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Circadian Disruption from Afternoon Caffeine Implicates Impaired Predictive Coding in High School Juniors

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ABSTRACT

Predictive coding refers to the hierarchical neuronal process in which the brain generates expectations about incoming sensory information and minimizes prediction error. This system is critically dependent on sleep quality-particularly REM (rapid eye movement). REM supports synaptic downscaling, hippocampal replay, and prefrontal-hippocampal plasticity. Although juniors in high school frequently consume caffeine late in the day, the potential impact of caffeine timing on predictive coding related functioning has not been extensively examined.

This study investigated whether caffeine intake after 3pm is associated with reduced predictive coding abilities in high school juniors. Forty juniors from a variety of North Carolina high schools completed an extensive survey assessing sleep timing, caffeine consumption, and everyday cognitive behaviors. These behaviors related to prediction, error detection, and mental sharpness, allowing us to assess predictive coding ability and cognitive processes.

Students who consumed caffeine after 3 pm reported a similar sleep duration to other juniors who avoided consuming caffeine in the late afternoon. Surprisingly, they went to bed significantly later and exhibited lower predictive coding scores. This suggests that caffeine may disrupt REM-dependant neural processes, even though total sleep time appears adequate. REM sleep supports synaptic homeostasis, hippocampal ripple-spindle coupling, and the updating of internal generative models. Because of this, reductions in REM quality may impair the brain's ability to efficiently process errors in prediction.

These results align with prior juvenile sleep research. These findings show that afternoon caffeine delays sleep onset, reduces REM sleep, and impairs attention and error monitoring. They also highlight the importance of caffeine timing in shaping cognitive efficiency during a period of increased academic demand, a common experience during junior year. Understanding how everyday habits such as late-day caffeine use influence prediction, attention, and cognitive stability (predictive coding) can potentially help students make positive choices that better support learning, performance, and well-being.

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1. INTRODUCTION

Junior year of high school is widely recognized as a period of intense academic pressure, increased workload, and heightened cognitive demand. Approximately 73% of US youth consume caffeine daily (Ahluwalia et al., 2014), while only 23% obtain the recommended 8-10 hours of sleep (CDC, 2020). Despite this, many students who report feeling mentally foggy or error prone still achieve seven or more hours of sleep, which is the same duration as peers who feel alert and cognitive stable. This suggests that sleep quality, rather than sleep quantity, may be the primary factor influencing cognitive performance.

Predictive coding, the brain's primary framework for generating expectations and minimizing error in predictions, may be particularly sensitive to sleep quality. Predictive coding operates under a hierarchical system: lower level sensory regions predict simple features, while higher-level cortical areas generate expectations about objects, language, and context. When predictions fail, the resulting mismatch, or predictive error, is used to update prediction models and improve accuracy in the future (Friston, 2010). Deficits in attention, working memory, and error monitoring-core components of predictive coding-have been linked to sleep disruption in adolescents (Killgore, 2010).

Sleep plays a vital role in maintaining this system. REM sleep, the sleep stage associated with vivid dreaming and heightened brain activity, supports synaptic downscaling, memory consolidation, and the integration of new information into existing generative models (Tononi & Cirelli, 2014). Synaptic downscaling refers to the nightly reset of neural connections to prevent overload, while sleep spindles (brief bursts of brain activity during lighter sleep) help stabilize memory traces and support learning (Rasch & Born, 2013). Even small shifts in sleep timing can disproportionately affect REM sleep and quantity of it. This illustrates that caffeine consumed in late afternoon may disrupt the very sleep stages most critical for cognitive stability.

Caffeine interferes with these processes by blocking adenosine receptors, which normally promote sleep pressure and signal the brain to wind down. Teenagers experience a biological circadian delay (a natural shift that makes one feel sleepy later in the night) making them biologically inclined to fall asleep later than adults (Crowley et al., 2018). Accumulating to this, teens metabolize caffeine 30-50% more slowly than adults (Temple et al., 2017). Caffeine has a half-life of approximately 5-7 hours in adults, and in youth this window can be even longer due to slower metabolic clearance (Temple et al., 2017). Because of this, caffeine consumed at 3 pm may remain active physiologically close to midnight, overlapping with the period when REM sleep becomes increasingly dominant.

