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The mediating role of cognitive arousal in the relationship between impulsivity and sleep quality among college students: a random intercept cross-lagged panel analysis

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Impulsivity, cognitive arousal, and sleep quality are critical factors affecting college students' well-being and academic performance. While impulsivity negatively influences sleep quality, the mediating role of cognitive arousal remains underexplored. The present study assesses how impulsivity affects sleep quality through cognitive arousal. Specifically, it explores whether impulsive behavior heightens cognitive arousal, leading to impaired sleep quality, and whether these relationships hold over time. A longitudinal design was employed, collecting data from 521 college students across three waves over an academic year. Standardized questionnaires were administered to measure impulsivity, cognitive arousal, and sleep quality at each wave. Structural equation modeling and random-intercept cross-lagged panel models (RI-CLPMs) were utilized to analyze the associations, assessing both the direct effects and the mediating role of cognitive arousal over time. Impulsivity significantly predicted increased cognitive arousal over time, which in turn negatively affected sleep quality. Cognitive arousal was confirmed as a significant mediator in the relationship between impulsivity and sleep quality. These relationships remained consistent across the three-time points, with significant direct effects of impulsivity on cognitive arousal and cognitive arousal on sleep quality. Interventions to reduce cognitive arousal and impulsivity-related behaviors could improve sleep quality among college students. Future research should explore additional environmental and psychological factors influencing these relationships.

Keywords Impulsivity, Cognitive arousal, Sleep quality, Random-intercept cross-lagged panel model (RI-CLPM), College students

The intricate relationship between sleep quality and college students has emerged as a critical area of investigation within health sciences[1], particularly amidst mounting evidence that highlights the pervasiveness of suboptimal sleep patterns among this demographic[2–4]. Transitioning into college life often coincides with significant alterations in sleep behaviors, characterized by delayed bedtimes, irregular sleeping schedules, and a general decline in sleep duration and quality[5,6]. These changes, exacerbated by academic pressures[7], social engagements[8], and environmental factors such as noise and light pollution in campus dormitories[9,10], have been linked to a myriad of adverse outcomes, including impaired cognitive function, heightened stress levels, and increased vulnerability to mental health disorders[11–13]. Moreover, the natural shifts in circadian rhythms during late adolescence and early adulthood further complicate the picture, suggesting that biological processes may

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undermine best efforts to maintain consistent, restorative sleep[14,15]. By unraveling the complexities of sleep quality among the student population, targeted interventions could be formed to help college students achieve the restorative sleep essential for thriving in their academic pursuits and beyond.

Impulsivity, characterized by acting without considering consequences[16], significantly affects various behaviors, including sleep quality among students[17]. This trait influences academic and social interactions[18,19], leading impulsive individuals to prioritize immediate gratification[20], often engaging in late-night activities like partying, excessive use of devices, or caffeine consumption, all of which disrupt sleep[21,22]. Impulsivity is also linked to poor emotion regulation and heightened stress reactivity[23], worsening sleep disturbances through rumination, or risky nocturnal behaviors that fragment sleep[24]. Additionally, impulsive students may experience delayed circadian rhythms[24], misaligning sleep-wake patterns with academic schedules, resulting in further sleep sacrifice. Environmental factors like dorm noise and roommate habits can exacerbate these effects. Longitudinal studies indicate a cyclical relationship between impulsivity and sleep quality, where impulsivity predicts sleep decline and poor sleep increases impulsive behaviors[25,26]. These findings highlight the need for interventions targeting impulsivity and sleep hygiene to improve student well-being. Academic institutions can use this knowledge to develop strategies that address impulsive behaviors, ultimately enhancing sleep quality, academic performance, and mental health among students.

Cognitive arousal, characterized by heightened mental alertness, rumination, and worry[27], has been found to play a central role in sleep disturbances, particularly in populations facing significant cognitive demands, such as students[28,29]. Research indicates that cognitive arousal is closely associated with delayed sleep onset, prolonged sleep latency, and disrupted sleep quality, primarily due to its impact on the mind's capacity to disengage before bedtime[30,31]. Cognitive arousal tends to sustain intrusive, racing thoughts that prevent relaxation, making it a critical factor in sleep disruption[32,33]. In academic contexts, cognitive arousal is particularly relevant. University students and educators often engage in high levels of cognitive work, associated with increased mental activity and rumination, which can interfere with initiating and maintaining sleep[34]. Compared to somatic arousal, which relates to physical manifestations of arousal such as heart rate increases, cognitive arousal has been shown to have a more substantial and more direct link to sleep disturbances due to its mental component, which directly impacts the pre-sleep period[28,35,36]. Focusing on cognitive arousal allows for a more targeted examination of sleep quality in populations that engage in intellectually demanding work, where mental alertness and rumination are more prevalent than physical arousal at bedtime. Given this established link between cognitive arousal and sleep quality, as well as its relevance to individuals in cognitively intensive environments, this study focuses on cognitive arousal as the primary mediator. By examining cognitive arousal specifically, we aim to capture the unique contributions of mental engagement on sleep outcomes, especially as they relate to impulsivity in a population with high cognitive demands.

