The Caffeine-Cognitive Connection: How Moderate Caffeine Consumption Enhances Working Memory of High Schoolers

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BRIEFS. This study examines the impact of caffeine on working memory of adolescents.

ABSTRACT. This study aims to explore the correlation between teenagers' habitual caffeine consumption and their working memory (WM). As caffeine consumption among adolescents rises, it is essential to understand its effects on cognition, specifically WM. While existing research has mainly examined caffeine's impact on WM in adults or young children, habitual caffeine consumption in high school students remains unexplored. To address this gap, the study used a quasi-experimental design involving 16 high school students aged 16-18 from diverse backgrounds. Participants' caffeine consumption habits were assessed through a survey, followed by the Digit Span Task in Aug-Sept 2023. Results demonstrated a significant improvement in WM, evidenced by improved speed and accuracy, after caffeine consumption. Notably, students with moderate caffeine intake (2-4 days per week) exhibited the most significant enhancements in WM, suggesting that moderate caffeine use may improve cognitive function in adolescents. However, the study's limitations include a small sample size and indirect caffeine administration, which could affect the results.

INTRODUCTION.

Memory is a crucial component of cognition that significantly impacts efficiency and effectiveness in our daily life. It is not a singular entity but comprises various systems, each managed by distinct brain regions. These systems include episodic memory for events, procedural memory for skills and habits, semantic memory for knowledge, and working memory (WM), which involves holding and processing information in the short-term amidst distractions [1]. Each memory system operates through different cortical areas and functions uniquely.

Approximately 10% of the global population experiences WM difficulties, which can severely affect their ability to complete everyday tasks [1]. Definitions of WM vary among researchers, with Cowan's definition, which our study used, emphasizing its role in retaining a small amount of readily accessible information [2]. Stress, mental illness, and sleep deprivation negatively impact WM [3][4].

In recent years, caffeine consumption has surged, with Americans consuming coffee more frequently than tap water. Approximately 80% of the global population consume caffeine [5][6]. Caffeine is a psychoactive substance that accelerates both mental and physical processes [7]. While coffee remains the primary source of caffeine, energy drinks have gained popularity among younger consumers. Caffeinated beverages contain varying caffeine concentrations, influencing cognitive function differently [8].

Studies indicate that moderate caffeine consumption benefits adult cognition, improving attention, efficiency, and reaction time. Optimal caffeine intake ranges from 38 to 400 mg, balancing benefits and risks [9]. A systematic review found that 14 out of 16 studies on healthy adults demonstrated improvements in alertness and short-term memory recall with moderate caffeine consumption [9]. Despite these benefits, excessive caffeine can negatively impact sleep and cognitive function, particularly in sensitive individuals such as those with anxiety disorders [10].

In young children, there is a divergence in findings on the effect of caffeine on WM. While some studies suggest caffeine improves cognition in children, particularly sustained attention and vigilance [11], others indicate negative impacts on various cognitive abilities, including WM and processing speed [12]. The effects of caffeine on developing brains are not fully understood, but it is believed that caffeine tolerance increases from childhood to adolescence, aligning adolescent responses more closely with those of adults [13]. Further research is needed to address the gaps in understanding caffeine's impact during critical developmental stages, as current literature solely analyzes the working memories of young children and adults in response to caffeine, omitting adolescents.

Neurologically, WM involves activation in the frontal-parietal regions of the brain, including the prefrontal, cingulate, and parietal cortices, with subcortical regions also playing a role [14]. Brain development typically concludes around age 26. High school students are in a transitional phase, with their cognitive profiles reflecting both adolescent and adult characteristics. Their cerebral structures are complex, but certain areas such as the prefrontal cortex, are still maturing. This development may affect how emotions and impulses interact with cognitive processes. Furthermore, the lateral prefrontal cortex experiences a higher brain entropy in adults after consuming caffeine, but due to the incomplete development, the effects on adolescents are inconclusive [15]

While the benefits of caffeine on adult WM are well-documented, its effects on high school students remain underexplored. Considering the neurological effects observed in different age groups, it is plausible that caffeine's cognitive effects in high school students may be more akin to those seen in adults rather than young children. Due to teenagers consuming increasing amounts of caffeine regularly, it is essential to investigate its impact on their developing brains' cognitive performance. This paper aims to illustrate the nuanced correlation between caffeine intake and cognitive function in this demographic.

METHODS.

