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Interindividual and intraindividual variability in adolescent sleep patterns across an entire school term: A pilot study☆

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Objectives: This study aimed to investigate sleep patterns in adolescent males over a 12-week period (a 10-week school term and pre and post term holidays).
Design: Intensive longitudinal design, with sleep data collected daily via actigraphy for 81 consecutive days.
Setting: Five Secondary Schools in Adelaide, South Australia.
Participants: Convenience sample of 47 adolescent males aged 14 to 17 years.
Measurements: Daily sleep duration, bedtimes, rise times, and sleep efficiency were collected via actigraphy with all (except sleep efficiency) also measured by sleep diary. Mood was measured weekly with *Depression Anxiety Stress Scale-21 (DASS-21)* and weekly wellbeing with the Satisfaction with Life Scale (SWLS). Age, body mass index, self-reported mood, life satisfaction, and chronotype preference assessed at baseline (pre-term holiday week) were included as covariates.
Results: Dynamic Structural Equation Modeling indicated significant but small fixed-effect and random-effect auto-regressions for all sleep variables. Collectively, these findings demonstrate day-to-day fluctuations in sleep patterns, the magnitude of which varied between individuals. Age, morningness, and mood predicted some of the temporal dynamics in sleep over time but other factors (BMI, life satisfaction) were not associated with sleep dynamics.
Conclusions: Using intensive longitudinal data, this study demonstrated inter-individual and intra-individual variation in sleep patterns over 81 consecutive days. These findings provide important and novel insights into the nature of adolescent sleep and require further examination in future studies.

Introduction

Currently, adolescent sleep research largely focuses on sleep length, particularly as adolescents are sleeping less than in the past,[1] but also because sleep loss has learning, mood and health consequences.[2,3] Consensus sleep duration guidelines suggest adolescents aged 14–17 years ideally require 8–10 hours total sleep time (TST) per night, although this recommended range can be widened to 7–11 hours in recognition of individual differences in sleep need.[4,5] Given that these guidelines are based on consensus rather than empirical research[5] and that they reflect large individual variation in sleep duration, it is therefore difficult to accurately determine the consequences of TST for daytime performance and mood deficits. Other sleep parameters may be the more helpful for determining the relationships between sleep and daytime mood and performance including.

sleep efficiency, sleep/wake schedules (eg, bedtimes and rise-times), as well as variability in sleep/wake schedules over time (also referred to as intraindividual variation). Amongst adolescents, school days are associated with significant sleep restriction compared

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with weekends[6] and school holidays.[7] This is primarily due to a progressive delay in the circadian timing of sleep and a subsequent delay in the nightly onset of sleepiness and sleep, along with a requirement to wake for school on weekday mornings.[6] The absence of this requirement on weekends and school holidays is associated with significant increases in adolescent TST.[3,7] This 'catch-up' sleep may reflect a recovery process to compensate for school-week sleep debt.[8] In addition, psychosocial factors such as academic workload, media usage and peer-related social and sport activities, also contribute to variability.[9]

Thus, some of the variability in sleep/wake schedules can be attributed to the pattern of week to weekend sleep differences (also known as yo-yo sleeping). Such variability is concerning because sleep loss accumulated during the school week and variability in TST between week and weekends can have important, independent effects on performance and mood.[6,7] Indeed, several studies have investigated the implications of sleep variability for adolescent wellbeing. Fuligni et al,[10] looked at the variability of TST in 761 adolescents based on two measures: (1) the deviation between their average sleep time (TST) and each individual night's sleep time and (2) the difference between the mean of TST between school and non-school days. Consistent with the literature, shorter TST was associated with worse mood. Further, those with more variable TST also showed worse mood, suggesting that TST and variable TST are both important. There was, however, no relationship between the difference in school and non-school night sleep and daily mood, suggesting that while overall variability was an important factor, the well-documented pattern of weekend 'catch-up' sleep was not.

Sleep/wake variability may also have an effect on physical wellbeing. Hall et al,[11] (2015) reported an increased risk of cardiovascular disease as measured by C-reactive protein dysfunction when 244 American adolescents slept in more than 2 hours on the weekends compared to weekdays. Wing et al,[12] by contrast, showed that compared to weekday TST, increased weekend TST was protective against the risk of childhood overweight/obesity in children (aged 8-10 years).

