on the 10-hour TIB schedule. For the oldest quartile, ~36% of participants took >30 minutes to fall asleep on 10 hours TIB, and

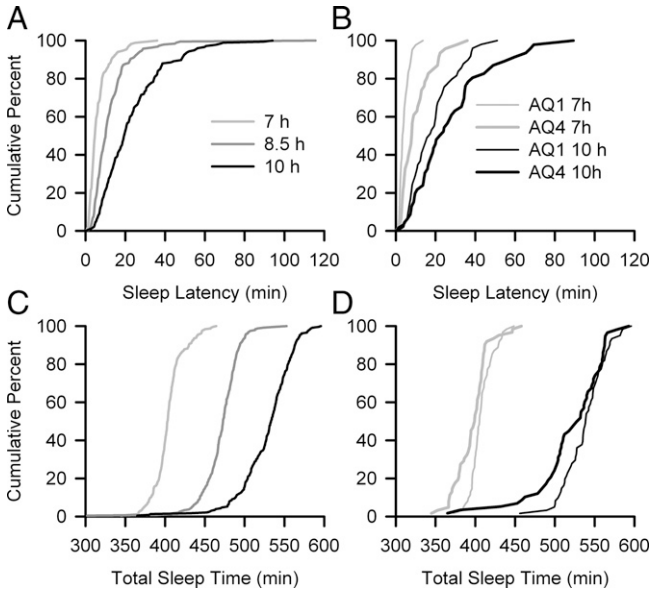

FIGURE 4

(A and B) SL and (C and D) sleep duration cumulative distribution plots for 7 hours (gray), 8.5 hours (dark gray), and 10 hours (black) TIB for (A and C) all subjects and (B and D) youngest (thin lines) and oldest (thick lines) age quartiles. A small percentage struggled with the 10-hour TIB schedule.

~10% took >1 hour. In comparison, <20% of the youngest quartile took >30 minutes to fall asleep on 10 hours TIB and none took >1 hour. Only 6% of all subjects, but 12% of the oldest quartile, obtained <8 hours of sleep when on the 10-hour TIB schedule.

Cross-Sectional Data

The results of the cross-sectional analyses (Table 2) were similar to those of longitudinal analyses. TST, stage REM duration, and NREM duration increased with TIB as did SL, WASO, and stage N1 duration. WASO was the only measure with a significant TIB by age interaction.

DISCUSSION

Our data clearly reveal that adolescents and young adults can increase sleep duration by advancing their bedtime. We discuss how these findings fit with our understanding of adolescent changes in circadian and homeostatic sleep regulation. We also comment on how these findings might influence approaches for increasing teen sleep duration.

The circadian phase is delayed as children mature through adolescence. Surveys of phase preference reveal preteen "larks" developing into adolescent "owls."[31] A hormonal marker of the circadian phase, dim light melatonin onset, is ~1 hour later in mature adolescents than in preadolescents.[20] However, this phase delay does not appear to be an inherent change in the circadian modulatory system. A free-running circadian period on a 28-hour light cycle is similar (24.19 hours vs 24.22 hours) in adolescents and young adults.[32] In addition, the circadian response to light cues is not altered in adolescents.[33] Instead, the most likely explanation for the adolescent phase delay is a permissive change in the homeostatic regulation of sleep. As children mature through adolescence, there is a decrease in the rate that sleep need accumulates across the day,[18] allowing them to delay their bedtime and shift their circadian phase.

Our data indicate that adolescents can overcome this preference to stay up later and increase their sleep duration with earlier bedtimes. Average sleep duration increased not only with TIB raised from 7 to 8.5 hours but increased by 1 additional hour with 10 hours TIB. Although sleep duration decreased slightly with age, the ability to increase sleep duration by advancing bedtime did not. The 3-hour bedtime advance increased average sleep duration by 130 minutes in the youngest age quartile (mean age 11.6 years) and by a similar 124 min in the oldest age quartile (mean age 17.9 years). We have previously reported that increases in sleep duration in the younger cohort are associated with decreased daytime sleepiness and increased vigilance.[26] Our current findings

TABLE 2 Effect of TIB and Age on Sleep Stage Measures, Cross-Sectional Data Set

	TIB Mean (SE) (Min)			TIB Stats		Age			Age × TIB	
Measure	7 h	8.5 h	10 h	F	*P*	Slope (min/y)	F	*P*	F	*P*
TST	401.91 (1.76)	470.38 (2.42)	528.08 (3.68)	693	<.001[a]	−1.72 (0.58)	8.93	.0031[a]	0.73	.48
REM	95.20 (1.95)	120.75 (2.23)	138.11 (2.44)	155	<.001[a]	+3.33 (0.47)	50.4	<.001[a]	1.38	.26
NREM	306.71 (2.40)	349.63 (2.50)	389.97 (3.56)	420	<.001[a]	−5.01 (0.59)	71.0	<.001[a]	0.44	.64
N3	101.77 (2.35)	98.59 (2.45)	99.20 (2.64)	0.53	.59	−4.80 (0.54)	77.7	<.001[a]	2.24	.11
N2	204.94 (2.28)	251.04 (2.77)	290.78 (3.33)	345	<.001[a]	−0.14 (0.67)	0.04	.84	0.67	.51
N1	3.99 (0.38)	5.02 (0.37)	8.61 (0.66)	30.1	<.001[a]	+0.15 (0.11)	1.85	.18	1.04	.36
SL	7.73 (0.68)	14.11 (1.42)	24.96 (1.82)	50.6	<.001[a]	+1.05 (0.30)	12.4	<.001[a]	0.34	.71
WASO	14.03 (0.89)	19.52 (1.17)	33.42 (2.85)	38.0	<.001[a]	−0.31 (0.38)	0.67	.41	3.72	.024[a]

