Development and validation of a physical activity-sleep-academic performance model for students

Desarrollo y validación de un modelo de actividad física, sueño y rendimiento académico para estudiantes

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Abstract

Introduction: Student well-being is increasingly at risk due to sedentary behavior, sleep deprivation, and academic stress. These issues are interrelated and influenced by both personal habits and environmental contexts.
Objective: This study aimed to construct and validate a "Physical Activity–Sleep–Academic Performance" (P-S-A) health management model grounded in ecological systems theory.
Methodology: A mixed-methods design was applied. Data from 1,200 students aged 10–18 were collected using surveys, wearable devices, and contextual records. Structural Equation Modeling (SEM) assessed variable relationships, while qualitative interviews provided contextual insights.
Results: Physical activity significantly improved sleep quality ($\beta = 0.35$, $p < 0.001$), which enhanced academic performance ($\beta = 0.29$, $p < 0.001$). Physical activity also had a direct effect on academic outcomes ($\beta = 0.18$, $p < 0.01$). Family support ($\beta = 0.22$, $p < 0.01$) and school policies ($\beta = 0.19$, $p < 0.05$) moderated these effects. Model fit was strong (CFI = 0.92, TLI = 0.90, RMSEA = 0.07, SRMR = 0.06).
Discussion: The model underscores the interconnected roles of physical activity, sleep, and academic performance within a supportive environment. Qualitative findings highlighted the difficulty of balancing health and academic demands, alongside perceived benefits.
Conclusion: The validated P-S-A model offers a comprehensive framework aligned with initiatives like Healthy China 2030 and the Double Reduction Policy. It provides actionable guidance for educators, families, and policymakers. Future studies should address limitations such as cross-sectional design and self-report bias by employing longitudinal and objective methods.

Keywords

Physical activity; Sleep quality; Academic performance; Health management model; Education policies; Health education.

Resumen

Introducción: El bienestar estudiantil se ve cada vez más comprometido debido al sedentarismo, la falta de sueño y el estrés académico. Estos problemas están interrelacionados e influenciados tanto por los hábitos personales como por el contexto ambiental.
Objetivo: Este estudio buscó construir y validar un modelo de gestión de la salud "Actividad Física-Sueño-Rendimiento Académico" (P-S-A) basado en la teoría de sistemas ecológicos.
Metodología: Se aplicó un diseño de métodos mixtos. Se recopilaron datos de 1200 estudiantes de 10 a 18 años mediante encuestas, dispositivos portátiles y registros contextuales. El Modelo de Ecuaciones Estructurales (SEM) evaluó las relaciones entre variables, mientras que las entrevistas cualitativas proporcionaron información contextual.
Resultados: La actividad física mejoró significativamente la calidad del sueño ($\beta = 0{,}35$, $p < 0{,}001$), lo que a su vez mejoró el rendimiento académico ($\beta = 0{,}29$, $p < 0{,}001$). La actividad física también tuvo un efecto directo en los resultados académicos ($\beta = 0{,}18$, $p < 0{,}01$). El apoyo familiar ($\beta = 0{,}22$, $p < 0{,}01$) y las políticas escolares ($\beta = 0{,}19$, $p < 0{,}05$) moderaron estos efectos. El ajuste del modelo fue sólido (CFI = 0,92, TLI = 0,90, RMSEA = 0,07, SRMR = 0,06).
Discusión: El modelo subraya la interconexión entre la actividad física, el sueño y el rendimiento académico en un entorno favorable. Los hallazgos cualitativos destacaron la dificultad de equilibrar las exigencias de salud y académicas, junto con los beneficios percibidos.
Conclusión: El modelo P-S-A validado ofrece un marco integral alineado con iniciativas como Healthy China 2030 y la Política de Doble Reducción. Proporciona una guía práctica para educadores, familias y responsables políticos. Estudios futuros deberían abordar limitaciones como el diseño transversal y el sesgo de autoinforme mediante el empleo de métodos longitudinales y objetivos.

Palabras clave

Actividad física; Calidad del sueño; Rendimiento académico; Modelo de gestión en salud; Políticas educativas; Educación para la salud.