Several potential reasons may explain why variability in sleep scheduling may be associated with wellbeing. Firstly, sleep schedule variability may increase the degree of intermittent sleep deprivation, where short sleeps are interspersed with long catch-up sleeps. Secondly, sleep schedule variability indicates desynchronization of sleep and circadian phase. Circadian mechanisms time the occurrence of sleep and sleepiness[13] and evidence in adults suggests that when sleep is outside of an individual's circadian phase, performance/mood deficits ensue.[14] This misalignment of circadian phase alters sleep patterns between school and non-school day sleep,[6] which is problematic given the circadian system adapts slowly to day-to-day variability in phase shifts.[15]

While sleep schedule variability is often related to changes in TST and/or variability, two studies have found independent effects on wellbeing. When measuring variability in sleep–wake schedules without focussing on TST, Biggs et al,[16] reported a relationship between variability in bedtimes, wake times and TST between school and non-school nights and poorer behaviour in pre-adolescent children (aged 9-11 years). Data however, were parental report which are prone to error. [17] Bei et al,[18] reported significant night-to-night variability in both bed and wake times as measured by actigraphy over 4 weeks in 146 adolescents, but mood was not measured. There is a paucity of adolescent literature examining objectively measured sleep over periods longer than 4 weeks.[19]

Furthermore, most existing studies have tended to average sleep values collected across multiple time points (eg, average TST on a school night versus average TST on a school night), which loses important information on day-to-day (intraindividual) variation in sleep. In the systematic review by Becker et al,[19] examining intraindividual variation in child and adolescent sleep patterns, the 52 identified studies, although individual standard deviation, coefficient of variance, and multilevel modeling were most commonly used, methods used to quantify intraindividual variation in sleep patterns differed significantly.

In the present paper we aimed to expand on these existing studies by providing a more comprehensive insight into variation in adolescent sleep patterns. We utilized Dynamic Structural Equation Modeling (DSEM[20]), to examine adolescent males' sleep patterns over a 12-week period, covering a 10-week school term and pre and post term school holidays. Adolescent males were targeted as they are recognized as a high-risk group in Australia, with elevated rates of undiagnosed depression with an increase in suicide risk and completed suicides in the last 20 years[21] and were the focus of a National Mental Health research focus by the funding body. Further, male adolescents are also more likely than females to trade sleep for other activities (eg, videogames and computers)[9] particularly on weekends,[22] increasing week to weekend variability in sleep schedules. We therefore examined adolescent male intraindividual and interindividual dynamics in TST, bedtimes, waketimes, and sleep efficiency. This included examining whether some key factors associated with adolescent sleep in previous research – age, body mass index (BMI), life satisfaction, mood, and chronotype preference – predicted sleep dynamics over time.

Participants and methods

All adolescent males attending the third and fourth years of high school program were targeted from 10 co-educational schools known to the research team in Adelaide (South Australia). Two private (fee-paying schools, from one middle and one low socio–economic postcode) and three (non–fee-paying schools, from one low and two high social-economic postcodes) public schools expressed interest. School start times were approximately 8:45 AM for all participating schools. Of the 295 students who attend preliminary information sessions, 206 left contact details as an initial expression of interest, 103 each from public and private schools. When contacted, 27/103 public school students (response rate of 26%) and 35/103 private school students (response rate of 34%), signed up and attended the research information session. Based on self-report General Health Questionnaire, no participants met exclusion criteria (reporting mood, sleep or neurodevelopmental disorders). Eight participants withdrew before starting, six withdrew (health or waning interest) within 3 weeks and one was excluded due to a high rate of missing data (data provided for only 30% of the study period). The final sample for analysis comprised 47 adolescent males between 14 and 17y (mean age = 15.6, SD = 0.9 y).

Data collection

Data collection began during the second (final) week of school holidays (6 days) and continued throughout the 10-week school term (70 days), with data also collected during the first 5 days of the end of term school holidays. Since South Australia adopts daylight savings timing between October and April, we controlled for "season" (daylight savings versus standard time) by including 'season' as a covariate. Participants' sleep schedules were not controlled prior to commencing, because we expected that sleep would have stabilized in the final week of holidays[18] and we would have a relative "baseline" sleep duration for use in comparison across the school term. Thus, data collected encompassed baseline, through the entire school term and one post term week of school holidays representing 81 consecutive days. As only one school participated per school term, data were collected across five *consecutive* terms during both the Australian summer and winter.

Procedure and materials

General Health Questionnaire (GHQ)

This questionnaire aided in excluding participants with previous medical or mental health issues, sleep disorders and gathered information about BMI.