Theoretical framework

Impulsivity, characterized by poorly conceived actions, prematurely expressed, unnecessarily risky, and inappropriate to the situation, plays a crucial role in various behavioral outcomes, especially those related to self-regulation and arousal mechanisms[16]. Understanding the impact of impulsivity on sleep behavior among college students is essential, as it frequently manifests in behaviors that can disrupt normal sleep patterns, such as engaging in stimulating activities late at night or failing to adhere to a consistent sleep schedule. Theoretical models that explain the role of impulsivity in affecting sleep often refer to the Behavioral Inhibition System/Behavioral Activation System (BIS/BAS) framework[37]. This theory posits that individuals with a dominant BAS are more prone to approaching potentially rewarding experiences, including those that may result in adverse outcomes like poor sleep. The BAS-driven behaviors are particularly relevant in understanding why impulsive individuals might engage in late-night activities that increase cognitive arousal and disrupt sleep[38]. Cognitive arousal, a state of mental alertness and wakefulness, is often elevated by activities that stimulate the mind and senses, such as using electronic devices or engaging in social activities right before bed[27,39,40]. The arousal regulation model of sleep provides a basis for understanding how heightened cognitive arousal can interfere with falling asleep and maintaining uninterrupted sleep cycles[41,42]. This model suggests that activities increasing cognitive arousal can delay sleep onset and reduce sleep quality by keeping the nervous system in a state of alertness that is incongruent with the relaxation needed for sleep[43].

Furthermore, the interaction between impulsivity and cognitive arousal can be explained through the dual-process model of sleep regulation[44], which posits that sleep is regulated by homeostatic and circadian processes but is influenced by cognitive and emotional factors. Impulsive individuals might struggle more with the self-regulation required to align their behaviors with these processes, often overriding sleepiness cues due to engaging in arousing activities or experiencing heightened emotional states that prevent sleep onset[45,46]. This framework is supported by empirical evidence linking impulsivity to poorer sleep outcomes[47]. Studies have shown that individuals with higher impulsivity scores are more likely to have irregular sleep patterns[48], shorter sleep duration[49], and poorer sleep quality[50]. These findings are consistent with the notion that impulsive behaviors contribute to heightened arousal that can be detrimental to sleep[51,52]. Secondly, the transactional model of stress and coping provides additional theoretical support for studying the mediating role of cognitive arousal between impulsivity and sleep quality. According to this model, how individuals appraise and cope with stress can affect their emotional and physiological well-being[53,54]. In the case of impulsive individuals, their typical responses to stress may involve seeking immediate but ultimately sleep-disruptive solutions, such as engaging in electronic media use or other stimulating activities to cope with stress or negative emotions[55]. This theory is particularly relevant for understanding the mediating role of cognitive arousal in the relationship between impulsivity and sleep quality. Cognitive arousal can be conceptualized as a direct consequence of impulsive decisions and as a mediating factor that explains the continuity from impulsive behavior to poor sleep outcomes[28]. This perspective suggests that interventions to reduce cognitive arousal or modify how impulsive individuals respond to stress could improve sleep quality.

In conclusion, this study's theoretical framework integrates concepts derived from the BIS/BAS theory, the arousal regulation model, the dual-process model of sleep regulation, and the transactional model of stress and coping (Fig. 1). These theories collectively illuminate the intricate mechanisms by which impulsivity affects sleep quality through the mediation of cognitive arousal. Comprehending these pathways is essential for formulating targeted interventions that may alleviate the negative impacts of impulsivity on sleep among college students. Such efforts aim to improve their overall health and academic performance.

Study contribution and objectives

Previous research on the relationships between impulsivity, cognitive arousal, and sleep quality has predominantly employed cross-sectional designs, which only provide a snapshot of these variables at a single time. This limits the ability to infer causality or to understand how these relationships develop or change over time. By contrast, our study utilized a random-intercept cross-lagged panel model (RI-CLPM) design, allowing for the assessment of changes and developments across three distinct time points. This approach enables a more nuanced analysis of the temporal dynamics and potential causal pathways between impulsivity, cognitive arousal, and sleep quality among college students. The study aims to enhance academic performance and overall well-being through these contributions, addressing significant research gaps and providing a foundation for future research in similar settings. Building upon the foundational theories of impulsivity and arousal regulation and recognizing the need to explore these phenomena within the diverse cultural backdrop of Rawalpindi, Pakistan, the present study seeks to longitudinally investigate the interplay between impulsivity, cognitive arousal, and sleep quality. The overarching aim is to delineate how impulsivity affects sleep outcomes via cognitive arousal, contributing new insights into these relationships' temporal dynamics. In pursuit of this goal, the study proposes the following research questions (Table 1):

Fig. 1. Theoretical framework of the current research.

Research question (RQ)	Objective Explanation (OE)
RQ-1: How does impulsivity impact sleep quality among college students over an academic year?	***OE-1***: This question aims to explore the direct effects of impulsivity on sleep quality, assessing whether higher levels of impulsivity correlate with poorer sleep across multiple time points.
RQ-2: How does cognitive arousal mediate the relationship between impulsivity and sleep quality among college students?	***OE-2***: This question seeks to understand whether cognitive arousal mediates the pathway from impulsivity to sleep quality. It investigates if impulsivity increases cognitive arousal, which in turn affects sleep quality negatively.
RQ-3: How do changes in cognitive arousal due to impulsivity affect sleep quality over time in a non-Western student population?	***OE-3***: Focused on the longitudinal dynamics, this question examines the temporal changes in cognitive arousal due to impulsivity and how these changes impact sleep quality across an academic year.

Table 1. Research questions.

Materials and methods

Sampling Approach and Study setting

This 3-wave longitudinal survey was conducted among HSSC-I (11th grade) and HSSC-II (12th -grade) students attending federal colleges for girls and boys in Islamabad, Pakistan, overseen by the Ministry of Federal Government[56]. The academic year at these institutions begins in September, and the study was structured around three critical data collection waves to capture the dynamics of impulsivity, cognitive arousal, and sleep quality. Data were collected at the start of the academic year (P_1), mid-year (six months later) (P_2), and at the end of the academic year (P_3) just before exams (For the academic session 2022–2023).