A recent sleep study on juveniles demonstrated that afternoon caffeine delays sleep and reduces the duration of REM sleep (Lunsford-Avery et al., 2022). Controlled sleep laboratory research likewise shows that evening caffeine reduces sleep efficiency, increases night time wakefulness, and alters sleep architecture (the pattern and structure of one's sleep across the night) in ways that affect REM periods and length (Drake et al., 2013). Caffeine also increases evening cortisol levels, which further delays sleep and reduces REM (Lovallo et al., 2005). Because REM sleep supports synaptic homeostasis (the brain's ability to maintain stable neuronal circuit function despite continuous learning), hippocampal ripples (high frequency electrical oscillations generated by neuronal assemblies), and spindle-driven plasticity (the brain's ability to reorganize, strengthen, or weaken connections between neurons during sleep), reductions in REM quality may impair the brain's ability to update models and process prediction errors effectively (Tononi & Cirelli, 2014; Rasch & Born, 2013). The combination of delayed sleep and reduced REM sleep creates a sleep architecture that is less supportive of neuronal adjustment required for efficient predictive coding.

This present study examines whether caffeine intake after 3 pm is associated with lower predictive coding abilities in high school juniors, a population undergoing neurodevelopment and facing extreme cognitive demands.

2. METHODS

2.1 Participants

Forty high school juniors from multiple North Carolina schools participated in the study. The sample included students of diverse socioeconomic backgrounds, genders, and school types (public and private). Participants varied in extracurricular involvement, including athletics, employment, and club participation, providing a diverse representation of junior-year lifestyles.

2.2 Procedure

Participants completed an anonymous online survey. To minimize variability in alertness, they were instructed to complete the survey in the morning. The survey required approximately 10-25 minutes and included items assessing bedtime (sleep timing), caffeine intake, and predictive-coding-related behaviors.

In addition to the survey, participants completed a week-long series of predictive coding questions, consisting of five questions per test delivered at three different times of day: morning, afternoon, and right before bed. This expanded procedure allowed for a more accurate assessment of daily fluctuations in predictive coding ability and provided a behavioral measure that complemented the self report survey.

2.3 Measures

2.3.1 Sleep Measures

Sleep patterns were assessed using self-report items measuring bedtime, wake time, total sleep duration, and perceived sleep quality. Participants reported typical weekday sleep schedules and whether they felt rested upon waking. Although the recommended sleep duration for teenagers is 8-10 hours, this study used 7 hours as the threshold for adequate sleep, considering the practical constraints of junior-year academic demands.

2.3.2 Caffeine Intake Measures

Participants reported whether they consumed caffeine after 3 pm, the type of caffeinated beverage (including coffee, soda, energy drinks), and the frequency of intake in late day. Responses were used to categorize participants in two groups: caffeine after 3 pm and no caffeine after 3 pm.

2.3.3 Predictive Coding Measures

Predictive coding ability was assessed using both self-report items and behavioral accuracy tasks.

The self-report portion included questions targeting response time, pattern recognition, error prediction, and mental sharpness. Example items included:

“How mentally sharp do you feel right now?”

“How often do you feel yourself making small mistakes in the morning?”

“How often do you reread or recheck things because you’re unsure?”

These questions served as behavioral indicators of predictive coding efficiency in everyday tasks.

To supplement these items, participants also completed predictive coding accuracy questions over the course of one week. These were administered in the morning, afternoon, and right before bed. These tasks required students to make quick predictions or identify patterns. Their responses were scored based on the percentage of correct answers at each time point.

2.3.4 Predictive Coding Ability Score (PCAS) Equation

All predictive coding data (self-report items and accuracy based questions) were converted into a unified scoring system to create the Predictive Coding Ability Score (PCAS).