Sleep patterns

Daily sleep patterns were measured via wrist activity monitors (Philips Respironics Actiwatch Mini-Mitter Co., Inc. Bend, OR, USA) previously evaluated in non-clinical samples and adolescents[23] and worn on the non-dominant wrist. Actiwatch-2 data were initialized and downloaded using Actiware 5 Software with sensitivity levels set at the medium threshold with epochs of 30 seconds and definitions of sleep/wake epochs based on a validated scoring algorithm.[24] To minimize participant burden, students were not interviewed from their diary, but actiwatch provided daily estimates of bedtimes, rise times, sleep duration, and sleep efficiency and were manually checked against daily sleep diaries (which provided self-reported bed time, lights out, sleep and wake time, sleep location, and unusual events (illness, exams, etc) and sleep diaries also helped separate periods of sleep from other times of low movement (eg, removal for showering, reading a book). Manual scoring and consensus between authors was used in cases of diary/actiwatch discrepancy rather than simple reliance on default settings,[25] but if insufficient, actiwatch data was prioritized,[26] (given actiwatch validity and objectivity[27,28]) and discrepancies resolved based on previous publications.[26,28]

Participants were also asked to note any unusual occurrences for the weeks of the study (for example, going on school camp, or leaving actiwatches off for longer periods than was normal). Actiwatches were recharged and exchanged every 4 weeks.

Subjective mood and wellbeing

Self-reported mood was assessed with the *Depression Anxiety Stress Scale-21 (DASS-21)*[29] and wellbeing with the Satisfaction with Life Scale (SWLS).[3031] These scales were administered to participants on a weekly basis throughout the study period; scale scores from the first week of the study period were used in the analyses. The DASS-21 is a 21-item, self-report inventory comprised of three scales (7 questions each), and assesses three dimensions of mood (depression, anxiety, and stress) over the previous week (eg, "I tended to over-react to situations") measured on a 4-point Likert scale ($0 =$ *did not apply to me at all* to $3 =$ *applied to me very much or most of the time)*. Individual items were summed, to provide an overall indication of mood, whereby higher scores reflect greater negative mood. Used in both longitudinal studies and adolescents,[29] the DASS-21 has excellent psychometric properties and had appropriate internal consistency in this paper (Cronbach's $\alpha = .87$).

The SWLS is a 5-item tool that assesses global judgements of satisfaction with life (eg, "in most ways my life is close to my ideal") on a 7-point Likert style response scale ($1 =$ strongly disagree and $7 =$ strongly agree). The possible score range is 5–35, higher scores indicating high life satisfaction. This scale had an adequate level of internal consistency in this paper ($\alpha = .80$).

Morningness eveningness questionnaire

The seven-item short scale of the MEQ utilized in previous[32,33] was completed during the first week. The seven items ask participants consider their "feeling best" rhythms and indicate preferred clock time blocks for sleep and engagement in various hypothetical situations (eg, physical exercise, tests,). MEQ scores can range from 7 to 32, with scores between 7 and 15 indicating evening types, scores between 16 and 22 indicating 'neither type', and scores between 23 and 32 indicating morning types. The MEQ had adequate internal consistency in this study ($\alpha = .71$).

Body Mass Index (BMI), also measured during the first week of the study period, was calculated from self-reported height and weight from the demographic questionnaire.

Ethics

Ethics approval was granted by The Central Queensland University Human Research Ethics Committee and the Ethics Committee of the South Australian Department of Education and Child Development.

Data analysis

Data were analyzed using DSEM, conducted with M*plus* Version 8.2. DSEM is ideal for analyzing intensive longitudinal data (eg, > 30 measurement points), and is a combination of several analytic techniques, including time series analysis, structural equation modeling, and time-varying effects modeling.[20] Whereas traditional time series analysis examines a single individual who has multiple time-points of data, DSEM allows for time series for multiple individuals to be analyzed simultaneously. This is achieved through a multi-level modeling framework, where level 1 describes within-person (intraindividual) processes (ie, the time series) and level 2 captures between-subjects (interindividual) differences in these dynamic features over time.[34]

We outline the DSEM approach used in the present paper below but more detail on DSEM can be found in Asparouhov et al,[34] and Hamaker et al,[20] (2018). The combination of sample size (N) and time points (T) is an important consideration when conducting DSEM since it influences the quality of the parameter estimation.[35] Schultzberg and Muthén[35] recently conducted a comprehensive simulation study to determine the required combination of N and T for different DSEM models. Based on these findings, the combination of $N = 47$ and $T = 81$ in this paper was sufficient to provide good quality statistical parameter estimation.

We tested separate DSEM's for each of the four sleep parameters (TST, bedtimes, rise times, and SE) following recommendations provided in the literature.[20,34,35] For clarity, we discuss the modeling approach below using TST as an example; the same approach was used for bedtimes, rise times, and SE. **Step 1** tested a Univariate Multilevel Autoregressive Model, which involved examining fixed and random effects for average TST over time (μ *TST*) and the day-to-day auto-regressions for TST (φ *TST*). The fixed auto-regression effect (also referred to as carryover or inertia) indicates how strongly TST on a given day is predicted by TST on a previous day, averaged across all participants. A significant fixed auto-regression indicates significant carryover in TST between subsequent days, with higher values indicating a stronger relationship and hence more stable TST over time. The random auto-regression effect assesses whether there are significant individual differences in the auto-regressions. A significant random auto-regression effect would indicate individual differences in the amount of carryover in TST between subsequent days.