This study involves a quasi-experimental method. The survey gathered data on participants' caffeine consumption habits, which was used to segment the group. The protocols of this study were reviewed and approved by an IRB prior to the conduction of the experiment

A sample of 16 high school students, aged 16 to 18, from a high school in New Jersey during the 2023-2024 academic year, was recruited. The sample, consisting of 10 females and 6 males, was homogeneous in terms of educational background. Students aged 18 were provided with informed consent forms and voluntarily agreed to participate in the survey. Students under the age of 18 were required to obtain parent permission and completed an informed assent form. Students with caffeine allergies and sensitivities were excluded. Additionally, one student with abnormal adrenal gland function was excluded.

Survey.

Prior to conducting the WM test, participants completed a detailed survey to baseline their frequency of caffeine intake, symptoms of caffeine sensitivity, and dependency on caffeine. The purpose was to understand how these external factors potentially impact high schoolers'

WM performance. Survey questions were sourced from various online sources and scientific journals, most significantly a study from the International Journal of Mental Health and Addiction [16]. Key questions included the average weekly consumption of caffeine, daily intake of caffeinated beverages, and self-reported reliance on caffeine.

Working Memory Test.

The study's second component consisted of a WM test utilizing the Digit Span Memory Test. Participants memorized and subsequently typed out a series of 8 flashing numbers to the best of their abilities. This test specifically focused on forward sequence recall to facilitate a more practical measure of WM [17]. The Digit Span Memory Test is a well-established tool in cognitive research, used to explore differences related to sex, age, and other factors [18][19]. Moreover, it has been utilized in studies targeting young adults, such as a 2020 examination of the effects of high-intensity interval training (HIIT) [20].

Procedure.

This experiment was conducted over the course of two weeks. Through the online survey, the 16 participants were segmented into three groups based on the number of times per week they consumed caffeine: low (0-2 times), moderate (3-5 times), and high (6+ times). To avoid demand bias, participants were not informed of the group they were a part of. The resulting sample carried the following mix: 6 high, 4 moderate, and 6 low. Participants completed an initial WM test under their usual caffeine habits. The following day, the testing conditions were adjusted: high consumers abstained from caffeine, while low consumers consumed caffeine (1 cup of coffee). For moderate consumers, half were tested without caffeine first and half were tested with caffeine first, to control for test familiarity biases. External variables remained consistent between tests, including test timing and environment, ensuring data integrity. A control group of non-daily caffeine users underwent online WM tests both with and without caffeine to evaluate its effects on individuals who infrequently consume caffeine. Each test was administered three times, and the average results were used. Due to ethical limitations and a majority of the participants being minors, participants self-administered caffeine, with a general guideline of 1 cup of black coffee or an equivalent in energy drink form.

Statistical Analysis.

Data analysis was conducted through Graphpad Prism 10 and Google Sheets. Statistical analysis was performed using t-tests comparing control to experimental data.

RESULTS.

Speed.

Twelve participants exhibited improved speed after caffeine consumption. This subset included 5 of 6 high consumers, all 4 moderate consumers, and 3 of 6 low consumers. Conversely, 4 participants, including 1 high and 3 low caffeine consumers, had slower results post-caffeine.

While the analysis revealed improved speed after caffeine intake across all segments (Figure 1), only moderate consumers showed a statistically significant improvement ($p=0.023$). High caffeine consumers demonstrated a 35% test time reduction (from 12.7 to 8.3 seconds); moderate caffeine consumers by 21% (from 13.2 to 10.4 seconds); low caffeine consumers by 8% (from 11.2 to 10.3 seconds).

Accuracy.

Like the speed analysis, only moderate caffeine consumers demonstrated statistically significant improvement in accuracy ($p = 0.0239$) following caffeine intake (Figure 2).

Fourteen of 16 participants demonstrated improved accuracy post caffeine consumption. This included all 6 high consumers, 3 of the 4 moderate consumers, and 5 of the 6 low consumers. While two participants made more errors following caffeine consumption, a robust correlation between caffeine intake and increased accuracy persisted across all participant categories.

In the absence of caffeine, low consumers averaged 3.5 mistakes, moderate consumers averaged 4.0 mistakes, and high caffeine users averaged 3.8 mistakes. After caffeine intake, the average number of mistakes decreased across all groups: low consumers averaged 2.4 mistakes (31% improvement), moderate and high consumers averaged 2.8 mistakes (30% and 26% improvement respectively.)

Average Trends.