The sampling strategy employed was a stratified random sampling approach to ensure representativeness among HSSC-I and HSSC-II students from federal colleges in Islamabad. All colleges under the federal government's jurisdiction were considered, and a random sample of classes was selected from each college. This method ensured that the sample was representative of the broader population of college students in Islamabad, providing a diverse mix of participants in terms of age, gender, and academic discipline.

The stratified random sampling (SRS) approach involved defining strata based on the student grades and selecting a random sample from each stratum to participate in the study. This method was chosen to reflect the diverse student population across the federal colleges and to maintain statistical efficiency. Each stratum's sample size was proportional to its size within the total student population, ensuring that each group was adequately represented.

Data collection was carried out at three different points during the academic year, and the aim was to capture changes and trends in study constructs that were under investigation over time. The SRS facilitated precise estimates and improved the study's representativeness by including all relevant sub-groups. This approach allowed for comprehensive data analysis and enhanced the findings' reliability by reducing potential sampling biases and ensuring comparability between different grades.

Participants were eligible for the study if they were enrolled as HSSC-I or HSSC-II students at the participating colleges. Initially, 3274 students participated in the first wave of data collection. The participation numbers in subsequent waves were 1438 in the second and 761 in the third wave, with an overlap of 521 students who participated in all three waves, allowing for longitudinal analysis of the overlapping sample (Fig. 2). Of these participants, 52.76% were females, and 47.24% were males, with an average age of 17.54.

Students were approached through a coordinated effort with college administrations, following approval from each college principal to conduct the study on their premises. Recruitment was facilitated by classroom announcements and postings on college bulletin boards, inviting all eligible students to participate. Consent forms were distributed and explained during these sessions, with students and their parents (if under 18) providing written informed consent.

Data collection and administration

The questionnaire, administered in English—the medium of instruction at the participating institutions—was designed to ensure clarity and accessibility for all participants. The same questionnaire was administered to maintain consistency in measuring study constructs under investigation across the different phases of the study. Data was collected using a paper-pencil approach in classroom settings monitored by research assistants to ensure consistency and provide clarifications as needed. Each data collection wave was strategically timed to coincide with a typical school day to maximize student participation and minimize disruptions.

To engage and motivate the students, the research team emphasized the potential benefits of the study findings for developing better strategies to manage student health and well-being, particularly focusing on sleep and stress management. The significance of their contribution to the broader understanding of student health in the Pakistani context was highlighted as a critical motivator. This comprehensive approach to sampling and data collection not only facilitates a robust analysis of the temporal relationships between impulsivity, cognitive arousal, and sleep quality but also enhances the reliability and applicability of the study's findings to the target population.

Measures

Impulsivity

In the present study, we employed the Barratt Impulsiveness Scale (BIS-11) to measure impulsivity among the participants[57]. The BIS-11 is a preeminent self-report instrument widely used to assess the personality and behavioral construct of impulsiveness. It comprises 30 items that evaluate three distinct dimensions of impulsivity: attentional, motor, and non-planning. Participants respond to these items using a 4-point Likert scale ranging from "rarely/never") to "almost always/always." Higher scores on the BIS-11 indicate elevated

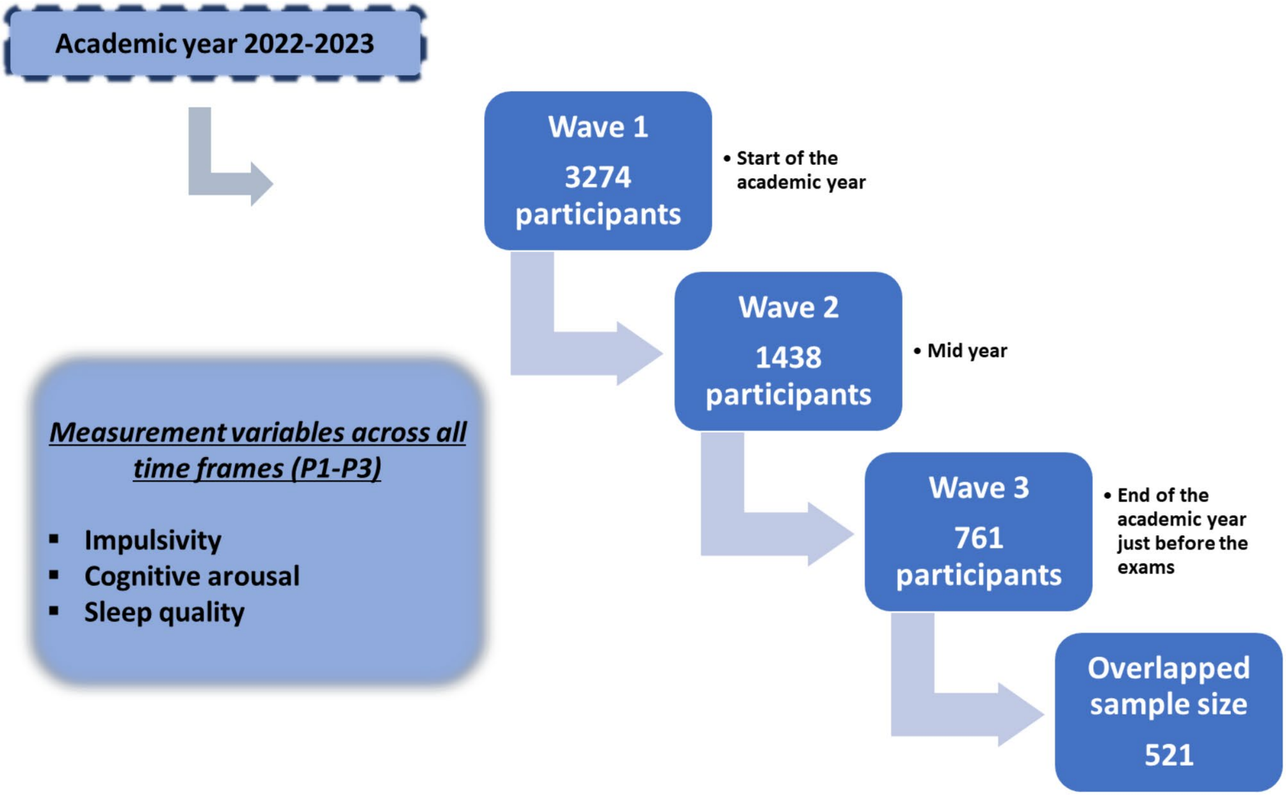

Fig. 2. Sampling procedure for the current research.

