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EMPIRICAL RESEARCH

Associations Between Multiple Dimensions of Sleep and Mood During Early Adolescence: A Longitudinal Daily Diary Study

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Abstract
Prior research has observed reciprocal associations between sleep and mood. However, these findings are primarily based on the examination of one or two aspects of sleep behaviors (e.g., duration, quality), neglecting how multiple dimensions of sleep (particularly indicators pertinent to adolescence, e.g., sleep variability) are linked to adolescent mood both daily and longitudinally. Drawing on a multidimensional framework for sleep, this study addressed the knowledge gap by examining the directionality of and differential effects for associations between multiple dimensions of sleep and mood during early adolescence. Participants were 273 Chinese early adolescents (34.39% girls; $M_{age} = 11.57$, $SD = 1.31$), who filled out a pre-survey on demographics (T1) and 7-day diaries on sleep (i.e., duration, quality, disturbance, and latency) and mood (i.e., positive and negative mood). Adolescents completed another wave of diary reports 1 year later (T2). Findings revealed both bidirectional and unidirectional, within-person effects depending on specific sleep parameters, suggesting differential associations between multiple dimensions of sleep and mood. Specifically, on days when adolescents had longer sleep latency and greater disturbance than usual, they reported higher negative mood the next day, whereas higher negative mood was linked to poorer sleep quality the next day. The longitudinal investigation found that greater variability in sleep quality at T1 was associated with higher negative mood at T2. These findings underscore the importance of understanding the complex interplay between sleep and mood by examining the directionality of and differential effects for the daily and longer-term associations between multiple dimensions of sleep and mood among early adolescents.

Keywords Sleep · Mood · Sleep variability · Early adolescence · Daily diaries

Introduction

Sleep insufficiency and disturbances are common among adolescents worldwide (Becker et al., 2015) and especially prevalent among Asian adolescents (Gradisar et al., 2011). Sleep is an important biobehavioral marker for adolescent mental health (Short et al., 2020), among which mood is one important factor closely associated with sleep on a daily basis (Kouros et al., 2022). Previous research has documented reciprocal associations between sleep and mood (for a review, see Konjarski et al., 2018); however, these findings are primarily limited to the examination of a few sleep indicators (e.g., duration, quality). Less clear are the day-to-day associations between other aspects of sleep and mood and whether their links remain in the longer-term developmental processes during early adolescence. Sleep is a complex, multifaceted construct (Buysse, 2014), and examining the extent to which sleep predicts mood (and vice versa) and how directionality of their associations differs by specific sleep dimensions are important priorities for research on sleep and youth development (El-Sheikh & Buckhalt, 2015). The present study addresses the research gaps by examining the day-to-day and longitudinal associations between multiple dimensions of sleep and mood among early adolescents.

Sleep and Mood During Early Adolescence

Early adolescence is an important developmental stage for the examination of sleep and mood (Tarokh et al., 2016).

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Physiological and social factors, such as delay in dim light melatonin onset and more access to social media, may disrupt adolescents' normative sleep patterns, which in turn, lead to increased sleep difficulties at this stage (Gariepy et al., 2020). Rapid cognitive changes (e.g., increased amygdala reactivity) associated with sleep and emotional regulation during early adolescence also make this stage particularly important for research on sleep and mood (Tarokh et al., 2016). Meta-analytic findings suggested that the detrimental impact of sleep loss on emotional health was more pronounced among younger samples such as early adolescents (Tomaso et al., 2021), suggesting that early adolescents may be more sensitive (or vulnerable) to sleep deprivation. The examination of stability of and changes in sleep patterns is especially pertinent to early adolescence, since this developmental stage is characterized by increased changes in sleep/wake schedules and higher demands for academic and social activities (e.g., more uses of social media), often contributing to fluctuating sleep patterns (Peltz et al., 2024). The investigation of the associations between sleep and mood during early adolescence was relatively rare (Kouros et al., 2022), and yet important especially for a more nuanced understanding of the complex interplay of sleep and mood during early adolescence, a crucial developmental period in which adolescents experience increasing biobehavioral and emotional changes (Tarokh et al., 2016).

Day-to-Day and Longitudinal Associations Between Multiple Dimensions of Sleep and Mood

Empirical findings (Neubauer et al., 2021) and systematic reviews (Konjarski et al., 2018) generally support bidirectional associations between sleep and mood. Specifically, sleep difficulties may weaken cognitive abilities in regulating emotion (Deliens et al., 2014), and thereby, lead to psychological maladjustment (e.g., negative mood, depressive and anxious symptoms; Kelly et al., 2022). Meanwhile, emotional arousal and dysregulation may cause vigilance, which in turn, contribute to sleep deprivation and disruptions (Kouros et al., 2022). Nonetheless, these findings primarily focused on one or two dimension(s) of sleep, i.e., sleep duration or quality (Neubauer et al., 2021), precluding a more comprehensive understanding of how other aspects of sleep (e.g., continuity) are associated with mood. Following a framework for multidimensional perspectives of sleep health (Buysse, 2014), the present study focuses on four important facets of sleep, i.e., quantity, quality, continuity and variability, and their day-to-day and longer-term relationships with mood during early adolescence.

The dimension of *quantity* (or duration) refers to the total amount of sleep an individual obtains from the sleep onset to offset (Buysse, 2014). Meta-analytic and empirical findings have consistently evidenced the associations between shorter sleep duration and poorer emotional health (Kortesoja et al., 2020). Specifically, less sleep duration was linked to 55% increased risk of mood deficits (e.g., more negative mood; Short et al., 2020). The dimension of *quality* refers to subjective feelings of having (un)restful sleep (Buysse, 2014), and this study focuses specifically on diary reports of sleep quality and disturbance (e.g., waking up in the middle of night). The extant literature largely supports the day-to-day associations between sleep quality and mood, such that poorer sleep quality was associated with less positive mood and more negative mood the next day (van Zundert et al., 2015), whereas the links from daily mood to next-night sleep quality were less evidenced (Neubauer et al., 2021). Sleep latency is another important indicator for the regulation of daily mood (Konjarski et al., 2018). Reflecting the *continuity* dimension of sleep health, sleep latency refers to the amount of time taken to fall asleep (Buysse, 2014). Prior research has observed bidirectional associations between longer sleep latency and greater negative mood (Kouros & El-Sheikh, 2015).