Step 2 then tested whether six covariates – age, mood, life satisfaction, chronotype preference, BMI, and season – predicted the fixed and random effects for mean TST and auto-regressions for TST. These models provide an indication of whether these five covariates predict the temporal dynamics of TST over time.

All analyses used Bayesian estimators, with the significance of the fixed and random effects determined from the 95% credibility intervals. There were some missing data over time (mean number of missing days per participant = 7.3 days; SD = 10.63), and these were handled in the analyses using Full Information Maximum Likelihood (FIML) estimation.[36] FIML estimation draws on all available information to estimate plausible values for missing time points, and

Table 1
Descriptive statistics for the sample of 47 male adolescents

	Mean	SD
Age	15.67	.91
Mood (DASS)	9.88	6.85
Life satisfaction (SWLS)	24.46	6.69
Morningness (MEQ-7 item)	17.69	5.25
Body mass index	21.74	4.38

DASS, Depression, Anxiety, Stress Scale (range, 0-41 – higher scores reflect worse mood).
SWLS, Satisfaction with Life Scale (range, 5-35 – higher scores reflect higher life satisfaction)
MEQ, Morningness Eveningness Questionnaire (range, 7-32 – higher scores reflect morning preference)
BMI, healthy range for ages 14–17 years: 19-21.5.

outperforms other missing data approaches such as listwise and pairwise deletion and multiple imputation.[36]

Results

Descriptive statistics

Descriptive statistics are shown in Table 1. The MEQ scores indicate that most participants were in the 'neither type' range, while scores on the DASS-21 and SWLS scale were comparable to population averages.[30,31] The average BMI values are below the cut-offs for overweight for this age range.[37] Figs. 1 and 2 show that TST was shorter on non-school days (including holidays) and showed variability between week and weekdays. On average, TST on school-nights was approximately 30 minutes shorter than TST on non-school nights, with bedtimes and waketimes being over an hour earlier. TST, Bedtimes, and rise-times were similar on non-school and holiday nights. Sleep efficiency was comparable across school, non-school, and holiday nights.

Temporal dynamics in sleep

The average values for bedtimes, rise times, TST, and SE across the 81 consecutive days are shown in Figs. 2, 2B, 2C and 2D. The fixed and random effects for bedtime, rise times, TST, and SE are shown in Table 2 and are described below. (See Fig. 3.)

Bedtimes

As shown in Table 2, step 1 of the DSEM indicated a significant auto-regression fixed effect for bedtimes (.24, 95% credibility interval [.18, .29]). This shows a positive relationship between bedtimes on subsequent days; however, the effect size is relatively small suggesting some day-to-day variability in bedtimes. This is evident in Fig. 2 and reflects a trend for later bedtimes on non-school nights compared with school nights. The significant auto-regression random effect (.03 [.01, .05]), suggests that the nature of the day-to-day relationship between bedtimes differs between individuals.

Step 2 of the analyses indicated that individuals with lower morningness had later bedtimes across the 81 day period (−.10 [−.17, −.03]). None of the other covariates were significantly associated with mean bedtimes or auto-regressions over time.

Rise times

In Step 1, the significant auto-regression fixed effect (.37 [.30, .43]) indicates some stability in rise times across the 81-day period, which reflects consistent rise times on school days (see Fig. 2B). However, there is also some variation in rise times, with later rise times on non-school days compared with school days. The significant auto-regressive random effect demonstrates individual differences in the relationships between rise times on subsequent days (.03 [.01, .05]). Similar to bedtimes, such individual differences are expected given that a range of factors could contribute to the fluctuations in rise times between days, particularly in relation to differences between school and non-school days.

Step 2 indicated that lower morningness was associated with later rise times across the 81-day period (−.08 [−.12, −.04]). Age, mood, life satisfaction, BMI, and season were not significantly associated with the temporal dynamics in rise times.