levels of impulsivity. Sample items include: "I do not pay attention (attentional)." "I act on impulse (motor)." "I plan tasks carefully (non-planning)" The scale has demonstrated excellent internal consistency and test-retest reliability across diverse populations[58–61].

Cognitive arousal

In the present study, we employed the Cognitive Arousal Subscale (8 items) of the Pre-Sleep Arousal Scale (PSAS)[62]to measure cognitive arousal levels preceding sleep. This subscale evaluates cognitive activities such as intrusive thoughts and pre-sleep worries. Sample items include: "I have thoughts running through my mind." "I cannot shut my mind off." Participant responses are indicated on a 5-point Likert scale that ranges from "Not at all" to "Extremely," where higher scores reflect more significant levels of cognitive arousal before sleep. The scale has shown good reliability across various disciplines and demographics[28,62,63]. While the Pre-Sleep Arousal Scale assesses cognitive and somatic arousal, this study focuses exclusively on cognitive arousal as the primary mediator.

Sleep quality

The Pittsburgh Sleep Quality Index (PSQI) is a widely adopted self-reported measure to evaluate sleep quality over one month[64]. This instrument encompasses multiple dimensions of sleep, such as duration, disturbances, latency, and daytime dysfunction. Sample items are as follows: "During the past month, how often have you woken up in the middle of the night or early morning?" During the past month, how often have you had trouble staying awake while driving, eating meals, or engaging in social activity?" Responses are quantified on a 4-point Likert scale, with the cumulative score ranging from 0 to 21. A cumulative score >5 suggests suboptimal sleep quality. The PSQI demonstrates good internal consistency, as evidenced by a Cronbach's alpha value of 0.83, and exhibits robust test-retest reliability[65–67].

Analytical approach

Data were analyzed using a series of statistical techniques to examine the temporal trends in impulsivity, cognitive arousal, and sleep quality across three waves of data collection. Descriptive statistics and bivariate correlational analysis were performed for all study variables at each time point to summarize the data and describe the characteristics of the sample. Reliability and validity of the study variables were assessed at each time point to ensure consistency and accuracy of the measurements over time[68–70]. For the longitudinal analysis, the data were first assessed for missingness, and Little's MCAR test[71]was conducted to determine if the data were missing completely at random. Missing data were handled using Full Information Maximum Likelihood (FIML) estimation to ensure unbiased parameter estimates[72]. Next, measurement invariance tests were performed to establish configural, metric, scalar, and residual invariance across the three-time points[73,74]. These tests were conducted to confirm that the constructs of impulsivity, cognitive arousal, and sleep quality were measured equivalently over time.

Additionally, RI-CLPMs were conducted using MPlus 8.3, following established methodologies. These models were used to examine the longitudinal relationships among all variables. In the RI-CLPMs, the factor loadings for both within-person latent variables and RI were fixed to one, while the measurement error variance was set to zero. To maintain model parsimony, all autoregressive and cross-lagged paths were initially allowed to vary over time. Subsequently, these paths were constrained to be equal across time in a stepwise approach, starting with within-person stability, followed by cross-lagged and concurrent effects. Later, an autoregressive mediation model was employed to investigate impulsivity's direct and indirect effects on sleep quality over time, with cognitive arousal as the mediator[75]. The model fit was assessed using standard fit indices, including the Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR)[76]. Indirect effects were estimated using bootstrapping techniques with 5,000 resamples to calculate confidence intervals and determine the significance of the mediation pathways[77]. This method provided robust estimates of the indirect effects, allowing for a clearer understanding of how changes in impulsivity influenced sleep quality via cognitive arousal over time.

Panel attrition

In order to investigate whether systematic attrition of participants between the baseline (P_1) and follow-up data collection periods may have influenced the results, a comparative analysis was conducted between the baseline group ($n = 3274$) and the overlapped group ($n = 521$) of participants utilizing Students' t-tests. No statistically significant differences were observed between the two groups for demographic and study variables. Consequently, we can infer that any systematic dropout did not significantly affect the study results (***Supplementary File 1***).