Prior findings on daily links between sleep and mood have primarily relied on one-time point of diary data (Konjarski et al., 2018). Less clear is the longer-term interplay between sleep and mood, which has important developmental implications for adolescents' subsequent health (Kelly et al., 2022). A longitudinal daily diary method allows for the examination of longer-term associations, providing more support for discussion on the directionality of the links between sleep and mood. Using two waves of diary reports spanning 1 year, this study delves into how the average levels and variability of sleep are linked to mood across time during early adolescence. Sleep variability is a rarely investigated, yet important, indicator for adolescent health (Becker et al., 2017). Reflecting intraindividual variation around the mean levels of sleep across multiple days, *sleep variability* offers an additional dimension beyond average sleep by demonstrating day-to-day fluctuations in sleep patterns (Bei et al., 2016). The literature drawing on late adolescence and adulthood suggests that sleep variability may reflect circadian rhythm dysfunction, such that more variability of sleep may impair neurodevelopment and emotional processing (e.g., more mood instability and impulsivity), which in turn, results in poorer emotional health among adolescents and young adults (Gillett et al., 2021). Regardless of the important health consequences of sleep (ir) regularity (Becker et al., 2017), research examining its impact on mental health during early adolescence remains largely limited (Kelly et al., 2022). Available findings demonstrated that variability in sleep was associated with greater negative mood (Bei et al., 2017) and more internalizing and externalizing problems (Kelly et al., 2022) among adolescents. Examining variability in multiple indicators such as sleep duration, quality and latency, this study expands the literature

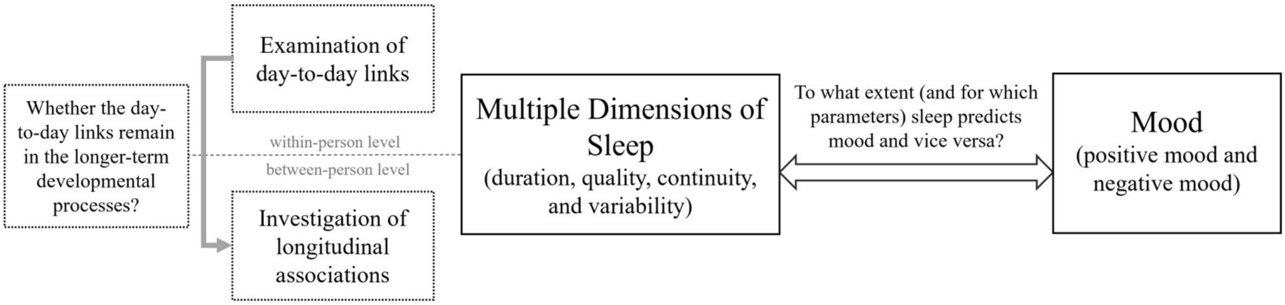

Fig. 1 Conceptual framework of the present study

by elucidating the longer-term developmental processes of multiple dimensions of sleep and mood during early adolescence. Unpacking these associations also contributes to developmental science more broadly regarding the nuances of how multiple dimensions of sleep, as essential biobehavioral markers, reciprocally interact with adolescent mood both for short-term and more protracted periods.

Prior research examining sleep and mood has been limited to WEIRD (i.e., western, educated, industrialized, rich, and democratic; Thalmayer et al., 2021) samples. In a meta-analysis of 73 studies examining the links between sleep duration and mood during adolescence (Short et al., 2020), only 3 (out of 19; 16%) longitudinal studies drew on non-WEIRD samples. Similarly, in a review of diary studies on sleep and mood (Konjarski et al., 2018), only 3 out of 29 studies (10%) drew on early adolescent samples (typically aged 10–13 years), none from non-WEIRD areas. This study, then, focuses on daily associations between sleep and mood among Chinese early adolescents. Multiple studies indicated that nearly 49.2%–69.8% of adolescents in China did not have sufficient sleep (i.e., <8 h; Huang et al., 2023; Lin et al., 2023), higher than the proportion in many countries in Europe or North America (ranging from 14 to 68%; Gariepy et al., 2020). Despite exhibiting a high prevalence of sleep disturbances (Liang et al., 2021), Chinese adolescents are largely neglected in the burgeoning literature on sleep and emotional health (e.g., Short et al., 2020), which will be addressed in this study.

Current Study

Prior research on sleep and emotional health has primarily relied on the examination of one or two aspect(s) of sleep behaviors (e.g., duration, quality), precluding a more nuanced understanding of how multiple dimensions of sleep, particularly parameters highly relevant to adolescence (e.g., sleep variability), are associated with adolescent mood both daily and longitudinally. Investigating the directionality (i.e., to what extent sleep predicts mood and vice versa) and differential effects (with which dimension) of these associations has important developmental implications for understanding changes in biobehavioral and emotional health during early adolescence. Adding novelty to the current literature, this study examines: (1) the day-to-day links between multiple dimensions of sleep (operationalized as sleep duration, quality, disturbance, and latency) and positive and negative mood; and (2) the longer-term associations between the stability (i.e., mean levels) and variability (i.e., intraindividual variation) of sleep and positive and negative mood during early adolescence (see Fig. 1 for the conceptual framework). Informed by reviews and empirical results, stronger links from nightly sleep to next-day mood was hypothesized, such that more sleep difficulties (manifested as shorter duration, poorer quality, greater disturbance, and longer latency) at night would be associated with less positive mood and more negative mood the next day, whereas the links from daily mood to next-day sleep would be less evidenced. For the longitudinal associations between sleep and mood, as suggested by prior findings, it was hypothesized that higher average levels of sleep difficulties and greater sleep variability would be associated with less positive mood and more negative mood 1 year later. Given the limited longitudinal diary research on sleep and mood, the examination of the directionality of their longer-term associations remains largely exploratory. Given the mixed (and limited) findings on the associations between multiple dimensions of sleep and mood, the investigation of the differential effects for each sleep or mood indicator is treated as exploratory.