TST

In Step 1, there was a significant but weak auto-regression fixed effect for TST (.06 [.00, .11]), suggesting considerable day-to-day variations in TST over time (see Fig. 2C). The significant auto-regression random effect (.01 [.00, .03]) indicates individual differences in the

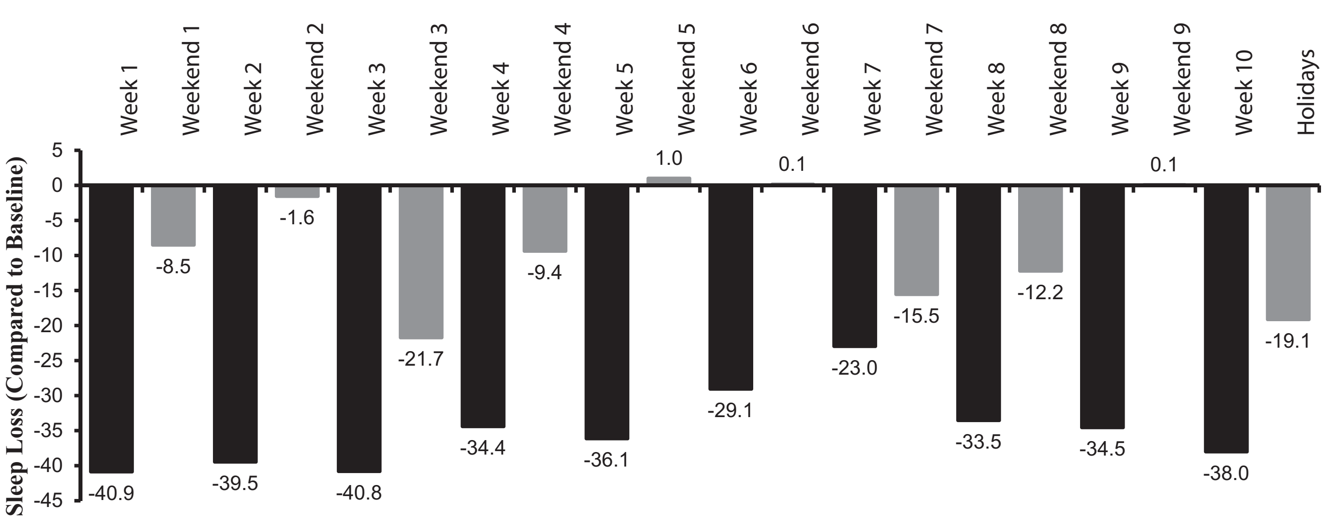

Fig. 1. Variation in average sleep duration from baseline over a school term, showing recovery sleep on weekends. The zero on the *x*-axis denotes average baseline sleep. Weekday sleep is indicated by the black bars, and weekend sleep by the gray bars

