

Weekly Exercise Dose Modifies the Association Between Bedtime Smartphone Use and Sleep Quality in University Students: A Multi- University Cross-Sectional Study

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Abstract

Background

Bedtime smartphone use, physical activity, sleep, and psychological well-being are closely intertwined in university students. Whether weekly exercise dose modifies the bedtime smartphone use–sleep quality association, and how sleep quality within this behavioral context relates to anxiety and depressive symptoms, remains unclear.

Methods

Cross-sectional questionnaire data from 4,730 Chinese university students were analyzed. Self-reported measures included bedtime smartphone use, exercise frequency, duration and intensity, chronotype, sleep quality, anxiety, and depressive symptoms. The principal multivariable linear model tested the bedtime smartphone use $\times$ constructed exercise-dose interaction for Pittsburgh Sleep Quality Index (PSQI) score with Benjamini–Hochberg false-discovery-rate correction. Secondary models quantified associations with anxiety and depressive symptoms and cross-sectional indirect associations through PSQI; exercise-dose decomposition was exploratory.

Results

The bedtime smartphone use $\times$ exercise-dose interaction was positive and statistically significant (standardized $\beta = 0.043$, $q = 0.011$) but small. The estimated smartphone-use slope for PSQI changed from $\beta = -0.016$ at -1 SD of exercise dose to $\beta = 0.027$ at the mean and $\beta = 0.070$ at $+1$ SD. Poorer sleep quality was strongly associated with anxiety ($\beta = 0.534$) and depressive symptoms ($\beta = 0.424$), whereas bedtime smartphone use was not independently associated with either psychological outcome after adjustment. Bootstrapped cross-sectional indirect associations through PSQI were statistically detectable but small (0.017 and 0.014, respectively). In the exploratory mathematical decomposition, frequency received the largest share (64%), followed by duration (28%) and intensity (8%).

Conclusion

The cross-sectional association between bedtime smartphone use and poorer sleep quality became more positive as weekly exercise dose increased, although the effect was modest. Sleep quality was the dominant correlate of anxiety and depressive symptom burden in the fitted models, whereas the indirect smartphone–psychological associations through PSQI were small. These findings support an integrated behavioral–sleep–psychological health interpretation but do not establish causal mediation or justify changing exercise recommendations.

1. Introduction

Sleep quality is central to health and functioning during the university years. Poor or insufficient sleep has been associated with worse academic performance and poorer psychological well-being, while anxiety and sleep-related behaviors are closely linked in college populations (Creswell et al., 2023; Peng et al., 2025; Yeo et al., 2023). Bedtime digital media use and physical activity are two common, modifiable behaviors that occur within the same daily routine. Considering them jointly may therefore help identify heterogeneity in sleep-related vulnerability that is not visible when each behavior is examined in isolation, while also clarifying how sleep quality relates to psychological symptom burden.

Bedtime smartphone use is especially relevant because the exposure occurs close to the intended sleep period. Earlier systematic-review evidence in school-aged children and adolescents also reported associations between screen time and sleep outcomes (Hale & Guan, 2015). In 122,058 adults, electronic screen use before bed was associated with later sleep timing, shorter sleep duration, and a higher prevalence of poor self-reported sleep quality, with stronger associations among participants with later chronotypes (Zhong et al., 2025). A meta-analysis of 55 studies involving 41,716 participants likewise found an overall association between electronic media use and poorer sleep, although effect sizes varied across media types and populations (Han et al., 2024). Recent population evidence has also linked bedtime smartphone use with anxiety symptoms (Tian et al., 2025). Together, these findings suggest that bedtime digital exposure may be relevant not only to sleep but also to broader psychological health, while its observed associations may depend on behavioral and circadian context.

Physical activity is generally associated with better sleep, but the exercise–sleep relationship varies with dose, timing, intensity, and recovery. Meta-analyses and intervention studies support overall sleep benefits of regular physical activity (De Nys et al., 2022; Dolezal et al., 2017; King et al., 1997; Kredlow et al., 2015; Siu et al., 2021; Zhou et al., 2025). At the same time, a device-based study of 14,689 physically active adults across more than four million person-nights found less favorable subsequent sleep when later or more strenuous exercise ended close to sleep onset (Leota et al., 2025). Meta-analytic evidence on evening high-intensity exercise also identifies proximity to bedtime as an important boundary condition (Frimpong et al., 2021). Thus, exercise dose may index behavioral context that changes the observed relationship between another bedtime exposure and sleep, even when exercise is beneficial on average.

Previous research in Chinese university students has shown joint associations of physical activity and smartphone use with sleep quality (Zhai et al., 2020), and a recent study reported that physical exercise moderated the association between smartphone addiction and sleep quality (Zhu et al., 2024). However, problematic or overall smartphone use is conceptually different from bedtime-specific exposure, and less is known about whether the bedtime smartphone–sleep association varies across a continuous weekly exercise-dose context while anxiety and depressive symptoms are evaluated in the same analytic framework. We therefore designated the bedtime smartphone use $\times$ exercise-dose interaction for PSQI as the principal analysis. Secondary analyses quantified how strongly sleep quality and the measured

behavioral context were associated with anxiety and depressive symptoms, estimated cross-sectional indirect associations through PSQI, and tested whether chronotype further modified the principal pattern. Finally, an exploratory mathematical decomposition described how frequency, duration, and intensity contributed to the constructed exercise-dose metric. This hierarchy preserves a focused sleep-related primary question while explicitly situating it within a broader behavioral–psychological health context.

2. Materials and methods

2.1 Transparency, reporting, and ethics

2.1.1 Preregistration

This cross-sectional study was not preregistered. Consequently, the labels principal, secondary, and exploratory describe the hierarchy of the present report rather than a prospectively registered analysis plan. The bedtime smartphone use $\times$ exercise-dose interaction for PSQI is treated as the principal inferential target. Models of anxiety and depressive symptoms, the cross-sectional indirect-association models, and the chronotype higher-order interaction are treated as secondary; the dose-component decomposition is treated as exploratory. This distinction is used to preserve the central sleep-related question while limiting overinterpretation of psychological, higher-order, and component analyses that are more susceptible to multiplicity or data-dependent refinement.

2.1.2 Data, materials, and code

The analyses used participant-level questionnaire data collected for this project. Participant-level data are not publicly posted because access is governed by participant consent and ethics requirements. De-identified data may be considered for academic use under an appropriate data-use agreement and ethics approval. The public analysis repository documents the model and figure-generation workflow so that the reported transformations and analytic sequence can be inspected without releasing identifiable participant data.

2.1.3 Reporting framework

Reporting follows STROBE guidance for cross-sectional studies. We report the sampling structure, exclusion sequence, exposure and outcome recall windows, variable definitions, analysis hierarchy, multiplicity control, and sensitivity analyses. Throughout the manuscript, “association” refers to a cross-sectional statistical relationship, “interaction” refers to statistical effect modification in the fitted model, and “indirect association” refers to a product-of-coefficients path estimate; none of these terms is used to imply temporal or causal effects.