Introduction

The health and well-being of primary and secondary school students have garnered significant attention in recent years, particularly as academic pressures and modern lifestyle changes increasingly affect their physical and mental development (Tracey & Francesca, 2019). Among the many factors shaping adolescent health, the dynamic interplay between physical activity, sleep quality, and academic performance has emerged as a critical determinant (Rathee, 2023). However, prior research often addresses these variables independently. For example, some studies examine the link between physical activity and cognitive function (Bidzan-Bluma & Lipowska, 2018), while others explore how sleep duration predicts academic achievement (Beattie et al., 2015). This siloed approach limits our understanding of how these factors function as part of a complex, interactive system a gap this study aims to address through an integrated, theory-driven model.

Ecological systems theory, proposed by Bronfenbrenner (1979), offers a robust theoretical foundation for understanding the multi-layered influences on human development. According to this theory, individual behavior and health outcomes are shaped by a nested structure of environmental systems, ranging from proximal factors like family and school to distal influences such as cultural norms and policy (Van Wormer & Besthorn, 2017). This framework has been applied in health promotion research to examine how family routines affect child physical activity (Davison & Birch, 2001) and how school environments shape adolescent sleep behaviors (Bartel et al., 2015). In the context of student well-being, this perspective underscores the importance of accounting not only for personal behaviors but also for the environmental contexts in which they occur. Moreover, research shows that environmental moderators such as family support and institutional policy can buffer or amplify the effects of health behaviors on academic outcomes (Fredricks & Eccles, 2004; Jelas et al., 2016).

Despite the explanatory power of ecological systems theory, few studies have applied it to construct integrated health management models supported by empirical data. Most research remains siloed investigating, for instance, the effects of sleep deprivation on academic outcomes (Dewald et al., 2010) or the benefits of physical activity for stress reduction (Biddle & Asare, 2011)—without addressing the synergistic relationships between these variables. This gap highlights the need for a comprehensive framework that connects theory with practice.

Given the multidimensional nature of the variables involved and the contextual factors at play, a mixed-methods approach was adopted. This design enables both the empirical testing of structural relationships (quantitative phase) and the contextual interpretation of environmental influences (qualitative phase), thus allowing for a richer and more comprehensive understanding of the P-S-A model.

To address these limitations, this study aims to construct and validate a "physical activity–sleep–academic performance" (P-S-A) health management model tailored to primary and secondary school students, grounded in ecological systems theory. The proposed model elucidates the interrelationships among these three core components while considering moderating environmental influences such as family support, school regulations, and community resources. This integrated approach seeks to contribute to both theoretical development and practical application.

Theoretically, this research advances ecological systems theory by applying it to a multidimensional health model that accounts for both behavioral and contextual variables. Practically, the validated model provides actionable insights for educators, parents, and policymakers. For example, the model can inform school initiatives that balance academic rigor with physical activity opportunities (Donnelly et al., 2016) or support family-based strategies that enhance sleep hygiene (Hale & Guan, 2015).

In summary, this study addresses a critical gap in the literature by constructing and empirically validating a comprehensive, ecology-informed health management model. The findings aim to inform multilevel interventions that promote holistic well-being and long-term academic success among primary and secondary school students.

Research objectives

1- Model Construction and Validation: To construct a "physical activity–sleep–academic performance" (P-S-A) health management model based on ecological systems theory and validate its predictive power using empirical data.

2- Contextual Analysis: To examine the moderating effects of environmental variables such as family support, school policies, and community resources on the P-S-A relationships.

3- Practical Implications: To derive actionable recommendations for educators, parents, and policymakers aimed at enhancing adolescent health and academic performance through integrated, multilevel interventions.

Literature Review

Ecological Systems Theory and Health Management

Ecological systems theory, originally developed by Bronfenbrenner (1979), offers a multidimensional framework for understanding human development. It posits that health and behavior are shaped by interactions across multiple environmental systems: the microsystem (e.g., family, school), mesosystem (e.g., family-school dynamics), exosystem (e.g., neighborhood resources), and macrosystem (e.g., societal norms and policies) (Bronfenbrenner & Morris, 2006). In educational settings, these systems interact to influence student outcomes (Tudge et al., 2009). For example, family routines and school policies significantly shape the relationship between student behaviors such as physical activity and sleep, and their academic performance (Cheng et al., 2025).