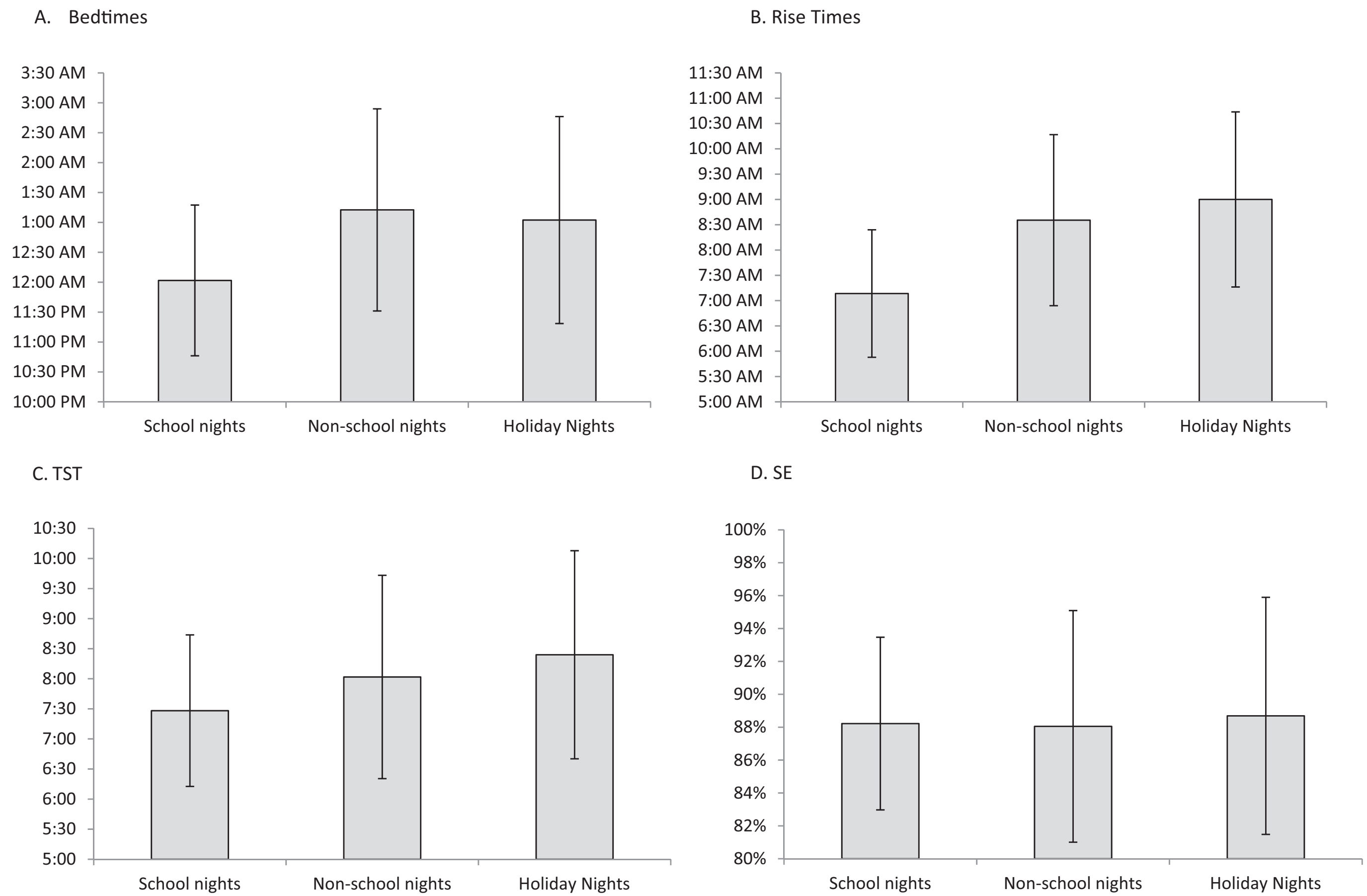

Fig. 2. A-D, Mean sleep variables averaged across school, non-school, and holiday nights.

Table 2
Results of the DSEM, whereby covariates were modeled as predictors of TST, bedtime, rise times, and SE over time. Results are presented as unstandardized coefficients, with 95% credibility intervals

	Total sleep time	Rise time	Bedtimes	SE
Step 1				
Fixed effects				
Mean (μ)	7.68 [7.46, 7.89]*	7.74 [7.53, 7.96]*	24.46 [24.09, 24.84]*	87.83 [86.83, 88.82]*
Auto-regression (φ)	.06 [.00, .11]*	.37 [.30, .43]*	.24 [.18, .29]*	.22 [.15, .28]*
Random effects				
Mean (μ)	.48 [.31, .78]*	.43 [.26, .74]*	1.50 [1.00, 2.40]*	11.29 [7.33, 18.23]*
Auto-regression (φ)	.01 [.00, .03]*	.03 [.01, .05]*	.03 [.01, .05]*	.03 [.02, .06]*
Step 2				
Mean (μ)				
Age	−.07 [−.32, .19]	.02 [−.22, .26]	.16 [−.26, .59]	−.57 [−1.86, .70]
Mood	−.01 [−.04, .02]	−.00 [−.03, .03]	.01 [−.04, .06]	−.16 [−.31, −.02]*
Life Satisfaction	.03 [−.03, .08]	−.01 [−.06, .05]	−.05[−.14, .07]	−.01 [−.32, .25]
BMI	−.04 [−.09, .02]	.01 [−.03, .06]	.05 [−.03, .14]	−.03 [−.28, .22]
Morningness	−.00 [−.05, .04]	−.08 [−.12, −.04]*	−.10 [−.17, −.03]*	−.01 [−.20, .20]
Season	−.27 [−.78, .23]	−.43 [−.90, .03]	−.18 [−1.00, .61]	−1.36 [−3.72, 1.02]
Auto-regression (φ)				
Age	−.07 [−.14, −.00]*	.01 [−.08, .08]	−.00 [−.08, .08]	−.02 [−.10, .07]
Mood	−.00 [−.01, .01]	−.01 [−.02, .01]	−.00 [−.02, .01]	−.00 [−.01, .01]
Life Satisfaction	−.01 [−.02, .01]	.00 [−.02, .02]	.01 [−.01, .02]	.02 [−.00, .03]
BMI	.01 [−.01, .02]	−.01 [−.03, .00]	−.01 [−.02, .01]	.01 [−.01, .03]
Morningness	−.00 [−.01, .01]	−.01 [−.02, .01]	−.01 [−.02, .01]	−.00 [−.02, .01]
Season	−.04 [−.17, .09]	−.08 [−.24, .07]	.01 [−.15, .15]	.08 [−.08, .223]

μ = average levels of sleep across the 81 day period
φ = autoregressions of sleep average across the 81-day period
* Significance based on 95% credibility intervals.

amount of carryover in TST between subsequent days. (−.01 [−.06, .03]).

Step 2 of the analyses indicated that older age was associated with lower auto-regressions (−.07 [−.14, −.00]). This result shows that younger adolescents had more stable TST across the 81-day period compared with older adolescents. Mood, life satisfaction, BMI, morningness, and season were not significantly associated with TST.