2.1.4 Ethics

The study protocol was reviewed and approved by the Ethics Committee of West China Hospital, Sichuan University (Approval No. 2022(830)). All participants provided written informed consent before completing the questionnaire, and the study was conducted in accordance with the Declaration of Helsinki.

2.2 Study design and setting

This multi-university cross-sectional survey was conducted from March 5 to March 30, 2023, during a non-examination period. Recruitment was coordinated through seven named university sites in mainland China; the source dataset also retained a residual “other institutions” category, which is reported separately in Table 1. Each participant completed the questionnaire once. Bedtime smartphone use and exercise behavior referred to the preceding week, whereas the PSQI retained its standard past-month recall frame. Recruitment was convenience-based rather than probability-based, so survey weights were not available. The primary models adjusted for institution and used heteroskedasticity-robust standard errors; institution-clustered standard errors were examined only as a robustness check because the number of institutional clusters was limited.

2.3 Participant selection and quality control

The flowchart begins with the 5,008 records remaining after platform-level duplicate and blank removal, because the pre-cleaning submission total was not used in the analytic flow. Sequential exclusions were completion time < 240 s ($n = 118$), reported nighttime sleep duration > 24 h ($n = 124$), and single-item response time > 3,000 s ($n = 36$), yielding 4,730 participants.

After platform-level removal of duplicate and blank submissions, 5,008 records entered quality control. We then applied three sequential quality-control rules: 118 responses with total completion time < 240 s were excluded, leaving 4,890 records; 124 responses reporting nighttime sleep duration > 24 h were excluded, leaving 4,766; and 36 responses with a single-item response time > 3,000 s were excluded, leaving 4,730 participants for analysis (Fig. 1). These rules were based on implausible or interrupted questionnaire completion and were applied before the reported regression analyses. They did not select participants according to the direction or statistical significance of the bedtime smartphone, exercise, or PSQI associations.

2.4 Data processing and psychometric assessment

Before modeling, variables were checked for missingness, range violations, and extreme values. All variables used in the reported models were complete after quality control (0% missing), so the analyses used complete cases and no imputation. Continuous values beyond ± 3 SD of the sample distribution were Winsorized according to the existing analysis workflow before standardized variables and interaction terms were generated. Internal consistency of the psychometric scales was summarized using Cronbach's α . Confirmatory factor analysis (CFA) was retained only as an ancillary measurement diagnostic; because the global fit indices were limited, the CFA was not used to claim strong construct validity and did not determine inclusion or exclusion of participants.

2.5 Measures

2.5.1 Demographic, academic, and bedtime smartphone variables

The questionnaire recorded sex, academic major, institution, degree program, perceived family economic status, interpersonal relationship quality, academic stress, and average daily study time. The multivariable adjustment set comprised age, sex, degree program, institution, perceived economic status, interpersonal relationship quality, academic stress, and daily study time, matching the covariates used in the study workflow. Bedtime smartphone exposure was defined as the participant's reported average duration of smartphone use per night before sleep during the preceding week. Responses were collected in ordered duration categories (Table 1) and entered using the numeric score implemented in the analysis workflow; the resulting standardized coefficient should therefore be interpreted as a change across the distribution of the self-reported bedtime-use score, not as a device-measured change in exact minutes.

2.5.2 Sleep quality

Sleep quality was measured with the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989). Its 19 self-reported items contribute to seven domains: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction. The standard recall period is the previous month. Global scores range from 0 to 21, with higher scores indicating poorer sleep quality; a score > 5 is commonly used as a screening threshold for clinically relevant sleep disturbance. We used the continuous global PSQI score as the primary outcome because continuous modeling preserves information across the score range and avoids introducing an additional dichotomization threshold into the interaction analysis.

2.5.3 Chronotype

Chronotype was assessed with the Morningness–Eveningness Questionnaire (MEQ) (Horne & Ostberg, 1976). The MEQ captures preferred timing of activity, alertness, and sleep–wake behavior across the morningness–eveningness continuum. Higher scores indicate greater morningness and lower scores greater eveningness. MEQ was modeled continuously in the interaction analysis. For visualization only, lower and higher MEQ values were used to display fitted curves; those curves were not treated as evidence of categorical chronotype subgroups unless supported by the formal higher-order interaction.

2.5.4 Depressive symptoms

Depressive symptoms were assessed with the 20-item Zung Self-Rating Depression Scale (SDS) (Zung, 1965). Each item is rated on a 4-point response scale, and higher total scores indicate greater depressive symptom burden. SDS was analyzed as a continuous secondary outcome. The analysis therefore estimates differences across the observed symptom continuum and does not classify participants as having or not having a depressive disorder.

2.5.5 Anxiety symptoms

Anxiety symptoms were assessed with the 20-item Zung Self-Rating Anxiety Scale (SAS) (Zung, 1971). Items are rated on a 4-point scale; the conventional index score is obtained by multiplying the raw total by 1.25, with higher values indicating greater anxiety symptom burden. SAS was analyzed as a continuous secondary outcome, so the reported coefficients refer to symptom severity rather than a clinical diagnosis.

2.5.6 Exercise frequency, duration, intensity, and weekly dose

Participants reported exercise frequency (EF), duration (ED), and intensity (EI) for the preceding week. EF categories were none, once, twice, or ≥ 3 sessions/week; ED categories were < 30 , 30–60, 60–120, or > 120 min/session; and EI categories were low, moderate, or high. The existing analysis workflow mapped these responses to prespecified numeric anchors spanning 0–3.5 sessions/week, 15–150 min/session, and 3.3–8.0 metabolic equivalents (METs). A constructed weekly exercise-dose metric was then calculated as MET value $\times$ minutes/session $\times$ sessions/week and expressed in MET-min/week equivalents. Because this metric is mathematically derived from self-reported categorical components, it is treated as an exposure summary rather than as a directly measured physiological dose. EF, ED, EI, and a standardized additive index were examined separately in sensitivity analyses.

2.6 Statistical analysis

The analysis was organized around one principal question: whether weekly exercise dose statistically modified the cross-sectional association between bedtime smartphone use and PSQI. A secondary psychological-health layer then quantified how sleep quality and the measured behavioral context were associated with anxiety and depressive symptom burden and estimated cross-sectional indirect associations through PSQI. Ordinary least-squares (OLS) regression, interaction analyses, and bootstrapped path models were conducted in SPSS version 27 with PROCESS version 3.5; figure generation and dose-decomposition steps were implemented in the study workflow. Continuous predictors used in interaction terms were mean-centered and z-standardized before product terms were formed. Standardized coefficients (β) are reported to place associations on a common scale. All tests were two-sided.

The principal PSQI model included bedtime smartphone use, weekly exercise dose, and MEQ as continuous predictors; all lower-order two-way interactions among these variables; the bedtime smartphone use $\times$ exercise dose $\times$ MEQ interaction; and the adjustment covariates age, sex, degree program, institution, perceived economic status, interpersonal relationship quality, academic stress, and daily study time. The coefficient for bedtime smartphone use $\times$ exercise dose was the principal estimand because it directly tests whether the fitted smartphone–PSQI slope changes with weekly exercise dose. The three-way interaction with MEQ was a secondary test of whether that effect-modification pattern

itself varied across chronotype. Heteroskedasticity-robust standard errors were used for the principal model.