Methods

Participants and Procedure

The present study used two waves of daily diary data (T1 and T2 data were collected in November 2020 and December 2021, respectively) from an on ongoing longitudinal project investigating academic, psychological, and behavioral outcomes of Chinese adolescents. The analytic sample comprised adolescents who completed T1 ($n = 273$) or T2

Table 1 Descriptive statistics and within-person level bivariate correlations of T1 primary study variables

	1	2	3	4	5	6
Bivariate correlations						
1. Duration	–					
2. Quality	0.17***	–				
3. Disturbance	−0.05	−0.16***	–			
4. Latency	−0.08	−0.14**	0.08*	–		
5. Positive mood	0.08	−0.01	0.08*	−0.01	–	
6. Negative mood	−0.01	−0.02	0.10*	0.03	−0.01	–
Descriptives						
M	3.00	3.31	0.25	1.70	3.35	1.56
SD	0.85	0.76	0.43	0.85	1.17	0.73
Minimum	1.00	1.00	0.00	1.00	1.00	1.00
Maximum	4.00	4.00	2.89	4.00	5.00	5.00
Skewness	−0.55	−0.96	2.37	1.17	−0.13	1.67
Kurtosis	−0.33	0.54	6.55	0.76	−0.90	3.01
ICC	0.69	0.53	0.72	0.68	0.73	0.61
Within-person reliability	[a]	[a]	0.78	[a]	0.82	0.76
Between-person reliability	[a]	[a]	0.91	[a]	0.98	0.94

Bivariate associations were estimated in a multilevel structural equation modeling framework in M*plus* 8.6. Coefficients are for within-person level correlations. Within-person reliability and between-person reliability indices were based on McDonald's omega, a reliability indicator for multilevel data

$^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

[a]Reliability was not available because the three variables were each based on a single item

($n=233$) daily diaries on sleep and mood (227 completed both T1 and T2 surveys). At T1, participants' (34.39% girls) ages ranged from 10 to 14 years ($M_{age}=11.57$, $SD=1.31$). This study used the Subjective Socioeconomic Status (SES) measure (Tan et al., 2020) to assess adolescents' perceived SES and subjective social position (e.g., income, educational level) of family, with a mean perceived SES of 5.82 ($SD=2.82$, range = 1–10) at T1.

Adolescents were recruited from two primary schools in a county in Eastern China. After obtaining approval from Beijing Normal University's institutional review board, the research team sought permission from school administrators and head teachers to proceed with recruitment. Students in grades 4 and 5 from the participating schools were invited. Students at grade 6 were not included due to the practical constraints (e.g., heavy curriculum burden in the graduating year). Only adolescents who provided informed assent and parental consent enrolled in this study. Adolescents initially completed a pre-survey on demographics. Next, they completed two 10-min daily surveys for 7 consecutive days, one in the morning (around 6:30 a.m., the time when students typically need to get up according to school day schedules) about previous-night sleep, and another before going to bed (around 8:30 p.m.) about positive and negative mood on that day. All study protocols followed Beijing Normal University's guidelines of ethics.

Measures

Descriptive statistics for primary study variables are displayed in Tables 1 and 2.

Multiple dimensions of sleep

Adolescent sleep was assessed by an adapted Pittsburgh Sleep Quality Index (Buysse et al., 1989), which is widely used for daily assessment of self-reported sleep health. Each day, adolescents reported their sleep on the previous night immediately after getting up in the morning. Four constructs of sleep were measured: *duration, quality, disturbance*, and *latency*. For *sleep duration*, adolescents reported "Last night, how many hours of actual sleep did you have?" (1 item) on a 4-point scale (1 = *less than 6 h* to 4 = *more than 8 h*), with higher scores reflecting longer duration. *Sleep quality* was assessed via the question "Last night, how would you rate your sleep quality overall?" (1 item) on a 4-point scale (1 = *very good* to 4 = *very bad*). The scores were reverse-coded, with higher scores reflecting better sleep quality. For *sleep disturbance*, adolescents reported the extent to which they had trouble sleeping the previous night (e.g., woke up in the middle of the night or early morning; 9 items) on a 4-point scale (1 = *not at all* to 4 = *a lot*), with higher score reflecting more disturbance. For *sleep latency*, adolescents reported "Last night, how long did it take for you to fall asleep?" (1 item) on a 4-point scale (1 = *less than 15 min* to 4 = *more than 1 h*), with higher scores reflecting longer latency (i.e., lower levels of sleep continuity). The *average levels* and *variability* of sleep were computed by taking the mean and the standard deviation values across 7 days for each adolescent (Fischer et al., 2021). Both average and variability values were created for the four constructs of sleep (i.e., duration, quality, disturbance, and latency), separately for T1 and T2, respectively.

Positive and negative mood

Positive mood and negative mood were assessed using the adjusted 10-item Positive and Negative Mood Schedule for Children (Ebesutani et al., 2012). Each day before going to bed, adolescents rated the extent to which they felt positive (i.e., joyful, cheerful, happy, lively, and proud) and negative (i.e., miserable, mad, afraid, scared, and sad) mood on a 5-point scale (1 = *very slightly* to 5 = *extremely*), with