Sleep efficiency

In Step 1, the small but significant auto-regression fixed effect for SE (.22 [.15, .28]) suggests some day-to-day variation in SE across the 81-day period (Fig. 2D). The significant auto-regression random effect (.03 [.02, .06]) shows that the amount of carryover in sleep varied between individuals.

Step 2 of the analyses indicated that positive mood was significantly associated higher SE across the 81-day period (−.16 [−.31, −.02]). Age, life satisfaction, BMI, and morningness were not associated with SE over time.

Discussion and conclusions

This study applied a new analytic technique – DSEM – to explore the temporal dynamics of objectively measured sleep in 47 adolescents over 81 consecutive days. Intraindividual variation in adolescent sleep patterns are recognized as important for a number of adolescent outcomes.[19] Previous longitudinal studies have examined sleep over relatively short periods of time (eg, 1–2 weeks), so are limited in capturing the dynamics of sleep that develop over time. Other studies collected more intensive longitudinal sleep data,[5] but have limited analytic exploration of important issues such as intraindividual variation in sleep patterns. In the present paper, the DSEM approach allowed for a more sophisticated insight into the nature of adolescent sleep over time.

Firstly, the present results show important yo-yo sleeping with considerable intraindividual variation in sleep patterns. This is reflected by the low (although significant) auto-regressions for bedtimes, rise times, TST, SE. This suggests that although there is some carryover in sleep patterns between subsequent days, factors other than the previous day's sleep may be significantly influencing daily sleep schedules. On average bedtimes and rise times were approximately 1 hour earlier on school days, and TST approximately 30 minutes shorter. This is consistent with findings in previous studies showing that adolescents have earlier bedtimes and rise times, and shorter sleep durations on school nights compared with non-school nights.[10,18] Plausibly school start times constrain sleep schedules for many adolescents, who attempt to catch up for lost sleep on the weekend.

A second important finding in this study is that there were significant interindividual differences and variations in sleep patterns over the 81-day period. That is, individuals differed in the amount of carryover in sleep (or sleep debt) between subsequent days. These findings are important because some adolescents may show highly variable sleep patterns reflecting the influence of a range of factors including but not exclusive to genetics, mood, personality, environmental factors (eg, noise, family stress), and sleep hygiene behaviors (eg, screen-time and social media). Plausibly, interindividual variations may be impacted by pubertal stage, (which was not measured), but is associated with increased eveningness as children move into adolescence.[38] Although our sample were neither evening nor morning types, measuring pubertal stage in the future may help to further understand these interindividual differences.

Interestingly, we found that several covariates predicted sleep dynamics across the 81-day period. As expected, greater morningness predicted earlier bedtimes and rise times across the 81-day period. The literature presents evidence that morning types are more aligned with intrinsic human preference for daylight activity and adapt better behaviourally and emotionally to a regular school day schedule.[39] This raises the question as to whether morning types are intrinsically more stable and less impacted by external factors. Further, evening types present with worse performance, and wellbeing[40] and a range of behavioral and emotional problems.[39] Perhaps evening types are more susceptible to extraneous social factors that are detrimental to sleep (eg, screen time and late night activities)? Perhaps the evening types were also older with a more advanced pubertal