Measurement invariance over time

To examine the measurement stability across temporal intervals, we designated one latent variable for each of the three-time points, corresponding to the measures of impulsivity, cognitive arousal, and sleep quality. Following prior work, the relationships between indicators and factors, specifically factor loadings and intercepts, must remain consistent across measurements Christian Geiser et al. (2010). To accommodate this requirement, we introduced factors specific to each indicator. The initial stage in assessing measurement invariance, termed configural invariance, involved verifying whether the included constructs maintain a consistent pattern of free and fixed loadings over time. This consistency suggests that underlying data support the association of indicators with the three latent factors, as it persists over time. Should configural invariance be confirmed, further constraints are applied for the subsequent evaluation stage, known as metric or weak invariance. This stage presupposes that each item contributes uniformly to the latent construct across time. Metric invariance was examined by ensuring the equalization of factor loadings for the constructs across time. The ensuing stage, called scalar/strong invariance, involves ascertaining whether the mean differences in the latent construct entirely capture the mean differences in the shared variance of the items. Scalar invariance was evaluated by equalizing the item intercepts over time while maintaining the constraints in the metric invariance model[79]. The ultimate step in assessing measurement invariance, termed residual or strict invariance, involves making the residual variables equivalent over time. If residual invariance is validated, variations in the observed variables can solely be ascribed to variations in the latent variables' variances. To ascertain the preeminence of a more robust model, we followed the guidance of Satorra &Bentler, (2001) Satorra & Bentler, (2001). We posited that the model incorporating the most significant number of invariance constraints provided it maintains an acceptable fit and does not substantially worsen the estimate, represents the final model[81]. As the statistic for assessing model fit is sensitive to sample size, we compared the CFIs (< 0.01) and RMSEAs (< 0.015) of the models[82,83].

Results

Convergent and validity analysis results

Table 2 demonstrates the convergent and discriminant validity analysis outcomes, which showed good reliability and validity across all three time points (P_1, P_2, P_3) for each construct. Cronbach's alpha values for impulsivity, cognitive arousal, and sleep quality were above 0.86, indicating high internal consistency for each construct. Composite reliability (CR) values were also high (0.87–0.90), further supporting the reliability of these scales.

	Cronbach's α	Composite reliability	Average variance extracted
Impulsivity (P_1)	0.89	0.87	0.71
Impulsivity (P_2)	0.88	0.89	0.68
Impulsivity (P_3)	0.91	0.90	0.75
Cognitive arousal (P_1)	0.90	0.89	0.72
Cognitive arousal (P_2)	0.90	0.88	0.69
Cognitive arousal (P_3)	0.89	0.87	0.65
Sleep quality (P_1)	0.87	0.88	0.58
Sleep quality (P_2)	0.88	0.89	0.59
Sleep quality (P_3)	0.90	0.89	0.71

Table 2. Convergent and discriminant validity analysis.

		1	2	3	4	5	6	7	8	9
1	Impulsivity at P1	1								
2	Impulsivity at P2	0.823***	1							
3	Impulsivity at P3	0.793***	0.810***	1						
4	Cognitive arousal at P1	0.309*	0.248**	0.453***	1					
5	Cognitive arousal at P2	0.345**	0.365**	0.534***	0.864***	1				
6	Cognitive arousal at P3	0.501***	0.532***	0.572***	0.883***	0.881***	1			
7	Sleep quality at P1	−0.355***	−0.457***	−0.488***	−0.512***	−0.556***	−0.603***	1		
8	Sleep quality at P2	−0.423***	−0.476***	−0.523***	−0.549***	−0.589***	−0.633***	0.739***	1	
9	Sleep quality at P3	−0.486***	−0.510***	−0.586***	−0.581***	−0.607***	−0.657***	0.791***	0.756***	1
	Mean (SD)	52.35 (5.61)	61.59 (7.02)	72.35 (9.73)	25.14 (5.13)	26.53 (6.07)	28.67 (8.05)	4.91 (2.15)	7.15 (3.14)	13.81 (5.17)

Table 3. Descriptive estimates and bivariate correlation analysis over three-time intervals. Note: *$p<0.05$. **$p<0.01$. ***$p<0.001$. SD: Standard deviation. P1: Baseline time. P2: Second phase. P3: third phase.

	Fit Indices					Model Comparison	
	CMIN/df	RMSEA	SRMR	CFI	TLI	△CFI	△RMSEA
Impulsivity							
Configural	1.31***	0.000	0.015	1.000	0.965		
Metric	1.21***	0.000	0.016	1.000	0.958	0.000 [a]	0.000 [a]
Scalar	1.28***	0.000	0.022	1.000	0.960	0.000 [b]	0.000 [b]
Residual	1.35**	0.000	0.023	1.000	0.966	0.000 [c]	0.000 [c]
Cognitive arousal							
Configural	1.42**	0.026	0.014	0.991	0.972		
Metric	1.31**	0.032	0.024	0.992	0.967	0.001 [a]	0.006 [a]
Scalar	1.25***	0.022	0.027	0.989	0.970	−0.003[b]	−0.001 [b]
Residual	1.20***	0.025	0.019	0.990	0.969	0.001 [c]	0.003 [c]
Sleep Quality							
Configural	1.46**	0.048	0.030	0.989	0.970		
Metric	1.39**	0.041	0.033	0.990	0.968	0.001 [a]	−0.007 [a]
Scalar	1.29***	0.036	0.035	0.989	0.966	−0.001 [b]	−0.005 [b]
Residual	1.18***	0.032	0.033	0.987	0.963	−0.002 [c]	−0.004 [c]

Table 4. Measurement invariance (configural, metric, scalar, and residual) comparison for all study models over three distinct time intervals (P_1-P_2). Note: As the chi-square statistic for assessing model fit is sensitive to sample size, we compared the CFIs (<0.01) and RMSEAs (<0.015) of the models[82]. [a] Comparison of metric invariance and configural invariance models. [b] Comparison of scalar invariance and metric invariance models. [c] Comparison of residual invariance and scalar invariance models. *$p<0.05$. **$p<0.01$. ***$p<0.001$.

Average Variance Extracted (AVE) values range from 0.58 to 0.75, suggesting adequate convergent validity, as most are above the 0.50 threshold. This means the constructs explained a sufficient proportion of variance in their indicators.