Table 2 Descriptive statistics and bivariate correlations of T1 and T2 primary study variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Bivariate correlations																				
1. T1 Dur (M)	–																			
2. T1 Dur (V)	−0.28***	–																		
3. T1 Qua (M)	0.22**	−0.02	–																	
4. T1 Qua (V)	−0.03	0.12	−0.39***	–																
5. T1 Dist (M)	−0.13*	0.02	−0.58***	0.16*	–															
6. T1 Dist (V)	−0.07	−0.02	−0.48***	0.27***	0.45***	–														
7. T1 Laten (M)	−0.10	−0.05	−0.38***	0.17*	0.39***	0.26***	–													
8. T1 Laten (V)	0.01	0.09	−0.16*	0.31***	0.14*	0.25***	0.36***	–												
9. T1 Pos (M)	0.10	−0.05	0.28***	−0.10	−0.10	−0.12	−0.07	−0.14*	–											
10. T1 Neg (M)	−0.28***	−0.04	−0.37***	0.03	0.53***	0.25***	0.19*	−0.04	−0.18**	–										
11. T2 Dur (M)	0.17*	0.02	0.14*	−0.08	−0.14*	−0.10	−0.03	−0.04	0.15*	−0.15*	–									
12. T2 Dur (V)	−0.17*	0.09	−0.04	0.03	0.10	0.05	0.08	0.06	−0.04	0.10	−0.15*	–								
13. T2 Qua (M)	0.02	−0.01	0.54***	−0.21**	−0.39***	−0.29***	−0.13	−0.02	0.21**	−0.29***	0.29***	−0.001	–							
14. T2 Qua (V)	0.000	0.07	−0.25***	0.23***	0.19*	0.30***	0.00	0.06	−0.08	0.05	−0.05	0.14	−0.37***	–						
15. T2 Dist (M)	−0.15*	0.03	−0.49***	0.19	0.59***	0.35***	0.26**	0.15*	−0.11	0.42***	−0.16**	0.11	−0.52***	0.26***	–					
16. T2 Dist (V)	−0.11*	0.02	−0.34***	0.17	0.43***	0.37***	0.17*	0.08	−0.07	0.34***	−0.11	0.24***	−0.47***	0.39***	0.68***	–				
17. T2 Laten (M)	−0.07	0.04	−0.28***	0.10	0.27***	0.15*	0.43***	0.10	−0.07	0.17*	−0.11	0.01	−0.34***	0.28***	0.40***	0.32***	–			
18. T2 Laten (V)	−0.16*	0.17*	−0.06	−0.02	0.13*	0.13	0.14	0.06	−0.05	0.09	0.01	0.15*	−0.15*	0.25**	0.18**	0.26***	0.38***	–		
19. T2 Pos (M)	−0.01	−0.01	0.23***	−0.14*	−0.19***	−0.09	−0.06	−0.17**	0.54***	−0.20**	0.31***	−0.03	0.36***	−0.12	−0.23***	−0.22***	−0.06	0.02	–	
20. T2 Neg (M)	−0.12	0.05	−0.34***	0.21**	0.42***	0.17**	0.12	0.08	−0.25***	0.49***	−0.17**	0.08	−0.41***	0.14*	0.53***	0.47***	0.18*	0.04	−0.36***	–
Descriptives																				
M	2.99	0.38	3.29	0.43	0.30	0.23	1.71	0.37	3.32	1.56	2.91	0.34	3.23	0.39	0.24	0.18	1.65	0.32	3.42	1.50
SD	0.70	0.35	0.58	0.31	0.37	0.16	0.69	0.37	1.05	0.61	0.68	0.35	0.51	0.30	0.29	0.16	0.60	0.32	0.92	0.56
Minimum	1.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	1.00	1.00	1.00	0.00	2.00	0.00	0.00	0.00	1.00	0.00	1.20	1.00
Maximum	4.00	1.53	4.00	1.60	2.41	0.97	4.00	1.50	5.00	3.88	4.00	1.64	4.00	1.21	1.39	0.69	3.86	1.47	5.00	3.54
Skewness	−0.40	0.83	−0.83	0.20	2.40	1.04	1.05	0.84	0.01	1.25	−0.07	0.91	−0.07	0.02	1.68	0.92	0.89	0.86	0.23	1.36
Kurtosis	−0.34	0.68	0.55	0.05	7.07	1.52	0.81	0.21	−0.83	1.02	−0.70	0.74	−0.79	−0.71	2.36	0.25	0.64	0.76	−0.80	1.23

Bivariate correlations were estimated in a path analysis framework in M*plus* 8.6. Both bivariate correlations and descriptive statistics were based on raw scores.

Dur duration, *Dist* disturbance, *Laten* latency, *Pos* positive mood, *Neg* negative mood, *M* mean, *V* variability

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

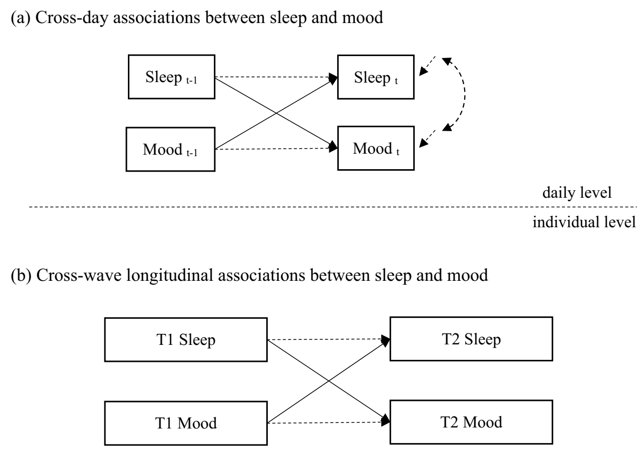

Fig. 2 Models linking multiple dimensions of sleep and mood. Solid lines indicate associations of primary interest (e.g., the link from $sleep_{t-1}$ to $mood_t$); dash lines indicate associations that are an integrative part of the model but not of primary interest (e.g., the link from $sleep_{t-1}$ to $sleep_t$). For both models (**a**) and (**b**), separate models were fitted for each sleep construct (i.e., duration, quality, disturbance, and latency). For model (**a**), separate models were fitted for positive mood and negative mood to improve model convergence. For model (**b**), positive mood and negative mood were examined in the same model

higher scores reflecting more positive or negative mood on a day. Average positive mood and negative mood were computed using the mean scores across 7 days, separately for T1 and T2, respectively.

Covariates

Daily-level covariates included weekday (1) versus weekend (0). Day in the study was accounted for by specifying it as an index (TINTERVAL command in M*plus*) in the modeling. Between-person covariates included adolescent age, gender (0 = *male*, 1 = *female*), and subjective SES (range = 1–10).