Although the theory has been influential in developmental psychology, its application in health management, particularly in constructing integrative, data-driven models remains limited. Most existing research continues to treat health determinants in isolation, thereby failing to capture the systems-level interconnections necessary for effective intervention design.

Physical Activity and Adolescent Health

Physical activity is well established as a cornerstone of adolescent health, contributing to improve physical, psychological, and cognitive outcomes (Erickson et al., 2019). Benefits include enhanced cardiovascular function, reduced symptoms of anxiety and depression, and improved academic performance (Donnelly et al., 2016). However, the effects of physical activity are not uniform; they are shaped by contextual variables such as access to facilities, parental involvement, and institutional support (Tanveer et al., 2024). For instance, students in schools with robust physical education programs are more likely to meet recommended activity guidelines and achieve better health outcomes (Neil-Sztramko et al., 2021).

Despite this strong evidence base, the interaction between physical activity and other health dimensions—particularly sleep and academic performance—remains underexplored in integrative models. Addressing this gap is crucial for developing comprehensive strategies that align with students' lived experiences.

Sleep Quality and Academic Performance

Sleep is a critical, yet often overlooked, determinant of student health and academic functioning. Inadequate sleep duration and poor sleep quality are linked to impaired cognitive performance, emotional dysregulation, and poor academic achievement (Mehta, 2022). Students who maintain regular, sufficient sleep patterns tend to demonstrate better concentration, memory, and classroom behavior (Hale & Guan, 2015). Yet, sleep is influenced by various social and structural factors, including digital screen use, family dynamics, and institutional demands (Maratia et al., 2023). Early school start times and excessive academic loads have been widely cited as key contributors to adolescent sleep deprivation (Vandendriessche et al., 2022).

Although the academic and behavioral implications of sleep have been well documented, few studies have examined sleep in conjunction with physical activity and academic performance within an ecological framework. This limitation hinders the development of integrated interventions.

Academic Performance and Health Outcomes

Academic performance both influences and is influenced by student health. On the one hand, high achievement correlates with improved self-esteem, emotional well-being, and future socioeconomic outcomes (Wu & Zhang, 2023). On the other hand, academic stress can contribute to physical ailments, emotional exhaustion, and disrupted sleep patterns (Suldo et al., 2018). The educational environment—

characterized by teacher support, peer competition, and parental expectations—plays a significant role in mediating this bidirectional relationship (Edgerton & McKechnie, 2023).

While the interdependence of academic performance and health is well acknowledged, research often overlooks how these dynamics interact with lifestyle behaviors such as physical activity and sleep especially under the influence of ecological moderators.

Gaps in the Literature

The literature provides valuable insights into the individual contributions of physical activity, sleep, and academic performance to adolescent health. However, three major gaps persist: (1) limited integration of these dimensions within a single, cohesive model; (2) underutilization of ecological systems theory as a guiding framework; and (3) lack of validated predictive models capable of informing policy and practice. Addressing these gaps is vital for designing effective, multilevel interventions.

This study responds to these deficiencies by proposing and validating the P-S-A health management model. Grounded in ecological systems theory, the model aims to provide a comprehensive tool for understanding and improving student health and academic outcomes.

Method

This study employs a mixed-methods design to construct and validate a "Physical Activity–Sleep–Academic Performance" (P-S-A) health management model for primary and secondary school students, grounded in Bronfenbrenner's (1979) ecological systems theory. The research integrates quantitative analyses with qualitative insights to capture the multidimensional and dynamic interplay among physical activity, sleep quality, and academic performance, moderated by environmental factors. This section details the study's conceptual framework, data collection procedures, instruments, analytical techniques, and validation strategies.

Research Framework

The study is anchored in ecological systems theory, which emphasizes the influence of multiple, interacting environmental systems on individual development. The P-S-A model integrates three core dimensions: physical activity, sleep quality, and academic performance, within a systemic context. These interactions are analyzed across:

- The microsystem (e.g., family, school),
- The mesosystem (e.g., family-school interactions),
- The exosystem (e.g., community and institutional resources).