For the behavioral accuracy tasks, percentage-correct values were converted into a scale of 1-5:

90% or above correct=5

70-80% correct=4

55-70% correct=3

25-55% correct=2

0-25% correct=1

Self-report items were also scored on a scale of 1-5. For questions in which higher numbers represented better functioning, values were reverse-scored so that a 5 became a 1, a 4 became a 2, etc., ensuring that all items were contributed in the same direction.

After scoring, all values were doubled to produce a final range of 1 to 10, with higher scores reflecting stronger predictive coding abilities and lower scores indicating greater difficulty with prediction, error monitoring, or mental sharpness. The final PCAS was calculated using:

$PCAS=2\times(\Sigma x/n)$

where Σx represents the sum of all predictive coding item scores (after reversing scoring and accuracy conversion), and n represents number of items.

3. RESULTS AND ANALYSIS

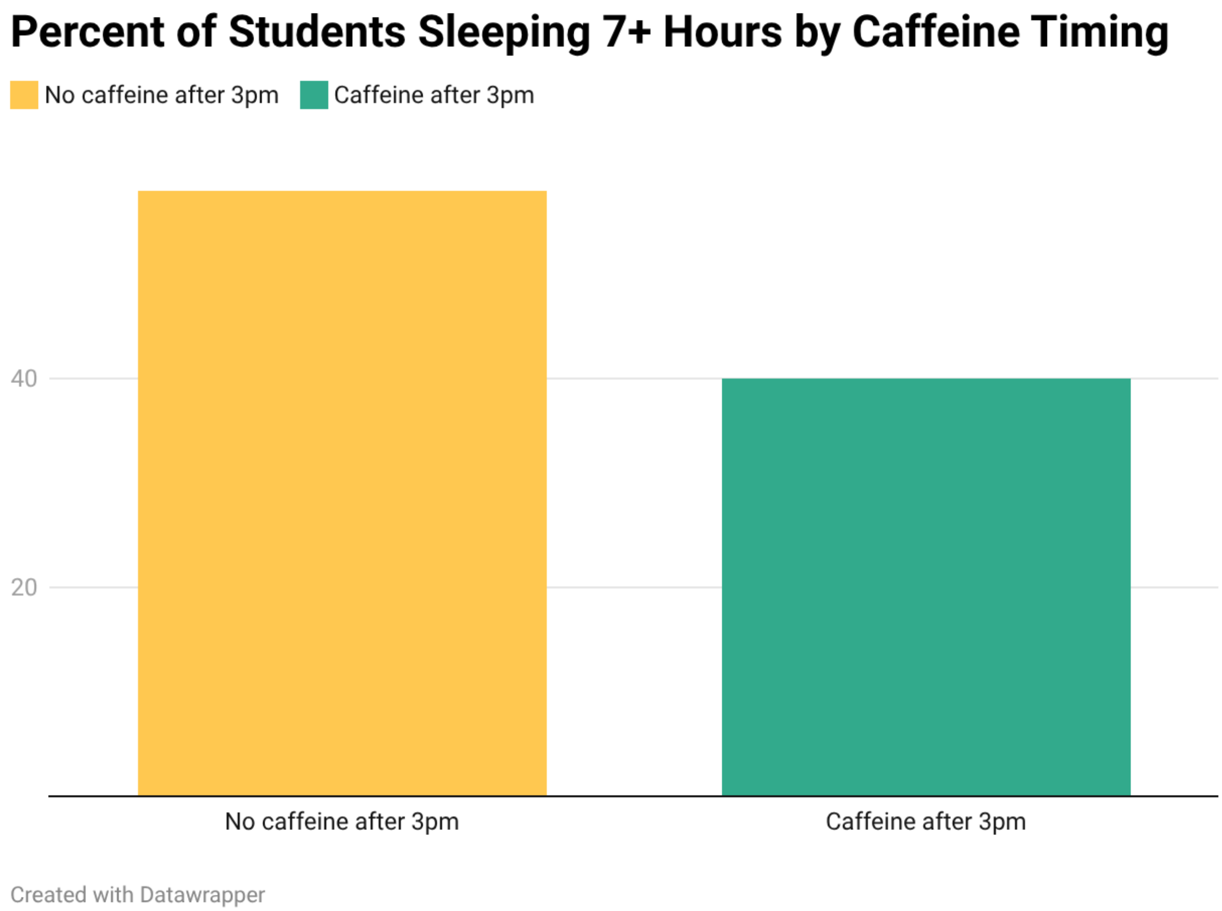

Figure 1.
Students consuming caffeine after 3 pm achieved a similar total sleep duration to those who avoided late-day caffeine, indicating that sleep quantity alone does not explain differences in predictive ability.

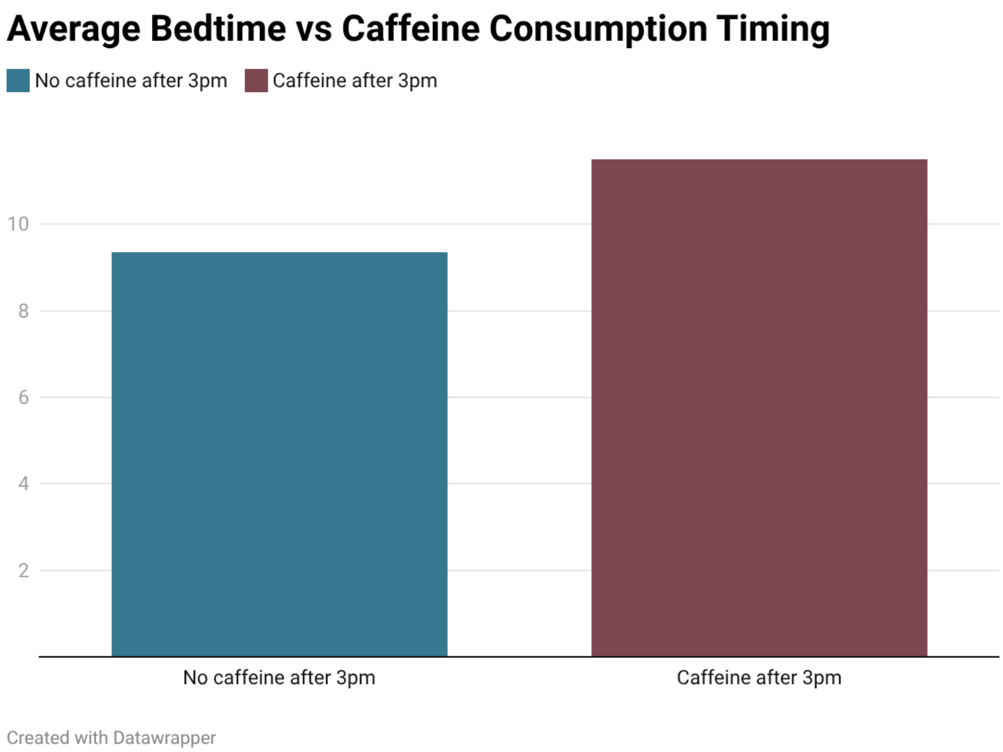

Figure 2.
Late-day caffeine users exhibited significantly later bedtimes, consistent with caffeine-related circadian delay.