When the principal bedtime smartphone use $\times$ exercise-dose interaction was supported, we characterized its magnitude with simple slopes for bedtime smartphone use at -1 SD, the mean, and $+1$ SD of standardized exercise dose. We also calculated model-based PSQI contrasts between higher ($+1$ SD) and lower (-1 SD) bedtime smartphone-use values across the plotted exercise-dose range. These conditional estimates were used to show the direction and scale of the interaction; they were not interpreted as diagnostic thresholds or as evidence that a specific exercise dose is harmful.

Secondary models for SAS and SDS included PSQI, bedtime smartphone use, exercise-related terms, MEQ, and the same adjustment covariates. These models were used to characterize psychological symptom burden within the same behavioral–sleep context, with particular attention to the relative magnitudes of the associations with PSQI and bedtime smartphone use. They were not intended to establish a causal chain from smartphone use to psychological symptoms or to diagnose anxiety or depressive disorders.

2.6.1 Cross-sectional indirect-association models

Separate path models used bedtime smartphone use as the exposure variable, PSQI as the intermediate variable, and SAS or SDS as the psychological outcome. Each model adjusted for the same covariate set used in the corresponding regression analyses. The indirect association was calculated as the product of the bedtime smartphone use $\rightarrow$ PSQI coefficient and the PSQI $\rightarrow$ outcome coefficient. Uncertainty was estimated with 5,000 bias-corrected bootstrap samples and 95% confidence intervals. Total, direct, and indirect associations were reported. Because exposure, intermediate variable, and outcome were measured in the same survey, the path ordering is a statistical decomposition only; it does not establish temporal ordering, causal mediation, or the fraction of a causal effect transmitted through sleep.

2.6.2 Multiplicity, sensitivity, and exploratory analyses

To address multiplicity, Benjamini–Hochberg false-discovery-rate (FDR) correction was applied within outcome families for PSQI, SAS, and SDS; $q < 0.05$ was used as the threshold for statistical significance. Effect estimates and confidence intervals were interpreted together with q values so that statistical significance was not used as a substitute for effect magnitude. Sensitivity analyses examined exercise frequency, duration, and intensity separately and compared the multiplicative MET-min/week dose with a standardized additive index. Institution-clustered standard errors were also examined as a robustness check. Finally, a Shapley-style decomposition implemented in the study workflow apportioned the constructed multiplicative dose across frequency, duration, and intensity. Because the decomposition operates on the same components used to create the composite, its percentages are mathematical shares of that composite—not regression coefficients, causal effects, or estimates of biological importance—and may depend on component coding, distributions, and the dose formula.

3. Results

Results are presented in the same order as the analysis hierarchy: participant characteristics, the principal PSQI effect-modification analysis, psychological symptom models and cross-sectional indirect associations, and the exploratory exercise-dose decomposition. This ordering retains sleep quality as the primary outcome while making the psychological-health relevance of the observed behavioral context explicit. All estimates derive from a one-time survey and are interpreted as cross-sectional associations.

3.1 Participant characteristics and key exposure distributions

The final analytic sample contained 4,730 university students (Table 1): 3,067 women (64.8%) and 1,663 men (35.2%). Most participants were undergraduates (88.9%), but master's, PhD, combined MD–PhD, and direct-PhD students were also represented; the cohort is therefore described as university students rather than undergraduates. Bedtime smartphone exposure was common: 42.5% reported > 1 h of smartphone use before sleep and another 30.0% reported 0.5–1 h. Exercise frequency varied substantially: 16.0% reported no weekly exercise, whereas 34.8% reported ≥ 3 sessions/week. All variables used in the reported models were complete after quality control.

Table 1
Participant characteristics (n = 4,730)

Variable	Category	n	%
Sex	Male	1663	35.2
	Female	3067	64.8
Academic major	Science & Engineering	1015	21.5
	Literature & History	649	13.7
	Agriculture	10	0.2
	Politics & Law	89	1.9
	Arts	37	0.8
	Medicine	2930	61.9
Degree program	Undergraduate	4206	88.9
	Master	392	8.3
	PhD	23	0.5
	MD-PhD combined	14	0.3
	Direct-PhD	95	2.0
University	North Sichuan Medical College	1773	37.5
	Sichuan University	1450	30.7
	Southwest Jiaotong University	752	15.9
	University of Electronic Science & Technology of China	46	1.0
	Chengdu University of Traditional Chinese Medicine	20	0.4
	Southwest Medical University	19	0.4
	Chengdu University	13	0.3
	Others	657	13.9
Bedtime smartphone use (min/night)	< 10 min	60	1.3
	~ 10 min	279	5.9
	~ 30 min	962	20.3
	0.5–1 h	1417	30.0

Variable	Category	n	%
	> 1 h	2012	42.5
Academic stress	None	312	6.6
	Mild	1267	26.8
	Moderate	1796	38.0
	Severe	1178	24.9
	Very severe	177	3.7
Daily study time	< 2 h	164	3.5
	2–4 h	319	6.7
	4–8 h	1427	30.2
	8–12 h	1123	23.7
	> 12 h	1697	35.9
Interpersonal relationships	Very good	410	8.7
	Good	2550	53.9
	Average	1653	34.9
	Poor	99	2.1
	Very poor	18	0.4
Family economic status	Affluent	43	0.9
	Well-off	1202	25.4
	Average	2703	57.1
	Difficult	623	13.2
	Very difficult	159	3.4
Exercise intensity	Low	2328	49.2
	Moderate	2159	45.6
	High	243	5.1
Exercise duration	< 30 min	1427	30.2
	30–60 min	1773	37.5
	60–120 min	912	19.3

Variable	Category	n	%
Exercise frequency	> 120 min	618	13.1
	None	755	16.0
	Once	1018	21.5
	Twice	1310	27.7
	≥ 3 times	1647	34.8

The constructed weekly exercise-dose variable ranged from 0 to > 1,700 MET-min/week and was right-skewed. The continuous dose score was z-standardized for the interaction models. For sensitivity analysis, frequency, duration, and intensity were also z-standardized individually and summed to create an additive exercise index; this alternative index was used to assess whether the main pattern depended on the multiplicative MET-min/week construction.

Internal consistency was higher for the PSQI (Cronbach's $\alpha = 0.81$) and SAS ($\alpha = 0.72$) than for the MEQ ($\alpha = 0.64$) and SDS ($\alpha = 0.62$). The ancillary CFA showed limited global fit ($\chi^2(2271) = 38,699.6$, CFI = 0.636, TLI = 0.624, RMSEA = 0.058). These diagnostics indicate that measurement quality was not equally strong across scales; accordingly, the CFA is treated as a psychometric limitation rather than confirmatory evidence of a common factor structure.