Table 3 illustrates the bivariate correlations among impulsivity, cognitive arousal, and sleep quality across three temporal measurements: Time Point 1 (P_1), Time Point 2 (P_2), and Time Point 3 (P_3). The results demonstrated a consistent pattern: impulsivity at each time point showed significant positive correlations with cognitive arousal and significant negative correlations with sleep quality. Notably, impulsivity at P_3 had the strongest correlation with both cognitive arousal ($r=0.572$, $p<0.001$) and sleep quality ($r = -0.586$, $p<0.001$), indicating that impulsive behaviors may intensify over time and have a more pronounced negative effect on sleep quality through increased cognitive arousal. Cognitive arousal consistently displayed strong positive correlations across all time points, particularly at P_3 ($r=0.883$, $p<0.001$), indicating a stable and increasing relationship between the variables. Similarly, sleep quality was negatively correlated with cognitive arousal across all time points, with the strongest correlation appearing between cognitive arousal at P_3 and sleep quality at P_3 ($r = -0.657$, $p<0.001$). This provided compelling evidence that cognitive arousal may mediate the relationship between impulsivity and deteriorating sleep quality over time.

The measurement invariance analysis showed robust model fit indices across all levels of invariance testing (configural, metric, scalar, and residual) for impulsivity, cognitive arousal, and sleep quality (Table 4). The CFIs remained consistently high (above 0.98), and the RMSEAs were below 0.05, indicating excellent fit. This invariance supports the stability of the measurement constructs across the three-time intervals, confirming that the relationship between impulsivity, cognitive arousal, and sleep quality remains consistent. Notably, the

Models	Fit Indices					Model Comparison	
	CMIN/df	RMSEA	SRMR	CFI	TLI	△CFI	△RMSEA
Measurement Model	1.23*	0.033	0.026	1.00	0.98		
Stability Model	1.18***	0.028	0.024	0.99	0.97		
Autoregressive Mediation Model	1.11***	0.031	0.026	0.99	0.97	0.000[a]	0.003[a]

Table 5. Model fit analysis. Note: *$p<0.05$. **$p<0.01$. ***$p<0.001$. [a]Comparison of autoregressive mediation model and stability model. As the chi-square statistic for assessing model fit is sensitive to sample size, we compared the CFIs (<0.01) and RMSEAs (<0.015) of the models[82].

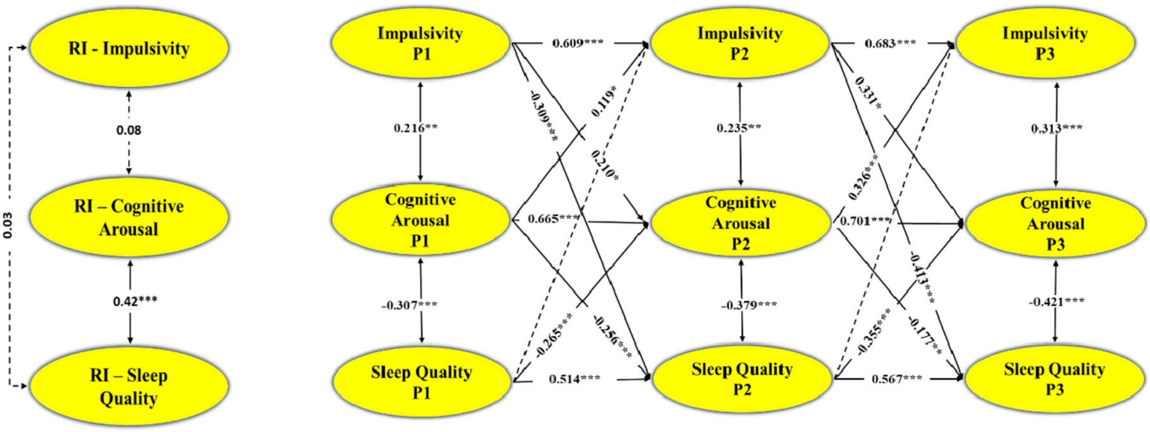

Fig. 3. RI-CLPM (Random intercept – Cross-lagged panel model) with mediation (P1: baseline period, P2: Second wave, P3: third wave). The dotted line shows an insignificant path, whereas the solid black line shows a significant one. (*$p<0.05$, **$p<0.01$, ***$p<0.001$).

invariance tests confirmed that the constructs are being measured similarly across time points, enabling reliable longitudinal comparisons.

The model fit analysis further solidified the robustness of the study's autoregressive mediation model (Table 5). The autoregressive mediation model had a strong model fit (CFI = 0.99, RMSEA = 0.031, SRMR = 0.026), which compares favorably to the stability model, showing no significant differences in CFI or RMSEA. This indicated that the autoregressive mediation model, which accounts for the temporal ordering of variables and mediates the effects of impulsivity through cognitive arousal to sleep quality, is a reliable and valid approach to understanding these relationships over time.

Figure 3 illustrates the results of RI-CLPM, which has provided valuable insights into the stability and relationships between impulsivity, cognitive arousal, and sleep quality over time. The autoregressive paths for impulsivity ($\beta=0.746$: P_1-P_2 and $\beta=0.810$: P_2-P_3), cognitive arousal ($\beta=0.845$: P_1-P_2 and $\beta=0.881$: P_2-P_3), and sleep quality ($\beta=0.615$: P_1-P_2 and $\beta=0.687$: P_2-P_3) showed strong stability, with impulsivity and cognitive arousal demonstrating relatively high levels of continuity across waves. The cross-lagged effects revealed that impulsivity at P1 significantly predicted cognitive arousal at P2 and P2 to P3, indicating that impulsivity directly influences cognitive arousal over time. Additionally, cognitive arousal negatively affected sleep quality over time, highlighting the disruptive role of heightened mental arousal on sleep. The random intercept (RI) for impulsivity was small and non-significant ($\beta=0.08$), suggesting minimal individual variability in impulsivity beyond what is accounted for by the autoregressive model. Similarly, the random intercept for cognitive arousal was also small and non-significant ($\beta=0.03$), indicating very low individual variability in cognitive arousal at baseline. However, significant individual variability was found in sleep quality ($\beta=0.42$), reflecting meaningful differences in baseline sleep patterns between participants.