The framework examines how environmental moderators such as family support and school policy impact the relationships among the three core health dimensions. A mixed-methods approach allows for a multidimensional assessment, blending empirical rigor with contextual understanding.

Specific Research Content and Methods

The table below summarizes the specific research dimensions and corresponding methods used in the study:

Table 1, Specific Research Content and Methods

Research Content	Methods
1. Physical Activity Measurement	Surveys: International Physical Activity Questionnaire (IPAQ). Wearable Devices: Fitbit to track daily activity levels.
2. Sleep Quality Assessment	Surveys: Pittsburgh Sleep Quality Index (PSQI). Wearable Devices: Fitbit to monitor sleep duration and patterns.
3. Academic Performance Evaluation	School Records: Grade point average (GPA) and standardized test scores.
4. Environmental Factors Analysis	Surveys: Family support and school policy questionnaires. Interviews: Thematic analysis of contextual influences.
5. Model Construction	Structural Equation Modeling (SEM): To test hypothesized relationships.
6. Model Validation	Cross-Validation: Split-sample analysis to assess model robustness.
7. Qualitative Insights	Thematic Analysis: To explore student perspectives on health behaviors.

Data Collection

Sample Selection

A stratified random sampling method was adopted to recruit participants from primary and secondary schools across urban and rural regions. Stratification was based on school location (urban/rural), education level (primary/secondary), and socioeconomic status (low/middle/high), derived from regional census data. Within each stratum, participants were randomly selected using a computerized random number generator to ensure representation. The final sample comprised 1,200 students aged 10–18 years, with balanced gender representation. Informed parental consent and student assent were obtained in compliance with the ethical guidelines of the American Psychological Association (APA, 2017).

Normality Test

Before performing SEM, a univariate normality test was conducted on all major variables to confirm the suitability of the data for parametric statistical analysis. The skewness and kurtosis values for each variable were evaluated. Skewness values less than |3| and kurtosis values less than |10| indicate acceptable normality for SEM.

Table 2. Test of Normality for Main Variables

Variable	Skewness	Kurtosis	Normality Assumption
Physical Activity	-0.42	1.75	Met
Sleep Quality	0.35	-0.87	Met
Academic Performance	-0.61	2.14	Met
Family Support	-0.13	0.45	Met
School Policy	-0.24	0.77	Met

As shown in Table 2, all variables met the criteria for normal distribution. Therefore, parametric statistical methods and SEM analysis were deemed appropriate for this dataset.

Data Sources

To ensure a multidimensional understanding of the P-S-A model, data were collected from multiple sources:

- Student Surveys: Captured self-reported physical activity (frequency, duration), sleep quality (using PSQI), and academic performance (GPA, study habits).
- Objective Measures: Wearable devices (Fitbit) monitored physical activity and sleep continuously over a 14-day period.
- Contextual Data: Academic records provided GPA and test scores. Parental and teacher surveys captured environmental factors such as family support and school policies.

Data Collection Instruments

Student Survey: Developed based on validated instruments including the International Physical Activity Questionnaire (IPAQ) and the Pittsburgh Sleep Quality Index (PSQI), this survey assessed behavioral and academic variables. Both instruments have demonstrated acceptable validity and reliability in adolescent populations (aged 10–18) across diverse international settings (Hagströmer et al, 2006; Tsai et al., 2005). Internal consistency coefficients in our pilot test (n=100) yielded Cronbach's alpha values of 0.82 (IPAQ) and 0.86 (PSQI).

Parent and Teacher Questionnaires: Adapted from existing measures of family functioning and school climate (Kurock et al., 2022), these instruments evaluated the role of external environmental moderators.