3.2 Primary sleep-quality associations and effect modification

In the adjusted PSQI model, greater morningness was associated with better sleep quality (standardized $\beta = -0.138$, 95% CI - 0.168 to - 0.109, $q < 0.001$). The principal bedtime smartphone use $\times$ exercise-dose interaction was positive and remained statistically significant after FDR correction ($\beta = 0.043$, $q = 0.011$). A positive interaction coefficient means that the fitted association between bedtime smartphone use and higher PSQI scores became more positive as weekly exercise dose increased. The standardized interaction was small, so the main result is evidence of heterogeneity in the association rather than a large shift in sleep quality. Other interaction terms did not remain statistically significant after correction. Poorer interpersonal functioning was also associated with poorer sleep quality (for example, "Average" vs "Very good": $\beta = 0.372$, $q < 0.001$).

In the secondary psychological models, greater morningness was associated with lower anxiety ($\beta = -0.212$, $q < 0.001$) and lower depressive symptom scores ($\beta = -0.249$, $q < 0.001$). The largest psychological-outcome coefficients were observed for PSQI: poorer sleep quality was associated with higher anxiety ($\beta = 0.534$, $q < 0.001$) and higher depressive symptom burden ($\beta = 0.424$, $q < 0.001$). In contrast, bedtime smartphone use did not show an independently significant association with either psychological outcome after adjustment, and the psychological-outcome interaction terms were not significant after multiplicity correction. Thus, within the fitted models, sleep quality rather than bedtime

smartphone use itself showed the strongest association with psychological symptom burden. These adjusted coefficients are shown in Fig. 2.

Forest plots show standardized regression coefficients with 95% confidence intervals. The upper row presents models using the multiplicative weekly exercise-dose measure (MET-min/week); the lower row presents sensitivity models using the standardized additive exercise index. Positive coefficients indicate poorer sleep for PSQI and greater symptom burden for SAS or SDS. FDR-adjusted results are reported in Supplementary Table S2.

Predicted marginal effects from the adjusted PSQI model are shown with 95% confidence intervals. (A) Estimated standardized bedtime smartphone use–PSQI slope across exercise dose. (B) Predicted PSQI contrast between higher (+ 1 SD) and lower (– 1 SD) bedtime smartphone use across exercise dose at lower MEQ (greater eveningness) and higher MEQ (greater morningness). (C–D) Predicted PSQI across exercise dose at lower and higher MEQ values, stratified by bedtime smartphone use. The chronotype-stratified displays are descriptive because the formal three-way interaction was not significant after correction.

Simple-slope estimates clarified the direction and magnitude of the principal interaction (Fig. 3). At – 1 SD of exercise dose, the standardized bedtime smartphone use–PSQI slope was close to zero and slightly negative ($\beta = -0.016$). At the mean exercise dose, the slope was $\beta = 0.027$; at + 1 SD, it was $\beta = 0.070$. Thus, the fitted association changed gradually from essentially null at lower exercise dose to a modest positive association at higher dose. Across the plotted dose range, the model-predicted PSQI contrast between higher (+ 1 SD) and lower (– 1 SD) bedtime smartphone use increased from approximately zero to about + 0.21 PSQI units. Curves appeared more divergent at lower MEQ values (greater eveningness), but the formal higher-order interaction was not significant after correction, so the chronotype-stratified pattern is descriptive.

3.3 Psychological symptom burden and cross-sectional indirect associations

Because PSQI showed the strongest associations with both psychological outcomes, we next examined whether the statistical linkage between bedtime smartphone use and psychological symptom burden contained a measurable indirect component through PSQI. The total associations of bedtime smartphone use with anxiety and depressive symptoms were small and not statistically significant, whereas the product-of-coefficients paths through PSQI were statistically detectable. These results characterize cross-sectional covariance among bedtime smartphone use, sleep quality, and psychological symptoms; they do not establish that smartphone use preceded poorer sleep or that poorer sleep subsequently caused anxiety or depressive symptoms. The corresponding cross-sectional path estimates are summarized in Fig. 4.

Standardized path models summarize cross-sectional associations linking bedtime smartphone use, PSQI, and psychological symptoms. For anxiety, bedtime smartphone use→PSQI was $a = 0.031$ ($p =$

0.035), PSQI→SAS was $b = 0.539$ ($p < 0.001$), the bootstrapped indirect association was 0.017, and the direct association was $c' = 0.011$ ($p = 0.33$). For depressive symptoms, the corresponding bootstrapped indirect association was 0.014 and the direct association was $c' = 0.020$ ($p = 0.082$). These arrows represent statistical path ordering in a cross-sectional model and not temporal or causal mediation. Full estimates are reported in Supplementary Table S3.

Notes: Coefficients are standardized (β). * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns = not statistically significant.

For anxiety, bedtime smartphone use had a small positive association with PSQI ($\beta = 0.031$, $p = 0.035$), whereas PSQI had a much larger association with SAS ($\beta = 0.539$, $p < 0.001$). The standardized bootstrapped indirect association was 0.017. The direct bedtime smartphone use–SAS association was small and nonsignificant ($\beta = 0.011$, $p = 0.33$). The relative path magnitudes show that PSQI was much more strongly associated with anxiety than bedtime smartphone use was, but the cross-sectional design prevents interpreting PSQI as a causal mediator.

For depressive symptoms, the standardized bootstrapped indirect association through PSQI was 0.014, and the direct bedtime smartphone use–SDS association remained small ($\beta = 0.020$, $p = 0.082$). Because the total bedtime smartphone use–depression association was also small, the originally calculated proportion-mediated statistic is not emphasized as a substantive result. Full path estimates are provided in Supplementary Table S3, and Supplementary Table S4 summarizes the interpretive limits of cross-sectional indirect-effect analyses.

3.4 Exploratory decomposition of the exercise-dose metric

Exploratory apportionment of the constructed multiplicative exercise-dose metric (intensity $\times$ duration $\times$ frequency). Percentages are mathematical shares of the composite and should not be interpreted as causal effects, independent regression contributions, or biological importance of the individual exercise components.

Within the exploratory decomposition of the constructed exercise-dose metric, frequency received approximately 64% of the apportioned share, duration 28%, and intensity 8% (Fig. 5). The ordering was similar across the plotted dose range. These percentages describe how the coded multiplicative composite was mathematically apportioned; they do not show that frequency has a 64% biological effect on sleep, that frequency independently drives the smartphone–sleep interaction, or that exercise frequency should be increased or reduced.

4. Discussion

4.1 Principal findings and contribution

This study produced three complementary findings within one behavioral–sleep–psychological framework. First, the principal bedtime smartphone use $\times$ exercise-dose interaction for PSQI was

statistically significant but small: the fitted smartphone–PSQI association was essentially null at lower exercise dose and became more positive as dose increased, with an approximately 0.21-unit maximum predicted PSQI contrast. Second, sleep quality showed substantially larger associations with anxiety and depressive symptoms than bedtime smartphone use itself, whose adjusted direct associations with the psychological outcomes were small and nonsignificant. Third, the cross-sectional indirect products through PSQI were statistically detectable but modest. Taken together, the results support heterogeneity in the smartphone–sleep association and identify sleep quality as a prominent correlate of psychological symptom burden, without establishing a causal behavioral pathway. The exploratory dose decomposition remained descriptive of the constructed exercise metric rather than an estimate of biological importance.