Data Analytic Strategy

Analyses examining the daily associations between sleep and mood were conducted using dynamic structural equation modeling (DSEM; Asparouhov et al., 2018) in M*plus* 8.7 (Muthén & Muthén, 1998–2017). DSEM integrates time series analyses and multilevel effects into structural equation modeling. The first-order auto-regressive AR(1) paths handled the correlations among repeated assessments of a variable; the cross-lagged paths estimated the daily bidirectional associations between two variables (McNeish & Hamaker, 2020). Specifically in the model, sleep and mood were each decomposed into a daily component and an individual component.

At the daily level, the effects on sleep (or mood) predicted by prior-day sleep (or mood) were estimated by two AR(1) paths (i.e., $sleep_{t-1} \rightarrow sleep_t$, $mood_{t-1} \rightarrow mood_t$). The effects for the bidirectional associations between sleep and mood, which are the primary interest of this study, were assessed by two cross-lagged paths between the two variables (i.e., $sleep_{t-1} \rightarrow mood_t$; $mood_{t-1} \rightarrow sleep_t$; see the conceptual model in Fig. 2a). The auto-regressive paths and cross-lagged paths, as well as the intercepts and variances, were all estimated as random effects and included at the between-person level. Since examining positive and negative moods in the same model led to model non-convergence, they were estimated in separate models. However, when examining one dimension of mood, the other dimension was included as a within-person level covariate. For example, when examining the association between sleep and positive mood, negative mood was included as a within-person level covariate on sleep and positive mood. Each sleep construct (i.e., duration, quality, disturbance, and latency) was examined in separate models.

Non-informative priors were specified using iterations = 2000 and thin = 10. Model convergence was evaluated based on three criteria: (1) potential scale reduction value close to 1; (2) posterior trace plots had no sign of upward or downward trend with two chains overlapping well; and (3) autocorrelations lower than 0.1 after initial iterations (Asparouhov & Muthén, 2020). The missing data patterns were investigated by examining if the frequency of missing days for each primary study variable (i.e., sleep, mood) was associated with (1) its mean score, (2) the mean of other primary variables, and (3) demographic covariates. None of the associations was significant, suggesting missing completely at random. Markov Chain Monte Carlo multiple imputation was used to handle missing data (Asparouhov & Muthén, 2010). Both daily-level and person-level covariates were simultaneously included in the model.

Path analyses were conducted in M*plus* 8.7 to examine the longitudinal associations between the average levels and variability of sleep and mood. Maximum likelihood estimator with robust standard errors handled the non-normal distribution of data. A cross-lagged model was fitted wherein T1 sleep (either average levels or variability) and mood predicted each other at T2 (e.g., T1 sleep mean → T2 mood mean; T1 mood mean → T2 sleep mean; see conceptual model in Fig. 2b). Sleep average levels and variability were examined in separate models. When assessing the associations between sleep variability and mood, the effects of average sleep were controlled for to partial out its potential contribution (Becker et al., 2017). Each dimension of sleep was examined in separate models. The values of prior wave of sleep and mood were also controlled for (e.g., T1 sleep mean → T2 sleep mean) to account for the potential carry-over effects. Person-level covariates (e.g., gender, age) were included in the model. Informed by previous research highlighting that the effects of average sleep and its variability on adolescent adjustment may be interdependent (Maciejewski et al., 2023), this study conducted supplemental analyses to examine the interaction between the average level and variability of a T1 sleep indicator (e.g., average duration × duration variability) on T2 mood. The average level and variability were grand mean centered to create the interaction term. To preserve power, the association between T1 mood and T2 sleep was excluded when estimating the interaction models.

To examine whether the sample size ($n = 273$) of this study has sufficient statistical power for the analyses, a series of Monte Carlo simulation studies were conducted in M*plus* 8.7. Details of power analysis were displayed in Supplemental Materials and Table S1. Results of the Monte Carlo simulations suggest that, overall, the non-significant findings were unlikely due to insufficient power within the analytical sample. Finally, this study applied 0.05 as the p value threshold for statistical significance for the analyses.

Results

The correlations among primary study variables are displayed in Tables 1 and 2. At within-person level, the bivariate correlations among sleep indicators were at small magnitude (Table 1). For the average and variability of T1 and T2 sleep indicators, all the bivariate correlations were at small to moderate magnitude (Table 2). These results suggest that multiple sleep indicators may capture distinct dimensions of sleep. The day-to-day and longer-term associations between multiple dimensions of sleep and mood are presented in Tables 3 and 4.

Daily Associations Between Multiple Dimensions of Sleep and Mood (Table 3)

Significant daily bidirectional associations emerged for sleep duration and negative mood: on days when adolescents had longer nighttime sleep duration than usual, they reported less negative mood the next day; on days in which adolescents reported more negative mood than usual, they had shorter sleep duration the next night. A unidirectional association emerged for sleep duration and positive mood: on days when adolescents who had longer sleep duration than usual, they reported more positive mood the next day, but not the reverse.

For sleep quality, a unidirectional association emerged for negative mood: on days in which adolescents reported more negative mood than usual, they had poorer sleep quality, but not the reverse. For sleep disturbance, a unidirectional association emerged for negative mood: on days when adolescents had greater sleep disturbance than usual, they reported more negative mood the next day, but not the reverse. No associations were found between positive mood and sleep quality and disturbance.

For sleep latency, a unidirectional association was observed for negative mood: on days when adolescents had longer nighttime sleep latency than usual, they reported more negative mood the next day, but not the reverse. No association emerged between sleep latency and positive mood.

Taken together, the findings revealed daily bidirectional associations between sleep duration and mood, unidirectional links from previous-night sleep latency and disturbance to negative mood, and a unidirectional link from previous-day negative mood to sleep quality. Since the between-person level effects are not the focus of this study, the results are presented in Supplementary Table S2.

Longitudinal Associations Between Multiple Dimensions of Sleep and Mood (Table 4)

For sleep quality, a unidirectional association emerged for its variability and negative mood: adolescents who had greater sleep quality variability at T1 reported more negative mood at T2 (1 year later), but not the reverse. The association between sleep quality variability and positive mood was not significant. The associations between average sleep quality and positive and negative mood were not significant.