In addition, the mediation analysis revealed a significant indirect effect of impulsivity at P1 on sleep quality at P3 through cognitive arousal at P2 ($\beta=0.128$; Boot 95% CI: 0.096–0.176). This confirmed that impulsivity indirectly impacts sleep quality via cognitive arousal, providing robust evidence for the proposed mediating role of cognitive arousal in the relationship between impulsivity and sleep quality. However, this mediation was partial, as the direct effect of impulsivity at P1 on sleep quality at P3 was also significant ($\beta=-0.263$; Boot 95% CI: −0.413 to −0.165).

Discussion

The present research aimed to investigate the longitudinal relationships between impulsivity, cognitive arousal, and sleep quality among college students. Specifically, it sought to assess whether cognitive arousal mediates the impact of impulsivity on sleep quality over time. The results revealed strong stability in impulsivity, cognitive arousal, and sleep quality across three distinct waves and demonstrated significant cross-lagged effects between these variables. Impulsivity was found to significantly predict cognitive arousal across time points, which in turn negatively affected sleep quality. Furthermore, cognitive arousal was confirmed as a significant mediator in the relationship between impulsivity at P1 and sleep quality at P3. These findings contribute to the growing literature exploring the intricate links between impulsive behavior, cognitive states, and sleep outcomes, highlighting the mediating role of cognitive arousal in the impulsivity-sleep quality relationship.

The stability of impulsivity across time is consistent with previous research, which has emphasized impulsivity as a stable personality trait. For instance, studies by Cyders & Smith, (2008) and Swann et al. (20022) Cyders & Smith, (2008) and Swann et al. (2002) have shown that impulsivity remains relatively consistent across developmental stages, particularly in adolescence and young adulthood. This aligned with our findings that impulsivity in P_1 strongly predicted impulsivity in P_2 and P_3, suggesting that impulsive tendencies are not transient but persist over time in the student population. This stable nature of impulsivity highlighted its potential as a critical predictor of other behavioral outcomes, such as cognitive arousal and sleep quality.

The observed positive cross-lagged effects between impulsivity and cognitive arousal indicated that individuals exhibiting higher levels of impulsivity are more likely to experience a subsequent increase in cognitive arousal over time. This finding is substantiated by prior research indicating that individuals characterized by high levels of impulsivity are more likely to participate in stimulating activities, frequently occurring during late-night hours, such as media consumption and socializing, which in turn enhance cognitive arousal[86]. Furthermore, the propensity to act without considering long-term ramifications, a defining characteristic of impulsivity, may lead to engaging in actions that disrupt the wind-down process before sleep, thereby escalating cognitive arousal[86,87]. This observation aligns with theoretical frameworks like the BIS/BAS model[88], which suggests that individuals exhibiting a heightened BAS, a characteristic intimately associated with impulsivity, are more prone to seek rewarding stimuli, thereby augmenting cognitive activity and postponing sleep initiation.

The negative relationship between cognitive arousal and sleep quality is well-documented in the literature. Research consistently showed that heightened cognitive arousal before sleep is one of the strongest predictors of sleep disturbances, including difficulty falling asleep and fragmented sleep[89]. Our findings supported this by demonstrating that higher levels of cognitive arousal at P_1 and P_2 significantly predicted poorer sleep quality at P_2 and P_3, respectively. These results aligned with the arousal regulation model[43], which suggested that increased pre-sleep cognitive arousal impedes the ability to initiate and maintain sleep, leading to poorer sleep outcomes. Cognitive arousal may prolong sleep latency and reduce sleep efficiency by preventing the relaxation and disengagement necessary for sleep onset.

Our study's findings aligned with the dual-process model of sleep regulation, which posits that sleep is governed by both homeostatic and circadian processes and cognitive and emotional factors[42]. Impulsivity, by disrupting self-regulation, may hinder individuals' ability to adhere to their circadian rhythms and respond appropriately to homeostatic sleep pressure[90,91]. This disruption is further compounded by heightened cognitive arousal, which interferes with the homeostatic process of sleep induction. The transactional model of stress and coping[92]also provided a valuable framework for understanding these dynamics. Impulsive individuals may cope with stress in maladaptive ways, such as engaging in stimulating activities late at night, which heightens cognitive arousal and further disrupts sleep[86,93].

Empirically, our findings extended previous cross-sectional research by providing longitudinal evidence that impulsivity and cognitive arousal predict poorer sleep quality over time. Prior studies have documented the link between impulsivity and sleep disturbances, but these studies primarily focused on single time points[94–96]. By employing a longitudinal design, our study demonstrated that the relationship between impulsivity, cognitive arousal, and sleep quality persists across different stages of the academic year, providing more substantial evidence for the causal direction of these associations. Furthermore, while much of the existing literature focuses on Western populations, our study contributed novel insights by examining these relationships in a non-Western context. Cultural differences in sleep patterns, media use, and stress coping strategies may influence how impulsivity impacts cognitive arousal and sleep, making our findings particularly relevant for understanding these dynamics in diverse populations.

One of this study's unique contributions was identifying cognitive arousal as a significant mediator between impulsivity and sleep quality. This finding aligned with research by Zhu et al. (2021), which also identified cognitive arousal as a critical mechanism linking impulsive behaviors to poor sleep outcomes[17]. However, unlike previous studies focusing primarily on bedtime procrastination or electronic media use as mediators[86], our study highlighted the broader role of cognitive arousal in mediating the impulsivity-sleep relationship. This suggested that interventions targeting cognitive arousal—such as cognitive-behavioral therapy for insomnia (CBT-I)—may effectively mitigate the negative effects of impulsivity on sleep.