4.2 Interpretation in relation to previous evidence

The findings refine, rather than replace, existing evidence on digital behavior and sleep. Previous studies show that pre-sleep electronic media use is associated with poorer sleep (Han et al., 2024; Zhong et al., 2025), and work in Chinese university students has reported joint associations of physical activity and smartphone use with sleep quality (Zhai et al., 2020). Zhu et al. (2024) further reported moderation by physical exercise in the association between smartphone addiction and sleep quality. Our study differs by focusing on bedtime-specific smartphone exposure rather than problematic smartphone use and by evaluating the interaction across a constructed continuous exercise-dose distribution while simultaneously characterizing anxiety and depressive symptom burden. The contribution is therefore not a claim that exercise is protective or harmful in this context, but evidence that the fitted bedtime smartphone–PSQI association was heterogeneous across exercise dose after adjustment for measured demographic and lifestyle covariates.

The interaction should not be interpreted as evidence that exercise is generally detrimental to sleep. Meta-analyses and trials show average sleep benefits of regular physical activity (Dolezal et al., 2017; Kredlow et al., 2015; Siu et al., 2021; Zhou et al., 2025). Our interaction instead asks whether the association of bedtime smartphone use with PSQI differs at different exercise-dose values. One possible explanation is that higher weekly dose partly marks unmeasured differences in exercise timing, strain, or recovery. Device-based evidence shows less favorable sleep when strenuous exercise ends close to sleep onset, whereas earlier completion attenuates that pattern (Leota et al., 2025); meta-analytic evidence similarly identifies timing as an important boundary condition (Frimpong et al., 2021). Because our questionnaire did not measure exercise timing or recovery, these mechanisms remain hypotheses and are not used to explain the observed interaction as if they had been tested.

The component decomposition answers a narrower mathematical question than the regression interaction. Frequency, duration, and intensity were first coded and multiplied to construct MET-min/week; the exploratory decomposition then allocated that constructed quantity back across its inputs. The 64% frequency share can therefore be influenced by coding ranges, the observed component distributions, and the multiplicative dose formula. It is neither an independent effect estimate nor

evidence that exercise frequency is biologically dominant. For this reason, the decomposition is used to describe the dose representation, not to motivate a frequency-specific intervention.

Chronotype was included as a plausible contextual modifier because circadian preference may influence both bedtime behavior and sleep timing. The fitted curves were more divergent among participants with greater eveningness, which is directionally consistent with previous work on later chronotype and bedtime screen exposure (Adan et al., 2012; Zhong et al., 2025). However, the formal bedtime smartphone use $\times$ exercise dose $\times$ MEQ interaction was not significant after multiplicity correction. The chronotype display is therefore descriptive and should not be interpreted as confirmed chronotype-specific effect modification.

4.3 Psychological relevance of sleep quality

The psychological analyses help place the primary sleep finding in a broader public-health context. Recent population research has reported an association between bedtime smartphone use and anxiety symptoms (Tian et al., 2025), and physical activity has also been examined as a contextual factor in sleep–psychological models among college students (Peng et al., 2025). In the present data, however, the adjusted direct associations of bedtime smartphone use with SAS and SDS were small and nonsignificant, whereas PSQI was strongly associated with anxiety ($\beta = 0.534$) and depressive symptoms ($\beta = 0.424$). This pattern argues against interpreting bedtime smartphone use as a direct psychological risk marker on the basis of these data alone; instead, sleep quality appears to be the more prominent cross-sectional correlate of symptom burden. The bootstrapped indirect products through PSQI were statistically detectable but modest. Because smartphone exposure, sleep quality, and psychological symptoms were measured concurrently, reverse directionality and common-cause confounding remain plausible, and the path models should be interpreted as statistical decompositions rather than evidence of mediation.

4.4 Strengths

The study has several strengths relevant to an observational behavioral-health analysis. The sample included 4,730 students from multiple university sources, providing substantial variation in bedtime smartphone use, exercise behavior, sleep quality, and psychological symptoms. The principal interaction was modeled continuously rather than by creating arbitrary high/low exposure groups, and its interpretation was supported by conditional slopes and predicted PSQI contrasts rather than p values alone. Anxiety and depressive symptoms were assessed in parallel, allowing the magnitude of their associations with sleep quality to be evaluated within the same adjusted framework. FDR correction addressed multiplicity within outcome families, sensitivity analyses compared alternative exercise representations, and the analysis hierarchy explicitly distinguished the principal interaction, secondary psychological and path analyses, and exploratory dose decomposition.

4.5 Practical interpretation

The findings do not support reducing exercise, lowering exercise frequency, or prescribing a specific exercise schedule. A defensible practical interpretation is more limited: bedtime smartphone behavior and exercise load may be worth considering together when sleep complaints are assessed, because their cross-sectional association with PSQI was not uniform across the exercise-dose distribution. In addition, the comparatively strong associations of PSQI with anxiety and depressive symptoms suggest that prominent sleep complaints in university students may warrant attention to concurrent psychological symptom burden, although the present study does not establish a screening rule or treatment pathway. General physical-activity recommendations should remain unchanged (World Health Organization, 2020), and minimizing unnecessary bedtime screen exposure remains a reasonable sleep-hygiene goal. The data do not identify a frequency-, chronotype-, or smartphone-based psychological intervention.

4.6 Limitations

Several limitations define the boundary of the conclusions. First, the cross-sectional design cannot establish temporal order and does not support a causal interpretation of either the interaction or the indirect-association models. This is particularly important for the psychological analyses because sleep quality, bedtime smartphone use, anxiety, and depressive symptoms may influence one another bidirectionally. Second, convenience recruitment through multiple university sources, including a residual “other institutions” category, limits population representativeness. Third, bedtime smartphone use, exercise behavior, sleep quality, and psychological symptoms were self-reported, creating potential recall, misclassification, and common-method error. Fourth, exposure windows were not aligned: smartphone use and exercise referred to the preceding week, whereas the standard PSQI refers to the preceding month. Fifth, exercise timing, modality, strain, recovery interval, caffeine intake, diet, and other potentially relevant confounders were not measured. Sixth, internal consistency was lower for MEQ and SDS, and the global CFA fit was limited. Seventh, the decomposition percentages are properties of a constructed dose metric and cannot be interpreted as independent causal contributions. Finally, because the study was not preregistered, the hierarchy used in this report should not be mistaken for prospective specification; secondary and exploratory findings require independent confirmation.

4.7 Future directions

Future studies should test the central interaction with stronger temporal and measurement resolution rather than simply repeat the same cross-sectional questionnaire in a larger sample. A longitudinal design combining device-recorded bedtime smartphone use with actigraphy or wearable-derived exercise volume, timing, and strain could align exposure windows with sleep measurement and distinguish within-person from between-person associations. Repeated assessment of anxiety and depressive symptoms would additionally allow investigators to determine whether changes in sleep temporally precede, follow, or co-occur with changes in psychological symptom burden. Independent replication should prespecify the bedtime smartphone use × exercise-dose interaction, the psychological outcome models, and the chronotype higher-order interaction. Experimental manipulation of bedtime

screen exposure or exercise timing would then be required before the observed heterogeneity could be interpreted as a modifiable causal process.