Wearable Device Protocol: Participants were provided with standardized instructions on how to use Fitbit Inspire HR devices. Metrics collected included step count, moderate-to-vigorous physical activity (MVPA) minutes, total sleep duration, and sleep efficiency. To enhance compliance, trained research assistants conducted weekly school visits to verify device wear, provide troubleshooting, and re-instruct students as needed. Participants and their guardians also received written and visual guides explaining correct device usage and charging routines. Compliance was monitored through device-synced logs,

with an overall compliance rate of 92.6%. Data were synchronized daily via a mobile app and uploaded to a secure cloud platform. Missing data were handled using multiple imputation methods for participants with ≥80% valid wear days; participants with >20% missing data were excluded from final analysis.

Analytical Scripts

To promote reproducibility and transparency, the following analytical tools were employed:

- Structural Equation Modeling Scripts: R and Mplus scripts were developed for data preprocessing, model construction, and calculation of fit indices.
- Thematic Analysis Scripts: Python scripts, in conjunction with NVivo software, were used to code and extract themes from qualitative interviews.
- Cross-Validation Scripts: R-based scripts implemented random sampling, model training, and predictive accuracy assessments.

Analytical Methods

Structural Equation Modeling (SEM)

SEM was used to construct and test the hypothesized relationships among physical activity, sleep quality, and academic performance. Latent variables were defined using both subjective (survey) and objective (wearable device) indicators. Moderating variables such as family support and school policy were incorporated to examine interaction effects. SEM's ability to model latent constructs and account for measurement error makes it well-suited to complex, multivariate frameworks (Jaccard & Wan, 1995).

Model Fit Indices

Model adequacy was evaluated using the following criteria:

- Comparative Fit Index (CFI) ≥ 0.90.
- Tucker-Lewis Index (TLI) ≥ 0.90.
- Root Mean Square Error of Approximation (RMSEA) ≤ 0.08.
- Standardized Root Mean Square Residual (SRMR) ≤ 0.08. (Sahoo, 2019)

Cross-Validation

To enhance model robustness, the dataset was divided into a training set (70%) and a validation set (30%). Stratified random sampling was used to ensure proportional representation across gender, school type, and region within both subsets. This approach reduces the risk of overfitting and enhances the model's applicability across different student populations (Zhong et al., 2010).

Qualitative Component

To enrich the quantitative findings, semi-structured interviews were conducted with a subset of participants (n = 50). The interview protocol was developed based on Bronfenbrenner's (1979) framework, covering domains such as daily routines, family and school support, and health behaviors. Interviews lasted 30–45 minutes and were audio-recorded and transcribed verbatim. Data were analyzed using thematic analysis. Coding was conducted independently by two researchers using NVivo, followed by intercoder reliability checks (Cohen's $\kappa = 0.82$). Thematic saturation was reached by the 42nd interview, with no new themes emerging in the final eight.

Ethical Considerations

The study adhered strictly to ethical standards for human subject research. Informed consent was obtained from all participants and their legal guardians. All data were anonymized to protect privacy and confidentiality. The research protocol was approved by the Institutional Review Board (IRB) of Yunnan Nationalities University.

Results

This section presents the findings derived from the quantitative and qualitative analyses of the "physical activity-sleep-academic performance" (P-S-A) health management model. The results are organized into three subsections: (1) descriptive statistics and preliminary analyses, (2) structural equation modeling (SEM) results, and (3) qualitative insights. All analyses were conducted using robust statistical methods to ensure the reliability and validity of the findings.

Descriptive Statistics and Preliminary Analyses

The study sample comprised 1,200 primary and secondary school students (mean age = 14.2 years, SD = 2.1), with balanced representation across gender (52% female, 48% male) and urban/rural settings (60% urban, 40% rural). The response rate was 95%, and 3.5% of the data were missing across variables, which were handled using full information maximum likelihood (FIML) estimation.

Descriptive statistics revealed that students engaged in moderate physical activity for an average of 45.3 minutes per day (SD = 15.7), while their average sleep duration was 7.2 hours per night (SD = 1.1). Academic performance, measured by grade point average (GPA), averaged 3.4 on a 4.0 scale (SD = 0.6).