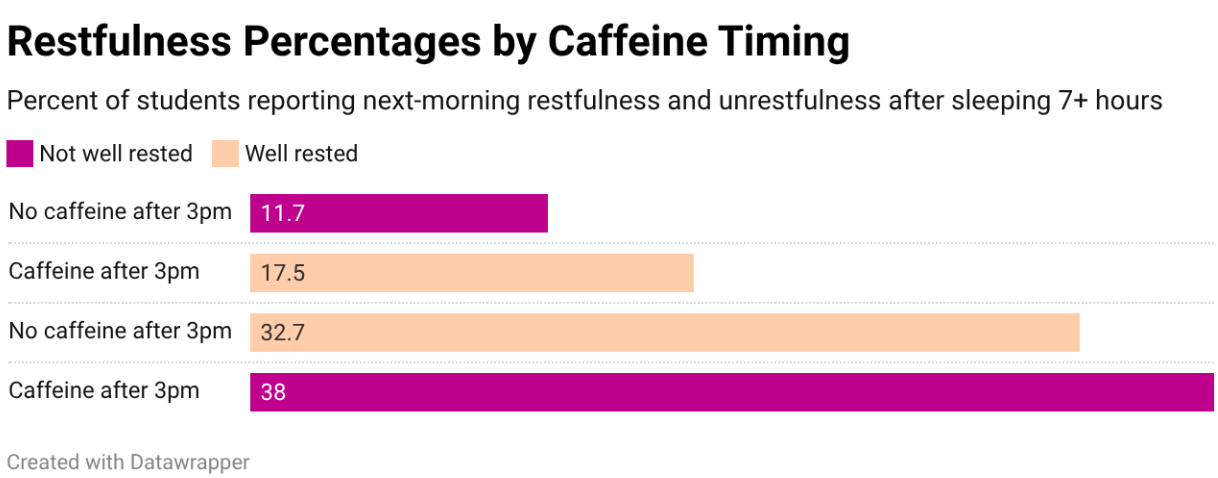

Figure 3.
Students avoiding late-day caffeine were more likely to report feeling rested. To contrast, students consuming late-day caffeine were more susceptible to report not feeling rested, suggesting differences in sleep quality.

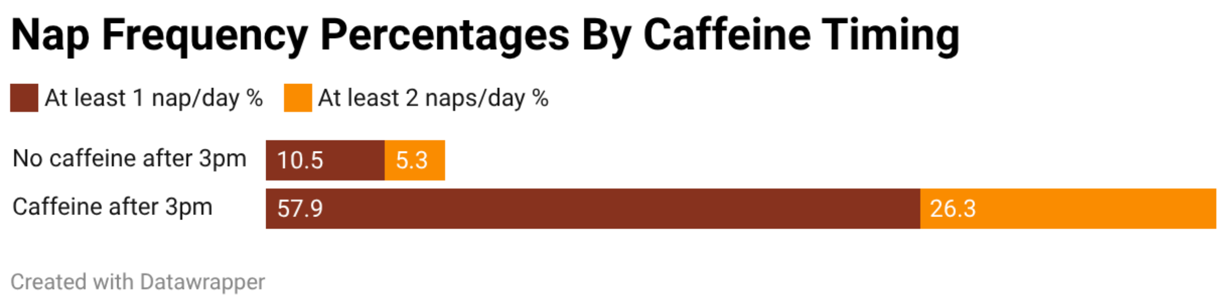

Figure 4.
Students consuming caffeine after 3 pm reported more frequent napping, consistent with reduced nighttime sleep quality.

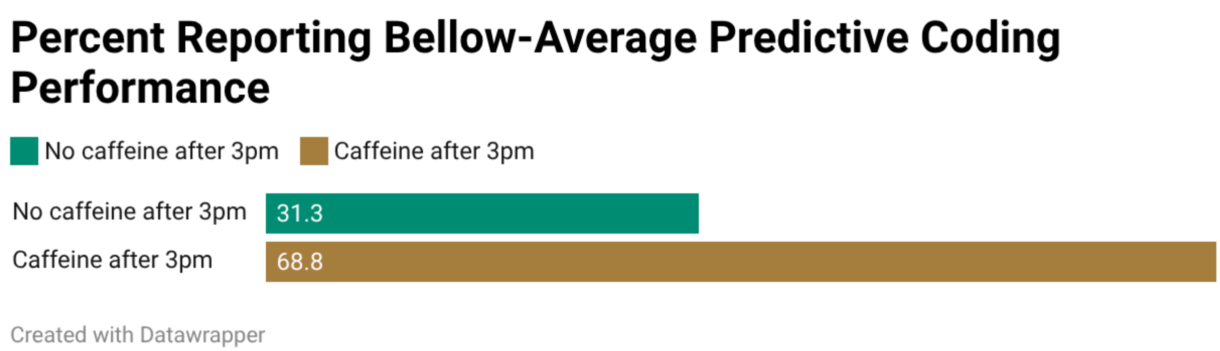

Figure 5.
Late-day caffeine users were more likely to report below average predictive coding ability and more frequent errors on the first self-reported survey.