5. Conclusion

In this multi-university cross-sectional sample of 4,730 university students, the association between bedtime smartphone use and poorer sleep quality became more positive as weekly exercise dose increased, although both the standardized interaction and the predicted PSQI contrast were modest. Sleep quality showed substantially stronger associations with anxiety and depressive symptoms than bedtime smartphone use itself, while the cross-sectional indirect associations through PSQI were small. The exercise-component decomposition remained descriptive of the constructed dose and did not identify an independent frequency effect. Overall, the study supports a behavioral–sleep–psychological health framework in which the smartphone–sleep association varies across exercise context and sleep quality is closely linked to psychological symptom burden; longitudinal and device-based studies are needed to determine temporal and causal relationships.

Abbreviations

PSQI

Pittsburgh Sleep Quality Index

MEQ

Morningness-Eveningness Questionnaire

SAS

Zung Self-Rating Anxiety Scale

SDS

Zung Self-Rating Depression Scale

EF

exercise frequency

ED

exercise duration

EI

exercise intensity

OLS

ordinary least squares

FDR

false discovery rate

CI

confidence interval

SD

standard deviation

MET

metabolic equivalent of task.

Declarations

Ethical approval

The Ethics Committee of West China Hospital, Sichuan University approved the study (Approval No. 2022(830)).

Ethics approval and consent to participate

The study protocol was reviewed and approved by the Ethics Committee of West China Hospital, Sichuan University (Approval No. 2022(830)). Written informed consent to participate was obtained from all participants before they completed the questionnaire. The study was conducted in accordance with the Declaration of Helsinki.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests. The funder had no role in study design; data collection, analysis, or interpretation; manuscript preparation; or the decision to submit the work for publication.

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Author Contribution

W.L. performed data processing, formal analysis, visualization, and drafting of the manuscript. W.L. and K.L. contributed to methodology and software implementation. W.L., K.L., Y.C., and S.L. contributed to data collection and curation. C.Q. conceptualized and supervised the project. W.L., K.L., Y.C., S.L., J.L., and C.Q. critically revised the manuscript. All authors reviewed and approved the final manuscript.

Code availability

Analysis scripts and an annotated, de-identified workflow are available at <https://github.com/jacobliuweizhi/sleep-dose-interaction-pipeline>. The repository documents the analysis structure without releasing participant-level data. A versioned release will be archived upon publication.

Data availability

Individual-level data are not publicly available because of participant privacy and ethics restrictions. De-identified data may be provided for academic use under an appropriate data-use agreement and with approval from the Ethics Committee of West China Hospital, Sichuan University (Approval No. 2022(830)). Requests should be directed to the corresponding author (cqiu@scu.edu.cn).