Preliminary correlation analyses indicated significant positive relationships between physical activity and sleep quality ($r = 0.32$, $p < 0.001$), sleep quality and academic performance ($r = 0.28$, $p < 0.001$), and physical activity and academic performance ($r = 0.24$, $p < 0.001$). Variance inflation factors (VIFs) for all variables ranged from 1.12 to 1.36, indicating no multicollinearity issues.

Table 3. Descriptive Statistics and Correlation Matrix

Variable	Mean (SD)	1	2	3
Physical Activity	45.3 (15.7)	1.00		
Sleep Quality	7.2 (1.1)	0.32***	1.00	
Academic Performance	3.4 (0.6)	0.24***	0.28***	1.00

Note：***p < 0.001

Structural Equation Modeling (SEM) Results

The SEM analysis yielded a well-fitting model:

$\chi^2(30) = 45.87$, $p = 0.01$

CFI = 0.93, TLI = 0.91, AGFI = 0.92

RMSEA = 0.06, SRMR = 0.05

These indices confirm the hypothesized relationships among physical activity, sleep quality, and academic performance.

Key Findings:

Physical Activity → Sleep Quality: β = 0.35, SE = 0.04, 95% CI [0.28, 0.42], $p < 0.001$

Sleep Quality → Academic Performance: β = 0.29, SE = 0.05, 95% CI [0.19, 0.39], $p < 0.001$

Physical Activity → Academic Performance: β = 0.18, SE = 0.06, 95% CI [0.06, 0.30], $p = 0.008$

Moderation Effects:

Moderation was tested via interaction terms using product-indicator methods in SEM.

Family Support (PA × FS): β = 0.22, SE = 0.07, $p = 0.002$

School Policies (SQ × SP): β = 0.19, SE = 0.08, $p = 0.016$

These results underscore that family support strengthens the link between physical activity and sleep, while school policies buffer or enhance the effect of sleep on academic outcomes.

Table 4, Structural Equation Modeling Results

Pathway	β	SE	95% CI	p-value
Physical Activity → Sleep Quality	0.35	0.04	[0.28, 0.42]	<0.001
Sleep Quality → Academic Performance	0.29	0.05	[0.19, 0.39]	<0.001
Physical Activity → Academic Performance	0.18	0.06	[0.06, 0.30]	0.008
Family Support (PA × FS)	0.22	0.07	[0.08, 0.36]	0.002
School Policies (SQ × SP)	0.19	0.08	[0.03, 0.35]	0.016

Qualitative Insights

Thematic analysis of the interview data revealed three key themes. A total of 60 students (30 primary, 30 secondary) participated in semi-structured interviews.

1. Balancing Act:
   "Sometimes I stay up late to finish homework, and then I feel too tired to exercise the next day." Many students described the difficulty of balancing physical activity, adequate sleep, and academic expectations.
2. Environmental Influences:
   "My parents set a strict bedtime, so I have to stop studying by 9 p.m." Family routines and school regulations (e.g., time for PE classes) were reported as shaping health behaviors.
3. Perceived Benefits:
   "When I play sports regularly, I don't feel sleepy in class, and I remember things better." Most participants believed that physical activity and sleep positively influenced energy and cognitive focus.

Thematic saturation was reached by the 42nd interview, and data coding was conducted using NVivo 14, applying Braun & Clarke (2006) six-step framework.

Cross-Validation Results

The cross-validation analysis confirmed the robustness of the P-S-A model using a randomized 70/30 training-validation split. The model demonstrated strong predictive accuracy in the validation set, with comparable fit indices (CFI = 0.92, TLI = 0.90, RMSEA = 0.07, SRMR = 0.06). This suggests that the model is generalizable across different populations and settings.

Table 5, Cross-Validation Results

Fit Index	Training Set	Validation Set
CFI	0.93	0.92
TLI	0.91	0.90
RMSEA	0.06	0.07
SRMR	0.05	0.06
AGFI	0.92	0.90
χ^2 (df)	45.87 (30)	48.12 (30)

Discussion

The findings of this study provide compelling evidence for the associations between physical activity, sleep quality, and academic performance within the ecological systems framework. By constructing and validating a "physical activity-sleep-academic performance" (P-S-A) health management model, this research advances our understanding of the complex dynamics shaping adolescent health and well-being. Below, we discuss the theoretical contributions, practical implications, and limitations of the study, along with directions for future research.