The increasing correlations between impulsivity, cognitive arousal, and sleep quality from P_1 to P_3 suggested that these relationships may intensify over time. This could be due to the cumulative effects of stress and academic pressures as the academic year progresses. Research by Becker et al. (2018) Becker et al. (2018) has shown that sleep quality tends to worsen during periods of high academic stress, such as exam preparation, which may exacerbate the effects of impulsivity and cognitive arousal on sleep. The fact that impulsivity and cognitive arousal at P_2 and P_3 are more strongly associated with sleep quality than at P_1 supports this notion, indicating that interventions to reduce cognitive arousal and impulsive behaviors may become increasingly important as the academic year advances.

The present investigation furnished robust empirical support for the enduring associations between impulsivity, cognitive arousal, and sleep quality, as observed longitudinally. Impulsivity exhibited temporal stability and consistently forecast elevated levels of cognitive arousal, which, in turn, adversely impacted sleep quality. Such revelations find corroboration in both empirical studies and preeminent theoretical models, including the Behavioral Inhibition System/Behavioral Activation System (BIS/BAS) framework, arousal regulation paradigms, and the dual-process model of sleep regulation. Notably, this investigation extends the boundaries of existing research by elucidating these relationships within a longitudinal context and among a non-Western demographic, thereby proffering crucial insights for devising interventions to ameliorate sleep quality in individuals characterized by heightened impulsivity.

In this study, we focused on examining unidirectional associations from impulsivity to cognitive arousal and sleep quality based on a theoretical model in which impulsive behaviors are considered precursors that heighten cognitive arousal and interfere with sleep. Prior research supports the influence of impulsivity on pre-sleep behaviors, such as electronic use or social engagement, which stimulate mental alertness and delay sleep onset[98,99]. While bidirectional relationships are possible, the study's primary aim was to test the time-ordered effects of impulsivity on sleep-related outcomes using an autoregressive model focused on predictive consistency rather than reciprocal causation. Future research may benefit from testing bidirectional pathways to explore these relationships further.

Theoretical implications
This study enriches our comprehension of the intricate relationship between impulsivity and sleep quality among college students by underscoring the mediating influence of cognitive arousal. It extends existing cognitive and behavioral theories, such as the Behavioral Inhibition System/Behavioral Activation System (BIS/BAS) theory, by providing empirical evidence that supports the role of cognitive arousal in exacerbating the adverse effects of impulsivity on sleep patterns. Furthermore, it augments the dual-process model of sleep regulation, elucidating how cognitive processes, modulated by impulsivity, can disrupt intrinsic sleep regulatory mechanisms. The findings advocate for an expanded theoretical framework encompassing cognitive arousal as a pivotal factor in the dynamic interplay between impulsive behaviors and compromised sleep quality.

Practical implications
From a practical standpoint, the study accentuates the imperative for interventions to mitigate impulsivity and cognitive arousal among college students to enhance sleep quality. Educational institutions are encouraged to devise targeted strategies, such as time management workshops and impulse control training, to curtail impulsivity-driven behaviors deleterious to sleep (e.g., late-night media consumption). Moreover, integrating cognitive-behavioral approaches, like Cognitive Behavioral Therapy for Insomnia (CBT-I), into student wellness initiatives can provide students with relaxation techniques and cognitive restructuring strategies to counteract pre-sleep arousal. Sleep hygiene education, attuned to the impulsive characteristics of this demographic, should promote consistent sleep schedules and reduce evening exposure to electronic devices. The longitudinal nature of the study's findings underscores the necessity for sustained interventions throughout the academic year rather than one-off initiatives. Such pragmatic applications have the potential to foster healthier sleep habits and improve overall well-being among college students.

Limitations
The present study has several limitations. First, relying on self-reported measures for impulsivity, cognitive arousal, and sleep quality may introduce bias due to inaccurate recall or social desirability. Future research could incorporate objective sleep measures like actigraphy. Second, the six-month intervals between data collection points may not capture short-term fluctuations in these variables. More frequent data collection could better understand how impulsivity and cognitive arousal influence sleep quality in the short term. Third, the sample was limited to college students from Islamabad, Pakistan, which may restrict the generalizability of the findings. Future studies should replicate the research in diverse cultural contexts. Additionally, this study did not control potential confounders, such as stress, physical health, circadian rhythm, academic workload, and psychological conditions, which may have influenced the observed relationships among impulsivity, cognitive arousal, and sleep quality. For instance, stress could increase cognitive and somatic arousal, potentially exacerbating impulsive behaviors and disrupting sleep quality[100]. Future research should consider controlling for these variables or examining them as moderators to better understand their impact on these dynamics.

Conclusion
In conclusion, this study provides valuable insights into the longitudinal relationships between impulsivity, cognitive arousal, and sleep quality among college students. The findings suggest that impulsivity directly impacts sleep quality and indirectly worsens it through increased cognitive arousal. These relationships remained stable over time, emphasizing the persistent influence of impulsivity on sleep disturbances. Addressing impulsive behaviors and cognitive arousal through targeted interventions may offer practical ways to improve sleep quality. Further research is needed to explore these dynamics in diverse populations and with more frequent data collection intervals to understand short-term variations better.

Data availability
The raw data supporting the findings of the present work are available upon reasonable request from the corresponding author Erum Rehman: erumrehman1990@gmail.com.

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Declarations

Competing interests
The authors declare no competing interests.

Informed consent
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