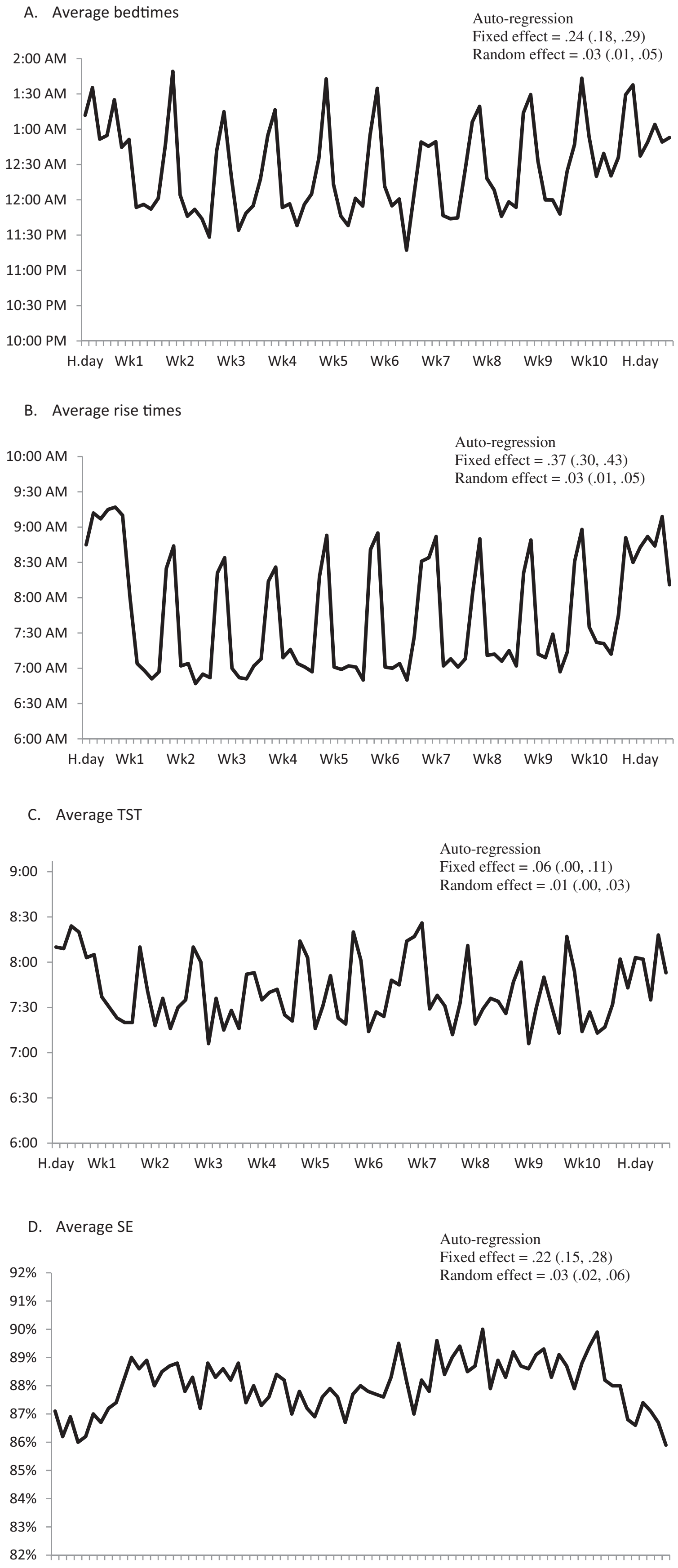

Fig. 3. A-D, Sleep values averaged across all participants, measured at each of the 81 consecutive days.

stage. Relationships we found between eveningness and mood suggest potential therapeutic pathways for mood disturbed adolescents through chronotherapeutic strategies such as sleep timing manipulation and sleep education.[41]

Positive mood predicted higher SE. It is unclear why this might be the case, but confirms the need to include sleep quality measures, when exploring adolescent mood and sleep. Indeed, unlike previous studies we found no significant relationships between mood and other sleep parameters. It is plausible that the design of the study may not have been ideal to capture the dynamic relationships between sleep and well-being and/or that the DASS questionnaire was not sensitive enough to identify potential subtle changes in weekly mood as measured by what is essentially a clinical instrument. However, given the length of the study, alternatively measuring daily DASS mood was deemed not feasible. Future studies with fewer time points (eg, 3–4 weeks, rather than 10 weeks) could feasibly take daily measurements of mood and examine their associations with daily sleep patterns.

Importantly our results indicate a link between age and the auto-regressions for TST. In particular, younger adolescents showed a higher auto-regression which means greater stability of TST relative to older adolescents.

There are some limitations of the study that should be noted. Participant response rates were low across the schools (26% to 34%), which indicate that the results may be biased and thus not generalizable beyond this sample. The combined sample size (N = 47) and number of time points (N = 81) were sufficient for the present analyses,[35] but larger sample sizes would be needed for more complex DSEM modeling. For example, DSEM has the potential to provide insights into how the temporal dynamics in sleep over time predict outcomes such as health and performance, and also whether temporal sleep dynamics mediate the relationships between predictors and outcomes. Absence of participant input to clarify discrepancies between actigraph and diary data and the repetitive nature of the testing may have resulted in response fatigue and/or inaccuracy. In addition, although the study sample was limited to males (due to high levels of undiagnosed depression and sleep restriction in this population), future studies should also include females. Recommendations for further research include using intensive longitudinal data, and a larger sample size to control for seasonal factors,[9] sleep hygiene[12,22] and ethnicity[42] given their potential impact on sleep behaviors. Finally, although age and Morningness/Eveningness were used to consider aged difference in sleep, pubertal stage could be added to future protocols.

In conclusion, despite these issues, this study is the first to utilize DSEM to assess variation in adolescent sleep patterns over an extended period, providing new insights into adolescent sleep patterns, and revealing important inter-individual and intra-individual variances in sleep. By replicating this study in further research, data will contribute to discussions on how to reduce sleep variability and increase opportunities for intervention to improve the sleep health of our young people.

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Conflicts of interest

None of the authors have any conflict of interest.

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