Theoretical Contributions

This study makes several significant contributions to the literature. First, it extends the application of Bronfenbrenner's (1979) ecological systems theory to the domain of adolescent health management. By conceptualizing physical activity, sleep quality, and academic performance as interrelated dimensions

influenced by multiple environmental systems, the P-S-A model provides a holistic framework for understanding student health outcomes. This approach addresses a critical gap in the literature, which has traditionally examined these factors in isolation. In line with previous research, the study emphasizes the need for multi-level perspectives that integrate both individual and environmental factors (Rahmania, 2024; McGregor et al., 2003).

Second, the study highlights the moderating role of environmental factors, such as family support and school policies, in shaping the P-S-A relationship. These findings align with previous research emphasizing the importance of contextual influences on adolescent development (Rahmania, 2024) but go further by quantifying their impact within a unified model. This contribution underscores the need for multi-level interventions that address both individual behaviors and environmental contexts. The role of family and school factors is consistent with ecological models that recognize the complex interaction between individual behaviors and their environments (Bronfenbrenner & Morris, 2006; Rhodes et al., 2020).

Practical Implications

The validated P-S-A model offers potential implications for policymakers, educators, and parents. First, the observed positive associations between physical activity and sleep quality suggest that schools could benefit from supporting physical education programs and extracurricular sports. Such initiatives may not only promote physical health but also support healthier sleep patterns, which are linked to cognitive functioning and academic engagement (Donnelly et al., 2016). Physical activity has long been associated with improvements in sleep quality, and this study reinforces its relevance to adolescent well-being (Wunsch et al., 2017).

Second, the significant association between sleep quality and academic performance points to the value of school-level considerations such as adjusted schedules and reduced academic pressures. However, these suggestions should be interpreted cautiously, given the cross-sectional nature of the study, which prevents causal inferences. Prior research indicates that early school start times may conflict with adolescents' circadian rhythms, potentially influencing both sleep and academic outcomes (Ziporyn et al., 2022; Wheaton et al., 2020).

Finally, the moderating effects of family support and school policies highlight the importance of coordinated efforts between home and school. Parents may support health outcomes by maintaining structured bedtime routines and encouraging physical activity, while schools can contribute through health-promoting policies. The findings align with prior work recognizing the role of family and school environments in shaping adolescent health behaviors (Buxton et al., 2015).

Comparison with Previous Studies

The findings of this study are largely consistent with the broader literature, though some differences and nuances are evident. For instance, Luengo et al., (2023) found no significant association between physical activity and sleep quality among Physical Education students during the pandemic, highlighting the influence of contextual disruptions such as increased screen time. Our study, conducted in a post-pandemic setting, revealed a different pattern, suggesting that environmental stability may influence these associations.

Similarly, Suárez-Manzano et al., (2023) identified links between muscle strength and reduced hyperactivity, which supports the broader view that physical activity is associated with improved behavioral and cognitive outcomes. Our study complements this by showing that physical activity correlates positively with both sleep and academic performance, reinforcing the multifaceted value of active lifestyles in adolescence.

Rusillo et al., (2023) reported that low physical fitness correlated with higher overweight risk. While we did not measure body composition, our findings suggest that promoting physical activity can yield cognitive and behavioral benefits beyond traditional fitness metrics.

However, unlike some studies, such as those that report null or contradictory findings between these variables (Luengo et al., 2023), our results consistently showed positive associations. This consistency warrants further exploration in longitudinal and experimental designs to determine whether these relationships hold over time or under different conditions.

Notably, our findings did not reveal significant gender differences in the relationships among physical activity, sleep quality, and academic performance. This contrasts with prior research suggesting that gender can moderate these associations. For example, a study by Vanaelst et al., (2012) found that girls reported lower physical activity levels and poorer sleep quality, which in turn affected their academic outcomes more significantly than boys. Several explanations may account for this: first, there may be a growing convergence in health behaviors between male and female adolescents, driven by shifting cultural norms. Second, our use of wearable data (alongside self-reports) may have minimized gendered reporting biases found in earlier studies. Lastly, it is possible that contextual factors such as equal access to school-based physical activity programs or cultural expectations specific to our sample mitigated these differences. The absence of such differences in our study may be attributed to the increasing convergence in health behaviors among adolescents or cultural factors specific to our sample. This warrants further exploration in future research using stratified or multi-group analyses.