For sleep disturbance, unidirectional associations emerged between average disturbance and mood: Adolescents who had greater sleep disturbance at T1 reported more negative mood and less positive mood at T2; however, the reverse associations were not found. The associations between sleep variability and positive and negative mood were not significant.

For sleep duration and latency, no associations emerged between the two constructs (regardless of average levels or variability) and mood.

Supplemental analyses were conducted to examine the interaction between the average level and variability of a T1 sleep indicator on T2 mood (Supplemental Table S3). One significant effect emerged for the interaction between T1 average and variability of disturbance on negative mood.

Table 3 Daily associations between multiple dimensions of sleep and mood

Predictor (day $t-1$)	Outcome (day t)	Unstd	Posterior SD	95% CI		p
				LL	UL	
Duration	Negative mood	−0.11	0.05	[−0.21,	−0.02]	0.020
Negative mood	Duration	−0.11	0.05	[−0.20,	−0.01]	0.036
Duration	Positive mood	0.11	0.05	[0.01,	0.21]	0.030
Positive mood	Duration	0.002	0.04	[−0.07,	0.07]	0.952
Quality	Negative mood	0.001	0.04	[−0.08,	0.08]	0.990
Negative mood	Quality	−0.11	0.05	[−0.21,	−0.02]	0.020
Quality	Positive mood	0.01	0.05	[−0.08,	0.09]	0.880
Positive mood	Quality	0.02	0.04	[−0.05,	0.09]	0.550
Disturbance	Negative mood	0.18	0.08	[0.03,	0.34]	0.018
Negative mood	Disturbance	0.02	0.03	[−0.03,	0.08]	0.394
Disturbance	Positive mood	0.13	0.09	[−0.04,	0.30]	0.136
Positive mood	Disturbance	0.02	0.02	[−0.01,	0.06]	0.174
Latency	Negative mood	0.11	0.04	[0.02,	0.19]	0.010
Negative mood	Latency	0.10	0.05	[−0.01,	0.19]	0.068
Latency	Positive mood	−0.02	0.05	[−0.12,	0.08]	0.648
Positive mood	Latency	−0.06	0.03	[−0.12,	0.01]	0.108

Each dimension of sleep was examined in separate models. When examining one dimension of mood, the other dimension was included as a within-person level covariate. For example, when examining the association between sleep and positive mood, negative mood was included as a within-person level covariate on sleep and positive mood

Unstd unstandardized estimates, *95% CI* 95% credibility interval, *LL* lower limits, *UL* upper limits

Specifically, the positive association between average sleep disturbance and negative mood became nonsignificant when sleep disturbance variability was above 0.25 units (8% sample falls within this region; Supplementary Fig. S1a). Simple slope analyses (Supplementary Fig. S1b) showed that the positive association between average sleep disturbance and negative mood was most salient among adolescents who had extremely low disturbance variability (2*SD* below mean), followed by adolescents who had moderately low disturbance variability (1*SD* below mean) and then by those who had moderately high disturbance variability (1*SD* above mean); the association was not significant for adolescents whose disturbance variability was extremely high (2*SD* above mean).

Taken together, findings revealed the longer-term, unidirectional links from average sleep disturbance at T1 to positive and negative mood at T2. The unidirectional link from average sleep disturbance at T1 to negative mood at T2 was observed, yet the magnitude of the link became less salient as the sleep disturbance variability increased. With regards to sleep variability, a significant unidirectional association linked variability in sleep quality at T1 to negative mood at T2.

Discussion

Empirical findings (e.g., Neubauer et al., 2021) and systematic reviews (e.g., Konjarski et al., 2018) have demonstrated reciprocal associations between sleep and mood. However, these findings are primarily limited to the investigation of sleep duration or quality; less clear is the interplay between sleep and mood in the longer-term developmental processes during early adolescence, an important developmental transition stage at which children experience rapid biobehavioral and emotional changes (Tarokh et al., 2016). Drawing on a multi-dimensional framework for sleep (Buysse, 2014), this study examined the day-to-day links between multiple dimensions of sleep (e.g., quantity, quality, continuity) and mood, as well as the longer-term associations between the stability and variability of sleep and mood during early adolescence. The data revealed both bidirectional and unidirectional, within-person effects depending on specific sleep parameters, suggesting differential associations between multiple sleep indicators and mood on a daily basis. Findings also revealed longer-term, unidirectional links from average sleep disturbance to mood. The longitudinal associations between variability in sleep and mood were mixed. Collectively, this study adds novel insight into the complex interplay between sleep and mood by examining the directionality of and differential effects for the daily and longer-term associations between multiple dimensions of sleep and mood among early adolescents.

As hypothesized and supported by prior findings (Kouros et al., 2022), this study found reciprocal links between sleep duration and mood: On days when adolescents had shorter nighttime sleep duration than usual, they reported more