Analysis of the mean speed across all participants demonstrated statistically significant improvement ($p=0.003$) in the speed of response post-caffeine intake (Figure 3). Specifically, the average WM test time

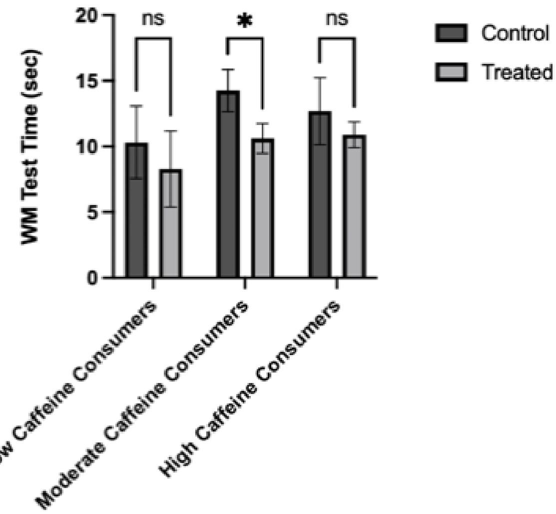

Figure 1. WM Time Grouped by Habits. Significant difference in control and experimental WM time in moderate caffeine consumer group (* indicates that $p<0.05$)

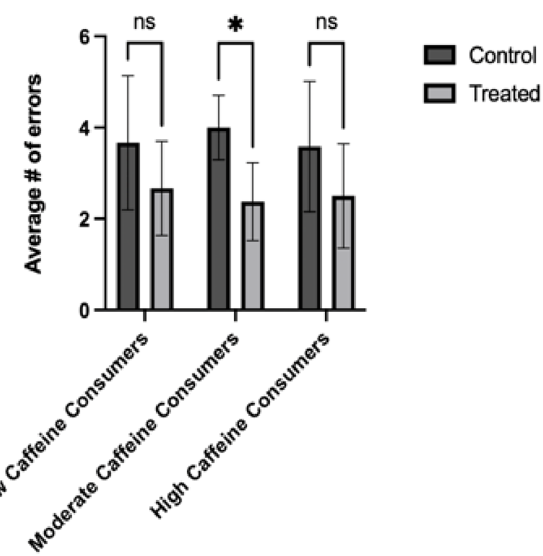

Figure 2. WM Errors Grouped by Habits**.** Significant difference in control and experimental number of errors in moderate caffeine consumer group (* indicates that $p<0.05$)

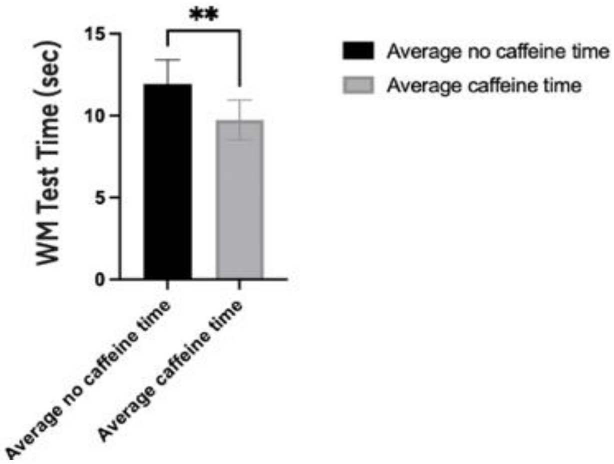

Figure 3. Average WM Time With/Without Caffeine. Significant difference between all participants before/after caffeine (** indicates that p<0.01).

following caffeine intake was 9.7 seconds versus 11.9 seconds prior (18% improvement).

Across all participant groups, an improvement in accuracy was evident, with 14 out of the 16 individuals demonstrating improved performance after caffeine intake. The average reductions in errors ranged from 0.5 errors to 2.5 errors, resulting in an overall average decrease of 1.3 errors among these participants.

DISCUSSION.

The results of this study demonstrated that irrespective of individual caffeine consumption patterns, caffeine intake improves the WM performance of high school students, as reflected in both improved speed and accuracy. This aligns with findings from studies investigating WM in adults.

While exceptions to this observed trend exist - attributable to the staggered neurological development among some teenagers - the overall trend indicates an enhancement in WM following caffeine consumption. As indicated by the existing research, the variability in teenagers' brain development at certain ages underscores the potential for variations in cognitive functioning among participants [21].