Statistics results are for mixed effects analyses with TIB as a class measure and age as a continuous measure. Age slope is the estimate (SE) from mixed effects analysis.
[a] Significant effect ($\alpha = 0.05$).

agree with those of Beebe et al, who recorded an increase of 155 minutes in average sleep duration as TIB was increased from 6.5 to 10 hours. Their further research found that even habitually short sleepers are able to increase sleep duration with earlier bedtimes, and the increased sleep is associated with emotional benefits.[34]

Both increased SL and increased WASO contributed to the age-related TST decrease that we recorded. Increased SL is consistent with a circadian phase delay and a reduction in the rate at which sleep need accumulates across the day. The 23.8-minute average SL for the 10-hour TIB condition and the absence of an interaction of the TIB and age effects on SL contradict a statement from the school start time position paper published in this journal,[21] "the average teenager in today's society has difficulty falling asleep before 11 PM." However, as shown in Fig 4, a small portion of participants had difficulty with the 10-hour condition, requiring >1 hour to fall asleep or being unable to sleep >8 hours. The WASO increase with age reflects the adolescent decrease in sleep depth indicated by lower slow wave EEG activity[35,36] and greater arousability index.[37] The age-related decline in sleep depth compounds the decreased sleep depth with TIB extended to 10 hours, producing a TIB by age interaction for WASO.

With TIB treated as a continuous measure, sleep duration increased by 41.5 minutes for each hour advance in bedtime. This increase compares favorably with increases in TIB or sleep duration associated with later school start times. Cross-sectional[38] and longitudinal[39–41] studies have revealed increases ranging from 13 to 37 minutes for each hour later in start time (increases standardized to a 1-hour start time delay). Although our sleep duration increases with advanced bedtime exceed those for start time delay, comparing a carefully controlled experiment with real-world studies is not fair. Despite recordings in the subjects' habitual sleep environment, our study required adolescent participants to adhere to a schedule and financially compensated them for doing so. In addition, we scheduled the 10-hour TIB condition on a week that would not conflict with participants' scholastic, extracurricular, or social demands. They would have been unable to adhere to this schedule on a consistent basis without advanced planning and major behavioral changes. We do not know if participants would have been able to keep the schedule for >4 nights or if the increased sleep duration would persist.

In addition to experimental versus real-world differences, the study had other limitations. We attribute age-related changes in sleep duration to a circadian phase delay but had no measure of the circadian phase. In addition, the subject pool was not a representative sample. Only subjects who could tolerate the assigned sleep schedules enrolled in the study, and subjects with sleep disorders were excluded. Strengths of the study include a large number of subjects and 3 years of longitudinal data for the younger cohort. Rather than relying on survey or actigraphy data, sleep durations and sleep latencies are precisely measured with polysomnography.

Despite its limitations, this study reveals important information regarding adolescent sleep. The increased sleep duration associated with advancing bedtime supports previous studies revealing that teens with parent-set bedtimes have longer sleep duration.[10,22] Our findings contradict statements on the Start School Later Web site: "Because of the shifted times in which adolescent brains produce melatonin, even the best-laid plans often result in the teenager staring at the ceiling until well after 11 p.m. ... most simply cannot fall asleep before about 11 PM."[42] Instead of disparaging its effectiveness, advancing adolescents' bedtime should be encouraged. However, previous studies on the effectiveness of sleep education programs have not produced lasting increases in sleep duration[43] or have increased sleep knowledge without increasing sleep duration.[44] Our current findings supporting the effectiveness of advancing bedtime require additional studies to determine how to translate these findings into real-world applications to increase adolescent sleep duration.

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This work would not have been possible without the contributions of Irwin Feinberg, MD, principal investigator of the grant, who, with Dr Campbell, conceptualized and designed the study. Dr Feinberg died in August 2022 while this manuscript was in the planning stage. We thank the many undergraduate student assistants who helped record hundreds of nights of EEG. We also thank the study participants and their families.

ABBREVIATIONS

NREM: non-rapid eye movement
REM: rapid eye movement
SL: sleep latency
TIB: time in bed
TST: total sleep time
WASO: wake after sleep onset

CONFLICT OF INTEREST DISCLOSURES: The authors have indicated they have no potential conflicts of interest to disclose.

Although this was not a clinical trial, anonymized individual participant data will be made available to researchers who provide a methodologically sound proposal for achieving goals stated in the proposal. Proposals should be submitted to Dr Campbell: igcampbell@ucdavis.edu.

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