Table 4 Longitudinal Associations between multiple dimensions of sleep and mood

Predictor (T1)	Outcome (T2)	Unstd	S.E.	95% CI LL UL	*p*	Std
Duration mean	Negative mood	0.01	0.02	[−0.03, 0.04]	0.738	0.02
Negative mood	Duration mean	−0.18	0.19	[−0.54, 0.19]	0.344	−0.06
Duration mean	Positive mood	−0.07	0.08	[−0.24, 0.09]	0.396	−0.06
Positive mood	Duration mean	0.07	0.05	[−0.02, 0.16]	0.109	0.11
Duration variability	Negative mood	0.05	0.04	[−0.02, 0.12]	0.195	0.08
Negative mood	Duration variability	0.10	0.12	[−0.13, 0.34]	0.394	0.07
Duration variability	Positive mood	−0.03	0.16	[−0.34, 0.27]	0.838	−0.01
Positive mood	Duration variability	−0.01	0.02	[−0.06, 0.04]	0.723	−0.03
Quality mean	Negative mood	−0.05	0.03	[−0.11, 0.01]	0.078	−0.15
Negative mood	Quality mean	−0.15	0.14	[−0.42, 0.11]	0.261	−0.07
Quality mean	Positive mood	0.07	0.10	[−0.14, 0.27]	0.524	0.04
Positive mood	Quality mean	0.01	0.03	[−0.05, 0.07]	0.647	0.03
Quality variability	Negative mood	0.09	0.05	[0.002, 0.18]	0.046	0.13
Negative mood	Quality variability	−0.03	0.10	[−0.22, 0.16]	0.753	−0.02
Quality variability	Positive mood	−0.20	0.19	[−0.57, 0.17]	0.297	−0.07
Positive mood	Quality variability	−0.004	0.02	[−0.04, 0.04]	0.859	−0.01
Disturbance mean	Negative mood	0.18	0.05	[0.08, 0.28]	0.000	0.25
Negative mood	Disturbance mean	0.16	0.09	[−0.01, 0.34]	0.072	0.13
Disturbance mean	Positive mood	−0.37	0.20	[−0.75, 0.01]	0.058	−0.12
Positive mood	Disturbance mean	−0.01	0.02	[−0.04, 0.03]	0.761	−0.02
Disturbance variability	Negative mood	0.004	0.07	[−0.13, 0.14]	0.958	0.003
Negative mood	Disturbance variability	0.11	0.07	[−0.03, 0.25]	0.127	0.11
Disturbance variability	Positive mood	−0.004	0.31	[−0.60, 0.60]	0.990	−0.001
Positive mood	Disturbance variability	0.01	0.01	[−0.02, 0.03]	0.753	0.02
Latency mean	Negative mood	0.04	0.05	[−0.05, 0.14]	0.377	0.05
Negative mood	Latency mean	0.07	0.06	[−0.05, 0.20]	0.254	0.07
Latency mean	Positive mood	−0.18	0.20	[−0.58, 0.22]	0.374	−0.05
Positive mood	Latency mean	0.000	0.01	[−0.03, 0.03]	0.992	0.001
Latency variability	Neg mood	0.04	0.04	[−0.03, 0.11]	0.300	0.06
Neg mood	Latency variability	0.08	0.11	[−0.13, 0.29]	0.456	0.06
Latency variability	Positive mood	−0.28	0.15	[−0.56, 0.01]	0.061	−0.11
Positive mood	Latency variability	−0.003	0.02	[−0.04, 0.04]	0.880	−0.01

Each sleep construct was examined in separate models. The average and variability of a specific sleep construct were examined in separate models. When examining the associations between the sleep variability and mood, its average level was controlled for (e.g., average sleep duration was controlled for when examining the associations between sleep duration variability and mood). Positive mood and negative mood were examined in the same model. Negative mood, latency mean, disturbance mean, and disturbance variability were square root transformed to address the skewness in the original scores. The between-person level effects are not the focus of this study, and the results are presented in Table S2 in the Supplementary Materials

Unstd unstandardized estimates, *S.E.* standard error, *95% CI* 95% confidence interval, *LL* lower limits, *UL* upper limits

negative mood the next day, and vice versa (i.e., greater negative mood was associated with shorter sleep duration the next night). Such findings may be explained by the incompatible status of sleep and strong mood states. Specifically, reduced sleep duration might impair emotional processing via affecting related neurocognitive connectivity (e.g., between the amygdala and prefrontal cortex; Motomura et al., 2017), and therefore, was associated with increased emotional reactivity and more negative mood. On the other hand, experiences of higher negative mood during the day may produce continuous processing of thoughts (e.g., rumination; Watkins & Roberts, 2020), and strong emotional states (e.g., higher negative mood) may result in sleep loss at night (Kouros et al., 2022). The findings also revealed a unidirectional link from nightly sleep duration to next-day positive mood, which is supported by results of a systematic review focusing on day-to-day associations between sleep duration and positive mood (Konjarski et al., 2018). Recent meta-analytic results drawing upon cross-sectional and diary studies also found strong effect sizes of sleep duration on positive mood (e.g., Short et al., 2020). Focusing on day-to-day, within-person effects, this study expands the literature by elucidating the intraindividual processes of sleep duration and mood, which provides empirical support for their reciprocal associations among early adolescents.

Results examining the daily interplay between the dimensions of quality (operationalized as sleep quality and disturbance) and continuity (operationalized as sleep latency) and mood are more mixed. Findings suggest two unidirectional, within-person links from sleep to mood (i.e., on days when adolescents had longer sleep latency and greater sleep disturbance than usual, they reported more negative mood the next day), but only one significant pathway for the reverse (i.e., higher negative mood was associated with poorer sleep quality the next night). These findings suggest stronger associations from nightly sleep quality and latency to next-day mood, whereas the opposite direction of effect was less evidenced, which are as expected and supported by prior diary studies (Kouros et al., 2022). Results examining the longer-term associations between sleep quality and mood also corroborated the day-to-day, within-person results: Greater average sleep disturbance at T1 was associated with less positive mood and more negative mood one year later at T2, but the opposite direction was not found. These findings collectively emphasize the essential role of sleep quality and latency in modulating adolescent emotional health (Pieters et al., 2015). A nuanced understanding of the relations between sleep (including quality and latency) and mood is particularly important for research on mental health during early adolescence, due to increased sleep problems and rapid emotional changes at this developmental period (Tarokh et al., 2016). Examining multiple sleep parameters and their links with mood during early adolescence, the present study adds novelty to research on sleep and mood by investigating the interplay between multiple dimensions of sleep and mood both immediately (i.e., day-to-day) and for more protracted periods (i.e., 1 year apart). Establishing stronger support for sleep quality and latency predicting mood (compared to the opposite direction of effects) during early adolescence, the findings suggest that intervention practices of mitigating sleep problems may be especially fitting for improving adolescent mental health at this stage.