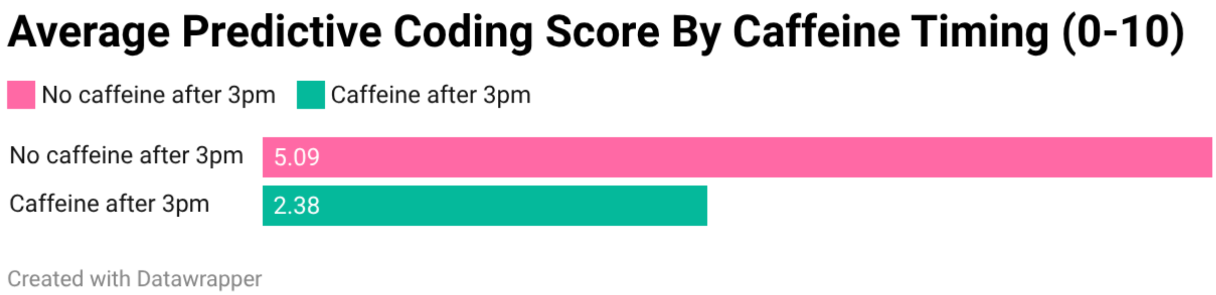

Figure 6.
Students consuming caffeine after 3 pm exhibited lower PCAS scores, indicating reduced predictive coding functioning.