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Figures

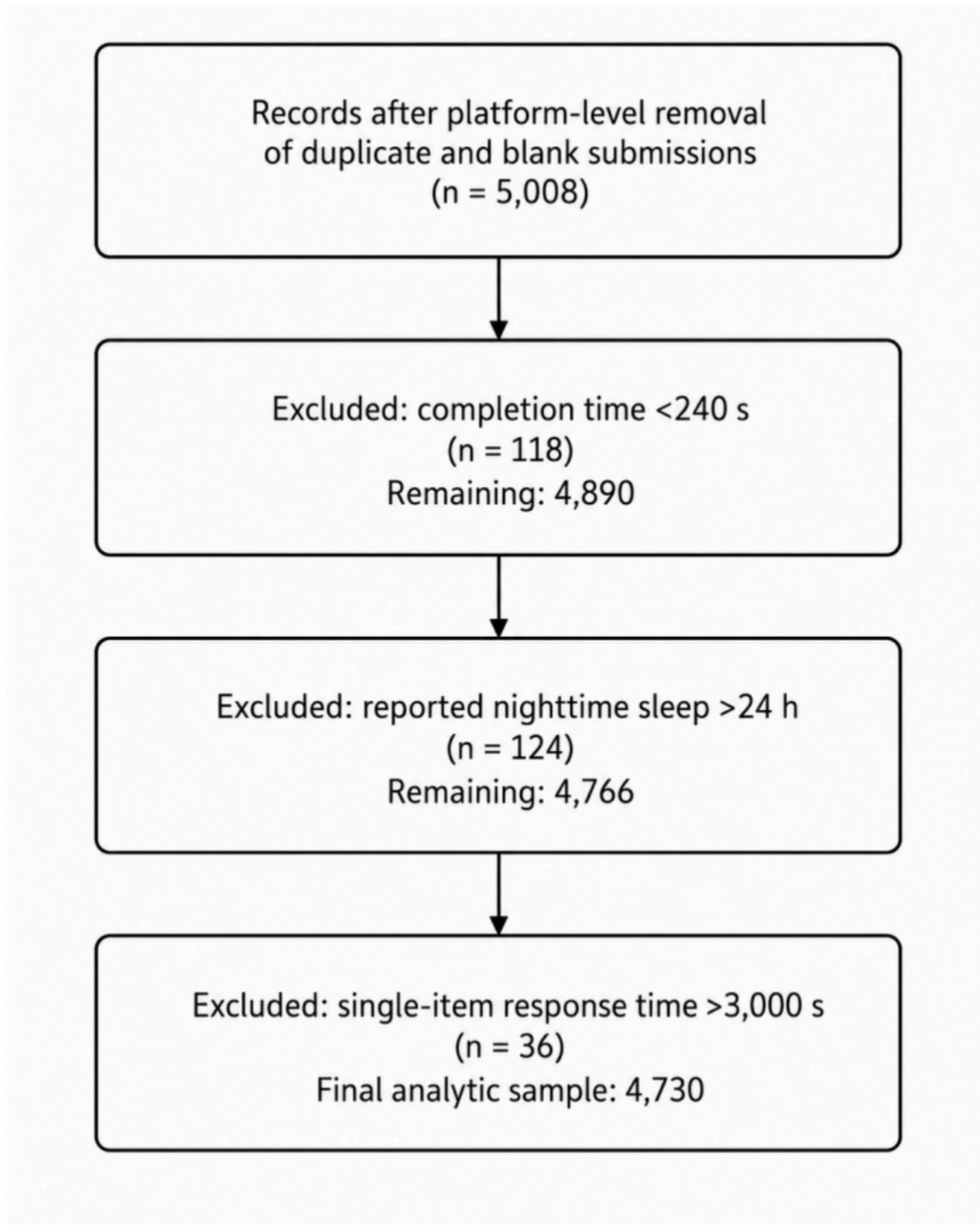


Figure 1

Participant selection and quality-control flowchart

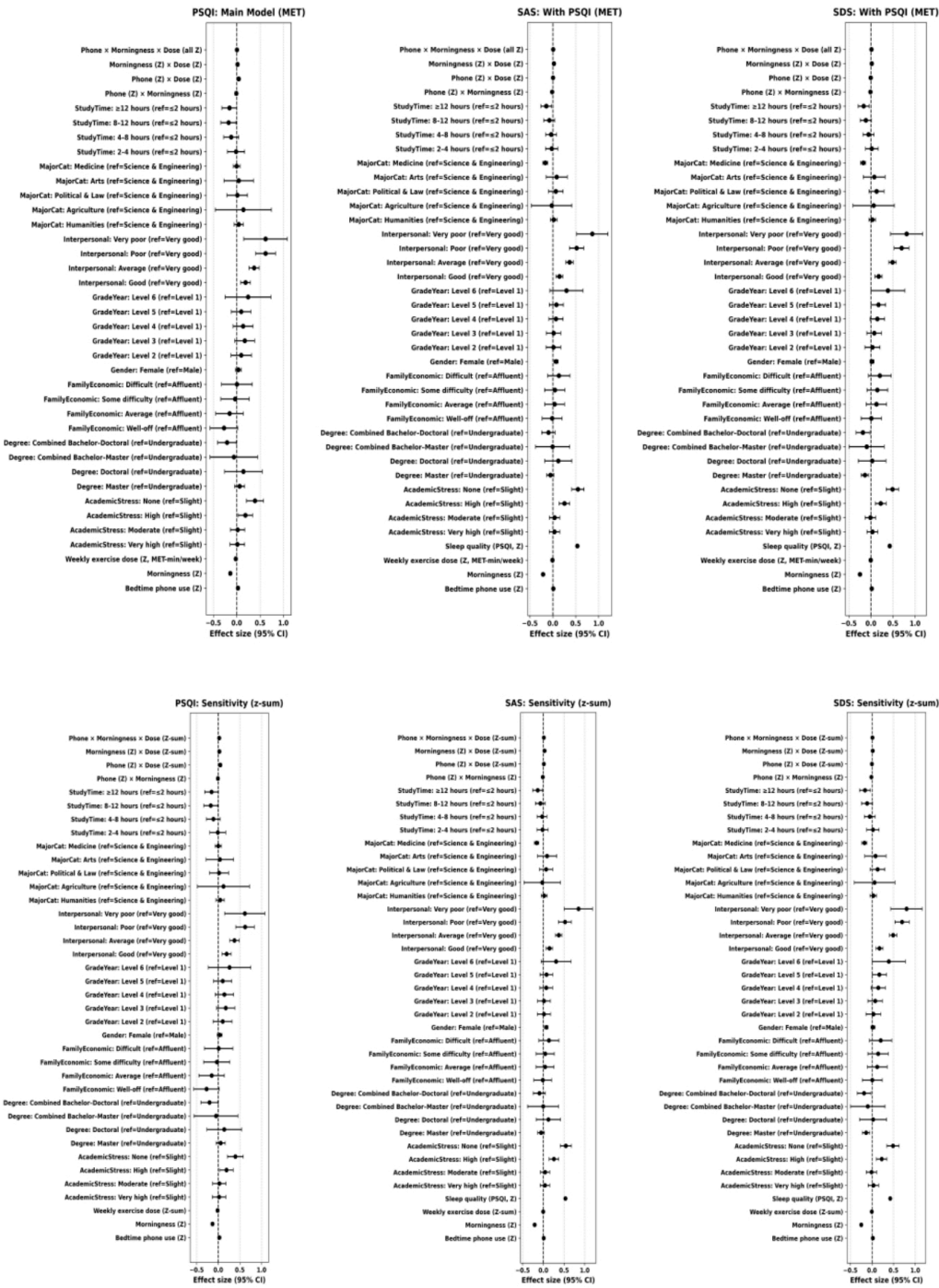


Figure 2

Adjusted associations with sleep quality, anxiety, and depressive symptoms

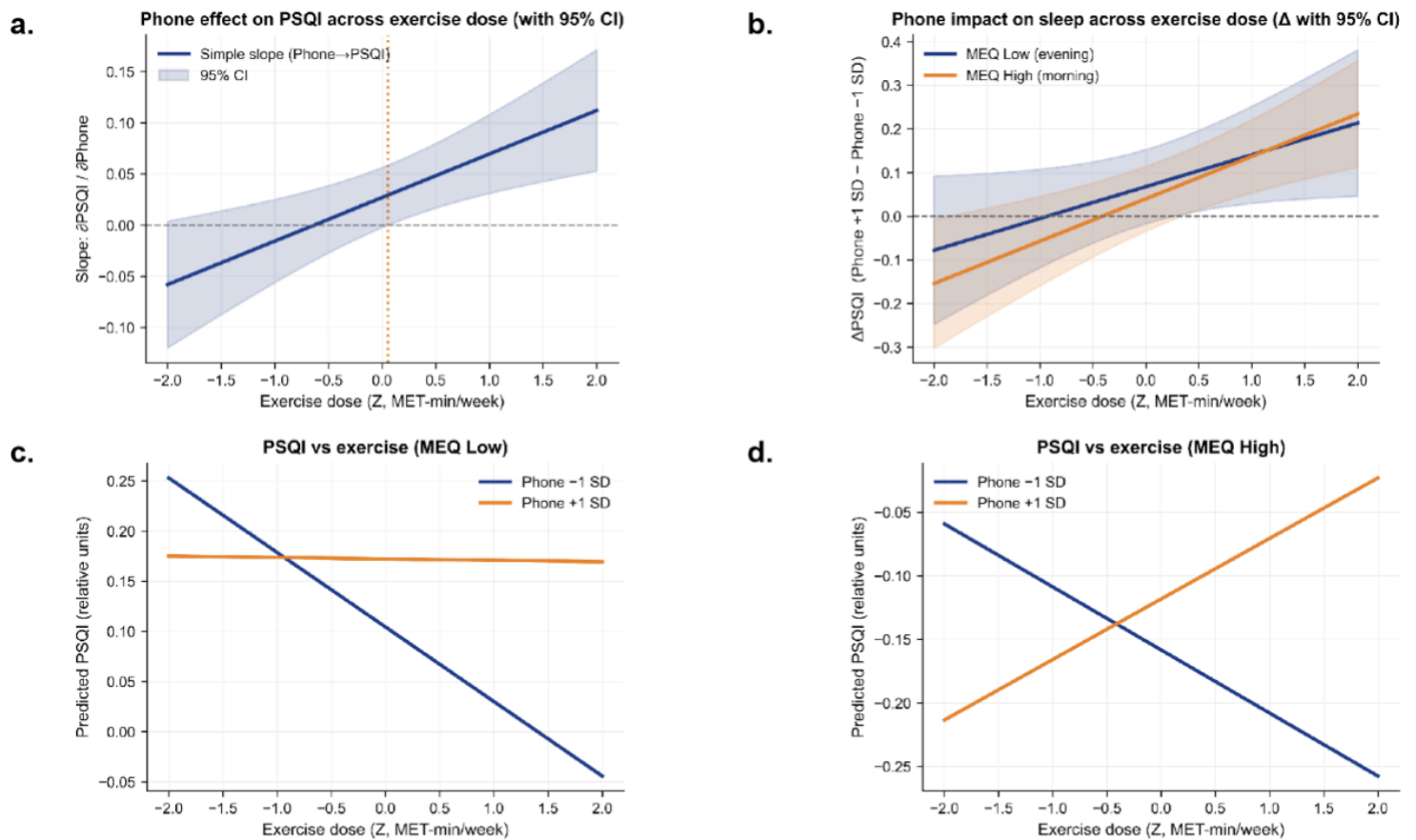


Figure 3