This study uniquely contributes to the literature by demonstrating the longer-term associations between sleep variability and mood among early adolescents. Sleep variability is an important, yet less frequently examined, indicator for adolescent health (Becker et al., 2017). Reflecting individuals' night-to-night fluctuations in sleep patterns across days, sleep variability adds information beyond the mean levels of sleep (Bei et al., 2016). The findings revealed a unidirectional link from variability in sleep quality (but not the average) at T1 to negative mood at T2. That is, adolescents who had greater variability in sleep quality at T1 reported higher negative mood one year later. Notably, this finding emerged in models controlling for the effects of mean sleep quality (e.g., Kelly et al., 2022), suggesting the unique contribution of quality variability to adolescents' negative mood. High variability in sleep patterns may be related to sleep disruption or circadian misalignment, which may lead to compromised mental health such as higher negative mood during adolescence (Gillett et al., 2021). Notably, compared to average levels of sleep, variability in sleep may be especially impactful during early adolescence (Becker et al., 2017) and more robustly associated with longer-term developmental outcomes (Kelly et al., 2022). Using longitudinal data spanning one year, this study contributes novelty to the literature primarily focusing on cross-sectional design (Bei et al., 2016) by elucidating the directionality of the associations between variability in multiple sleep parameters and mood during early adolescence. Given the important developmental implications of sleep regularity for adolescent mental health, it is necessary for clinicians and professionals to consider maintaining sleep regularity as one of the recommended healthy behaviors for early adolescents. Efforts to reduce sleep variability (e.g., keeping a regular sleep/wake schedule) may be especially valuable to adolescent mental health due to increasing fluctuations in sleep at this stage (Becker et al., 2017).

This study did not find significant longitudinal associations between sleep duration and latency (both the average levels and variability) and mood during early adolescence. Prior findings on sleep duration and adolescent mental health are mixed. For instance, reduced average sleep duration predicted more internalizing symptoms among adolescents 3 years later (Kelly & El-Sheikh, 2014); however, a recent study found that variability (but not mean levels) of sleep duration was associated with adolescents' anxiety and depressive symptoms 1 year later (Kelly et al., 2022). Prospective research focusing on sleep latency is more limited relative to other sleep indicators such as duration or quality. Daily diary data evidenced links from sleep duration and latency to next-day mood, but their associations dissipated in the longitudinal examination (i.e., 1 year apart). It is possible that the quantity (i.e., duration) and continuity (i.e., sleep latency, reflecting the amount of time taken to fall asleep) dimensions of sleep are more pronounced for short-term, day-to-day effects on adolescent mood, whereas sleep parameters reflecting the quality (i.e., subjective quality and disturbance) and regularity (i.e., sleep variability) dimensions may be more impactful in regulating emotion for the long-term. These nuanced findings highlight the value of investigating multiple dimensions of sleep and their associations with mood during early adolescence. Continued examination would be informative for elucidating the key dynamic process of how multidimensional perspectives of sleep contributes to adolescent emotional health.

Although advancing research on adolescent sleep and emotional health, this study is not without limitations. First, this study focuses on early adolescence. Sleep and emotional problems tend to co-occur during adolescence, especially after entering puberty (Tarokh et al., 2016). As such, the associations between sleep and mood may be different at late adolescence. More research is needed to examine the dynamic interplay between multiple dimensions of sleep and mood among older adolescents. Related to this, the present study focused only on age, not pubertal status, when examining the longitudinal bidirectional associations between sleep and mood. Previous research has shown that pubertal status, beyond chronological age, is linked to poorer sleep quality in adolescents (Kirshenbaum et al., 2023). Future studies should collect data on both age and pubertal status to separate their distinct effects and more accurately examine the differential associations between sleep and mood at specific developmental stages (e.g., early adolescence). Second, chronotype may be another factor that contributes to adolescents' actual sleep. Future studies should consider accounting for chronotype in evaluating the dynamic linkages between multiple dimensions of sleep and mood. Moreover, it is worth noting that for the daily bidirectional associations between sleep and mood, the time lag is shorter for the link from sleep to mood (i.e., previous-night sleep to mood) than from mood to sleep (previous-day mood to sleep). It would be informative for future research to use novel approaches (e.g., DSEM for diary data with temporal misalignment; Luo & Hu, 2024) to model the dynamic associations between daily mood and nightly sleep. Additionally, this study includes self-reported sleep data collected in a naturalistic setting; the 7-day dairy data of sleep also limited the examination of sleep variability beyond weekday versus weekend differences. Continued work investigating objectively measured (e.g., via actigraphy) or experimentally manipulated sleep (Ten Brink et al., 2022), and more daily assessments (e.g., 14–21 days) of sleep may help disentangle the associations between multiple assessments of sleep and adolescent mood. Lastly, the limited representativeness of the sample (i.e., from a county in Eastern China) may preclude the generalizability of the findings. Future studies sampling a larger group of geographically representative adolescents would be informative.

Conclusion

Despite both empirical findings and systematic reviews establishing reciprocal associations between sleep and mood, they are primarily limited to a few sleep indicators (e.g., duration, quality). The associations between other aspects of sleep and mood remains unclear. As previous studies have often focused on late adolescence to examine the links between sleep and mood, it is less clear how this interplay unfolds over the longer-term developmental processes during early adolescence, an important developmental transition stage during which children experience rapid biobehavioral and emotional changes. This study addressed these gaps by examining the day-to-day links between multiple dimensions of sleep (e.g., quantity, quality, continuity) and mood, as well as the longer-term associations between the stability and variability of sleep and mood during early adolescence. The data revealed both bidirectional and unidirectional within-person effects depending on specific sleep parameters, suggesting differential associations between multiple sleep indicators and mood on a daily basis. Findings also revealed longer-term, unidirectional links from average sleep disturbance to mood, and that greater variability in sleep quality was associated with higher negative mood one year later. These findings underscore the importance of understanding the complex interplay between sleep and mood by examining the directionality of and differential effects for the daily and longer-term associations between multiple dimensions of sleep and mood among early adolescents.

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Authors' Contributions M.X. conceived of the study, reviewed the literature, and drafted the manuscript; Y.Z. performed the statistical analyses, drafted the methods section, and presented the results; W.W. helped to interpret the data and edit the manuscript; H.C. participated in the interpretation of the data and editing the manuscript; D.L. designed and supervised the original data collection and edited the manuscript. All authors read and approved the final manuscript.

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Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

Ethical Approval The study procedures were approved by Beijing Normal University Institutional Review Board. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee.

Informed Consent Informed consent was obtained from primary caregivers of participating children and adolescents. Informal assent was obtained from children and adolescents.

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