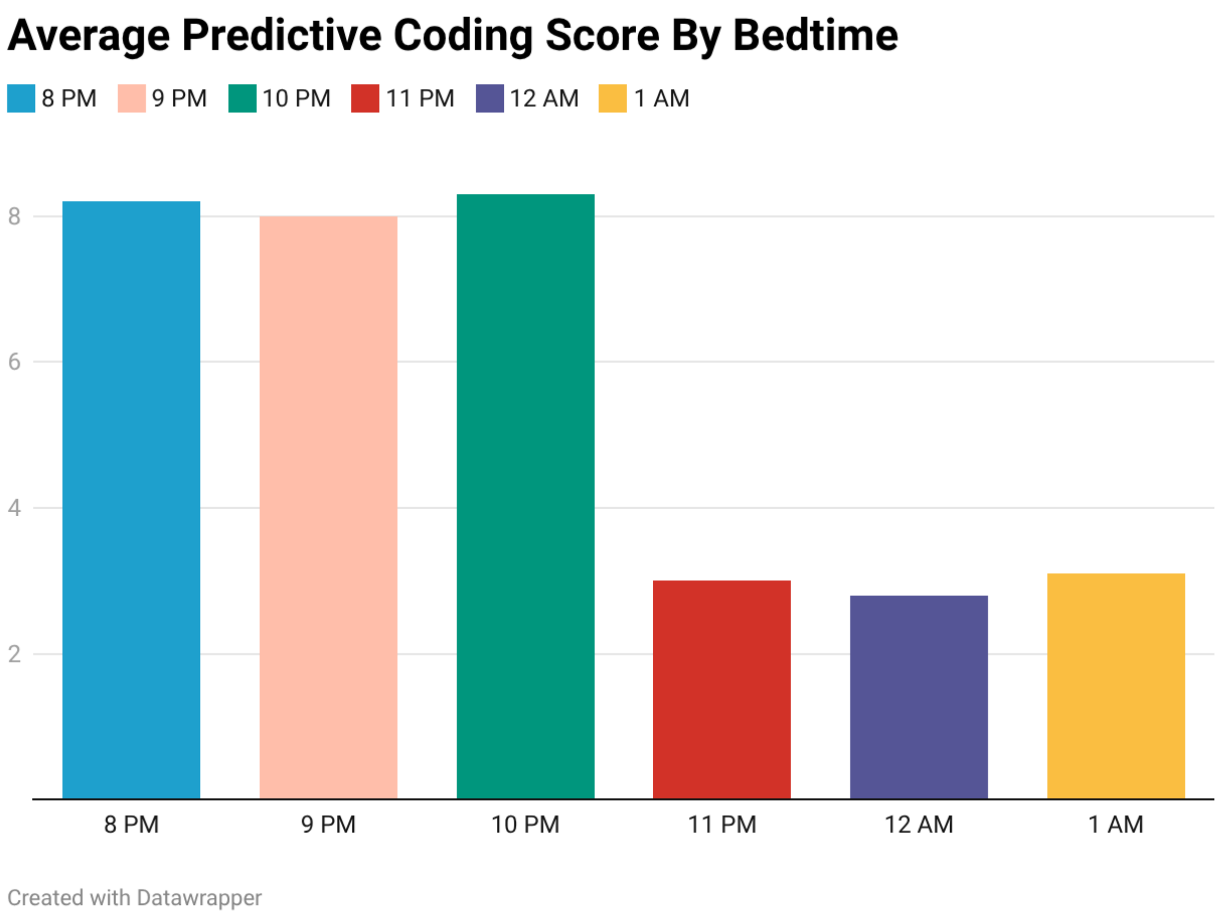

Figure 7.

Later bedtimes were associated with lower PCAS scores, suggesting that sleep timing, rather than duration, affects predictive coding.

4. DISCUSSION

Although both groups in this study reported sleeping seven or more hours, their predictive coding scores differed significantly. Students who avoided caffeine after 3 pm demonstrated higher PCAS scores and earlier bedtimes. These findings suggest that sleep timing and REM quality may be more important for predictive coding function than total sleep duration. This distinction is crucial because teenagers often assume that meeting a minimum sleep duration is sufficient for cognitive performance. These findings indicate that even when sleep quantity appears adequate, disruptions to sleep architecture may impair the mechanisms that support predictive coding ability.

Juniors may underestimate the cognitive consequences of late-day caffeine use. This is another important implication of these findings. Many students consume caffeine in the afternoon to cope with academic demands, believing that it will improve alertness and productivity; however, the results suggest that this strategy may backfire by impairing the REM-dependant processes that support learning, attention, and error detection. Caffeine may delay REM sleep or reduce its continuity. If this occurs, students may experience increased prediction error, slower cognitive processing, and reduced mental clarity the following day. These effects can accumulate over time. This could potentially contribute to chronic predictive coding inefficiencies during periods of heightened academic pressure.

The findings also highlight the importance of circadian timing. When caffeine is added to this already delayed circadian rhythm teenagers experience, the effect may push REM sleep even later into the night or compress it into a shorter window. Students with later bedtimes tended to have lower predictive coding scores. This suggests that circadian misalignment itself may impair predictive coding. Afternoon caffeine consumption may therefore exacerbate an existing developmental vulnerability, amplifying the consequences of delayed sleep timing on the predictive coding abilities of juniors in everyday life.

An additional consideration is the steep decline in predictive coding scores observed between 10 pm and 11 pm. Although this appears abrupt, it aligns with known circadian and homeostasis dynamics in teenagers. Between 10 pm and 11 pm, teenagers enter a period in which homeostatic sleep pressure (the biological drive to sleep that continuously builds the longer one sleeps) is high, but circadian alerting (a 24 hour biological process that actively promotes wakefulness and alertness) remains high or strong. This variance is associated with lighter sleep, reduced REM continuity, and less efficient memory consolidation. Because predictive coding performance depends heavily on the prefrontal cortex efficiency (one of the first cognitive domains to decline when sleep becomes fragmented) this transition may produce a sharper drop than would be expected from bedtime differences alone. However, additional data with finer time resolution would help determine whether this drop reflects a true physiological threshold or sample-specific variability.