Conditional association between bedtime smartphone use and sleep quality across

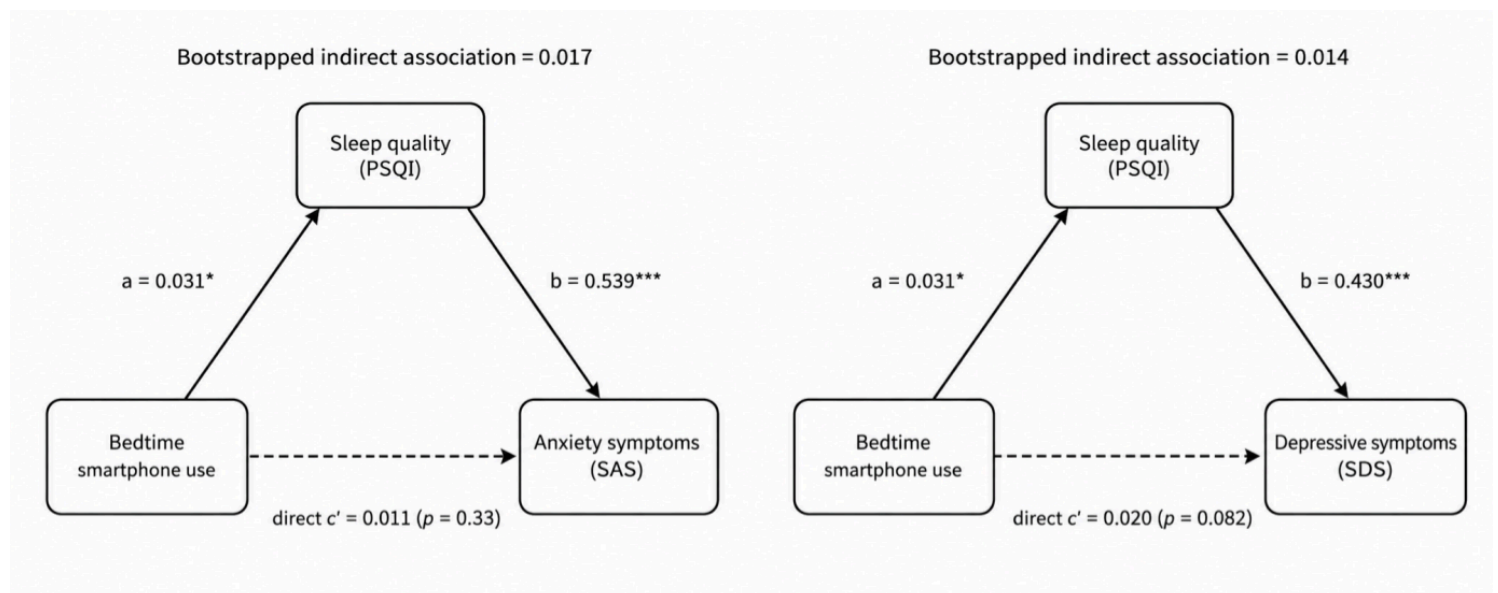


Figure 4

Cross-sectional path models linking bedtime smartphone use, sleep quality, and psychological symptoms

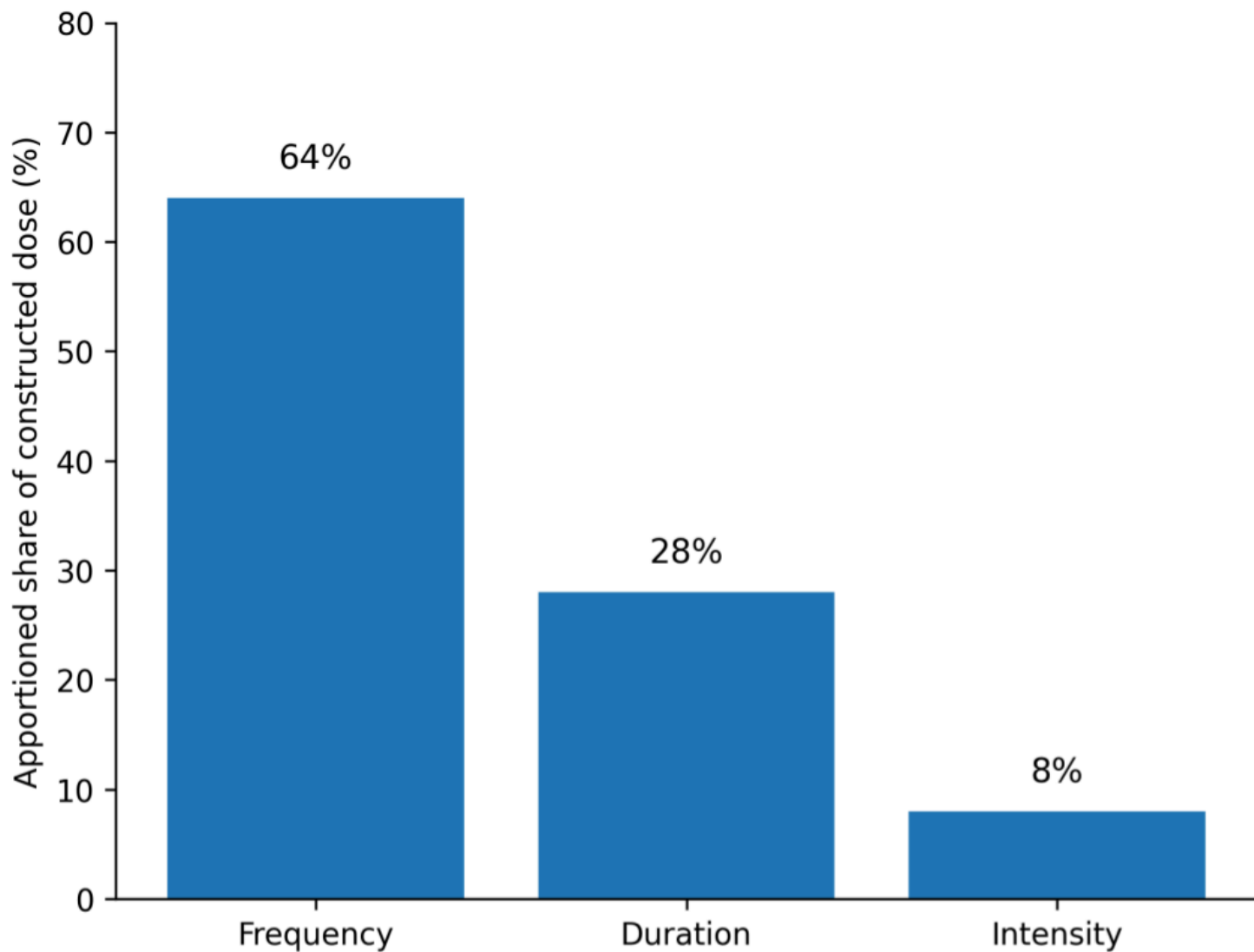


Figure 5

Exploratory decomposition of the constructed exercise-dose metric

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