Furthermore, individuals with moderate to high caffeine consumption demonstrated a greater effect compared to those with infrequent caffeine intake. This finding aligns with prior studies on habitual caffeine consumption in adults, which explore the neurological effects of caffeine among regular consumers. This heightened effect could be due to the increased tolerance to cerebral vasoconstriction induced by caffeine, resulting in a significant reduction in cerebral blood flow [22].

The low caffeine consumption group displayed varied outcomes. While three out of the six low consumers experienced an improvement in speed following caffeine consumption, the remaining three exhibited the opposite. Notably, two out of the three participants who showed an increase did so by less than one second. This minimal change lacked significance and could be influenced by other factors. Overall, the WM response among low consumers proved inconsistent in terms of a discernible trend, suggesting variability in individual responses to caffeine. This variability likely reflects diverse neurological processes, including those governing WM, underscoring the intricate nature of caffeine's effects on cognitive function.

In the moderate consumer group, all participants experienced an improvement in speed following caffeine consumption. However, one participant displayed a decrease in accuracy after caffeine intake. Notably, the increase in errors for this participant was insignificant at 0.5, whereas the remaining three moderate consumers demonstrated decreases in errors by 1.5, 2.5, and 1 respectively. This pattern suggests that individuals consuming moderate levels of caffeine may exhibit varied reactions, yet the majority tend to benefit neurologically from caffeine consumption [23][24].

Finally in the high caffeine consumption group a notable improvement in both speed and accuracy was observed post-caffeine ingestion. Although not statistically significant, the observed trend indicates a potential positive impact of high caffeine consumption on WM. Notably prior research indicated a negative impact of high caffeine intake, underscoring the need for further investigation [25].

Other studies have found that most healthy individuals are able to recall seven digits ±two digits, corroborating this study's findings. However, one study indicated that individuals ages 16 to 18 recalled an average of 10 digits, a significantly higher number than our baseline scores. Additional studies on teenagers should be conducted to confirm this result as it may have been influenced by uncontrolled environmental factors.

Outliers.

Subject 13 displayed a substantial increase in WM time following caffeine consumption, with a difference of 2.8 seconds. However, it is crucial to contextualize that this participant belonged to the low consumer group and had no prior caffeine consumption history prior to this study. This "outlier" aligns with the study's hypothesis, indicating that individuals who do not habitually consume caffeine may experience a greater negative impact compared to those accustomed to caffeine intake. This finding is supported by research indicating that caffeine consumption induces emotional arousal and psychosocial stress, thereby elevating false memory rates without enhancing veridical memory among non-habitual caffeine consumers [26].

Another outlier worth noting was Subject 10, a high consumer who had a slower response time following caffeine consumption, suggesting a potential decline in WM efficacy with caffeine. However, this participant's increase in WM test time by 0.06 seconds was insignificant.

Limitations.

The primary limitation of this study is the small sample size - larger samples are typically used in comparable neuroscience studies[27]. Additionally, the uneven distribution of caffeine consumers in each group could skew results. Variations in caffeine intake also arose due to ethical constraints on administering caffeine to minors in a school setting; participants were instructed to consume one cup of tea or coffee, but individual intake differences may have introduced bias. These issues collectively impact the robustness and applicability of the study's conclusions.

Next Steps.

Beyond a larger sample, future studies could benefit from more stringent control by directly administering caffeine, which was not feasible due to ethical constraints in this study. By employing more precise measures of WM using techniques like fMRI and fNIRS, which measure brain blood flow to gauge cognition [22][25], this research could provide a more quantifiable measure of change compared to Digit Span Memory Test.

CONCLUSION.

This study delved into the correlation between habitual caffeine consumption and WM among high school students. While existing research has extensively examined caffeine's influence on WM in adults and young children, there is a notable gap concerning its effect on high school students, particularly habitual consumers. Employing a quasi-experimental design involving surveys and WM tests, this study aimed to address this gap and shed light on the cognitive ramifications of caffeine consumption among adolescents.

This study revealed an improvement in speed across all groups following caffeine consumption, with statistically significant results for moderate caffeine consumers. Additionally, there was a notable improvement in accuracy, underscoring caffeine's improvement in adolescent WM performance. These findings imply that habitual caffeine consumption among high school students may contribute to heightened cognitive function, particularly in terms of WM.

By uncovering the potential cognitive advantages associated with caffeine intake among high school students, this research has implications for educational strategies and interventions aimed at enhancing cognitive performance in academic settings.

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