Finally, these results have practical implications for junior's health and education. High school juniors face substantial academic demands, including complex problem-solving, sustained attention, and rapid error detection. Predictive coding supports each of these functions. If afternoon caffeine disrupts the neuronal processes behind predictive coding, students may experience increased small mistakes, reduced mental sharpness, and difficulty anticipating outcomes-symptoms commonly reported by adolescents who rely on caffeine to manage academic workloads. Teachers, parents, and students may benefit from greater awareness of how caffeine consumption timing affects predictive coding.

5. LIMITATIONS

This study has several limitations that should be considered when interpreting the findings. First, although participants were drawn from multiple high schools, the sample was limited to students within North Carolina. Regional differences in school start times, academic culture, caffeine availability, and sleep norms may limit the reliability of the results to adolescents in other states or countries. A broader, more geographically diverse sample would strengthen the validity.

Second, some measures relied on self-report, including caffeine timing, sleep duration, sleep quality, and predictive coding related behaviors. Self-reported data are vulnerable to recall bias, social desirability bias, and inaccurate estimation of sleep timing. Teenagers often misjudge their own sleep onset and wake times, and they may underreport caffeine intake. Objective measures such as actigraphy (a non invasive method used to record sleep), polysomnography (test that records physiological activity while one sleeps), or biochemical caffeine assays (measures used to detect, identify, and measure caffeine) could provide more precise and reliable data.

Third, the study design was correlational, preventing causal conclusions. While late-day caffeine use was associated with lower predictive coding scores and later bedtime, it cannot be determined whether caffeine directly caused these differences. Unmeasured variables may also contribute to the observed patterns. These include academic stress, chronotype, baseline anxiety, or individual differences in caffeine sensitivity. Experimental designs manipulating caffeine timing would allow for stronger inferences.

Fourth, the steep decline between 10 and 11 in figure 7 should be interpreted cautiously, as additional data with finer time resolution would be needed to determine whether the pattern truly reflects a psychological pattern or is sample-specific.

Finally, the sample size of forty participants, while adequate for exploratory analysis, limits statistical power and the ability to detect subtle effects. Larger samples would allow for more robust group comparisons and the examination of moderating variables such as gender, extracurricular load, or habitual caffeine use. Despite these limitations, the study provides meaningful preliminary evidence that caffeine timing may influence predictive coding related functioning in high school juniors and highlights the need for further research using longitudinal approaches.

6. FUTURE DIRECTIONS

Future research could examine how different types of caffeine (such as coffee, soda, energy drinks) influence predictive coding differently. Tracking sleep stages directly using wearable devices would allow for more accurate measurement of REM sleep. Expanding the study to include multiple age groups could clarify whether late-day caffeine has stronger cognitive effects in juniors in high school than in adults.

Future work using larger samples could help determine whether the sharp decline between 10 pm and 11 pm reflects a true pattern in neuroscience.

7. CONCLUSION

This study suggests that caffeine consumed after 3 pm is associated with reduced predictive coding abilities in high school juniors, even among students who report obtaining 7 or more hours of sleep. The key difference appears to be sleep timing and REM quality rather than total sleep duration. Students who consume caffeine later in the day tended to fall asleep later and exhibited lower predictive coding scores. This is consistent with research linking caffeine to disrupt sleep architecture and impaired cognitive functioning. These findings highlight the importance of caffeine timing for junior’s brain function and suggest that even small shifts in sleep patterns meaningfully affect cognitive processes involved in prediction, attention, and error monitoring. As academic demands intensify during junior year, understanding how everyday habits influence cognitive performance may help students make choices that support everyday habits influence cognitive performance may help students make choices that support learning and well-being, and allow them to thrive in one of the most vital years of study.

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