Limitations and Future Directions

Despite its contributions, this study has several limitations. First, its cross-sectional design limits causal interpretations. Statements about "effects" should be interpreted as statistical associations rather than definitive causal pathways. Future studies employing longitudinal or experimental designs are needed to clarify temporal sequences and causality.

Second, the reliance on self-reported data for physical activity and sleep introduces potential measurement biases. Although some wearable device data were included, social desirability and recall bias may affect responses. More comprehensive use of objective tools such as actigraphy and accelerometry is recommended in future work (Hickman et al., 2024).

Third, the study may be subject to selection bias, as participants voluntarily joined the study, possibly representing more health-conscious individuals. Furthermore, potential confounding variables, such as socioeconomic status, screen time, and diet, were not controlled for. These variables could influence all three core domains (physical activity, sleep, and academic performance) and should be included in future models to refine the accuracy of inferences.

Fourth, while the study confirmed its hypothesized model, it did not explicitly address unexpected or contradictory findings. For example, no significant gender differences emerged, which contrasts with some previous studies that reported gender-specific patterns in physical activity and sleep. Future research should further explore such discrepancies to enhance the explanatory power of the model.

Finally, while the study offers practical recommendations, policy suggestions such as school start time delays should be approached with caution. The findings support further exploration but are insufficient, on their own, to warrant large-scale policy shifts. Replication across diverse populations and contexts is essential to justify such interventions.

Conclusions

This study contributes to the development and preliminary validation of the "Physical Activity–Sleep–Academic Performance" (P-S-A) health management model for primary and secondary school students, grounded in ecological systems theory. Rather than asserting causal effects, the findings support meaningful associations among physical activity, sleep quality, and academic performance with physical activity positively linked to sleep quality ($\beta = 0.35$, $p < 0.001$), sleep quality associated with academic performance ($\beta = 0.29$, $p < 0.001$), and physical activity also showing a direct relationship with academic outcomes ($\beta = 0.18$, $p < 0.01$). The moderating roles of family support ($\beta = 0.22$, $p < 0.01$) and school policies ($\beta = 0.19$, $p < 0.05$) further emphasize how environmental factors shape these interdependencies.

Theoretically, the study reinforces ecological systems theory by integrating individual health behaviors and broader environmental moderators into a unified framework. This integrated model helps clarify how adolescent well-being is shaped by both proximal behaviors and distal systems, thereby contributing to a more holistic understanding of educational and public health interventions.

From a practical perspective, the findings offer initial guidance for designing school- and family-based programs aimed at improving adolescent health and learning outcomes. Rather than prescribing immediate policy changes, this study provides a foundation for future interventions that could align with national priorities. For example, the findings are consistent with the goals of the Healthy China 2030 initiative, which promotes physical and mental well-being, and the Double Reduction Policy, which aims to alleviate academic pressure and enhance overall student development. However, the study does not directly evaluate these policies.

Despite its contributions, the study has limitations that should inform future research. The reliance on self-reported data may introduce recall and social desirability bias, and the cross-sectional design precludes causal inference. There is also a risk of selection bias and unmeasured confounding (e.g., socioeconomic status, screen time habits), which future research should address through controlled, longitudinal, and more diverse designs. Additionally, specific questions for future work include: how do the P-S-A relationships evolve across school transitions? What role does gender play in moderating these relationships? And how do these dynamics manifest in different cultural or educational systems?

In conclusion, while this study offers preliminary support for the P-S-A model, its validation should be viewed with caution given the methodological constraints, particularly the cross-sectional nature of the design. Nevertheless, the model presents a promising framework to guide future research and multilevel interventions aimed at promoting adolescent health and academic success. These findings contribute to broader interdisciplinary discussions on how to support student well-being across family, school, and societal contexts.

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