STATS 101B - A Factorial Approach to Assessing Nicotine and Caffeine's Effects on Short-Term Cognitive Performance

Alexander Rike, Mason Lee, Mackenzie Lindholm, George Longridge & Claire Nabours

Introduction

The general interest of this experiment is to investigate the effects of nicotine and caffeine on the brain, specifically on short-term memory. Our motivation for this experiment stems from its relevance to college students' academic pursuits. Many students frequently consume caffeine or nicotine to help stimulate their brains while studying, often believing these substances will enhance cognitive performance and focus. Understanding how these two substances impact short-term memory, either negatively or positively, is key to understanding the effects of caffeine and nicotine on both academic performance and overall short-term cognitive ability.

Our general expectation is that both nicotine and caffeine will increase short-term memory in people over the age of 18. This claim is supported by previous research studies testing our same hypothesis and also reaching similar conclusions. Furthermore, this reasoning supports our intuition, as both substances are stimulants which should enhance short-term cognitive abilities within the brain. We are explicitly focusing on short-term memory– long-term effects of these substances would likely produce different results. Our plan is to systematically test the individual and combined effects of nicotine and caffeine through a controlled simulated factorial experiment, including blocking for confounding variables like age and time of day. We hypothesize that the time of day will alter performance on short-term memory tasks as participants may be more fatigued later in the day. Additionally, we believe that nicotine and caffeine may have different effects on different age groups. By measuring changes in memory test performance before and after treatment, we aim to find definite and meaningful insights into how these stimulants impact short-term cognitive function.

Design of the Experiment

We selected a 2^2 factorial design with blocking to investigate both main and interaction effects of nicotine and caffeine on short-term cognitive ability. We use a complete randomized block design so that no variables are confounded with our blocks. Our two factors for our experiment are nicotine and caffeine with levels of present, coded with 1, and not present, coded with -1. The levels for our caffeine factor are a caffeinated sports drink and normal sports drink as the control. The levels for our nicotine factor are the presence of a 2 mg nicotine inhaler or no inhaler at all. To control confounding variables, we blocked for the age of the participant and time of day the experiment was conducted. Age was included in our blocking as it could potentially impact the results given the different stages of brain development and growth that occur throughout adulthood. We are not testing children in this experiment, as their brains are not fully developed, nor do they have legal access to nicotine in the United States. Therefore, we chose to block with respect to age, having one block with adults aged 20-30 and the other block with adults aged 40-50. Furthermore, time of day could confound our results. Although it varies from individual to individual, the brain functions differently throughout the day due to fatigue and other factors. In order to account for this, we added a block for time of day, testing individuals either from 9-10 in the morning or from 3-5 in the afternoon. As a result, we should be able to isolate our two factors of interest from these potential confounding variables. Our response variable, short-term memory, is measured by the difference in time to complete the post-test minus the pre-test.memory test. The specific memory task involves matching 30 cards as quickly as possible. Each participant took an initial memory test, used as a baseline for their personal performance. It is crucial that we use a pretest-posttest design as performance on this short term memory task is highly variable between individuals. After receiving their assigned treatment combination of caffeine and nicotine, each participant repeated the timed memory test. The difference in completion between the post treatment and baseline attempts was recorded to capture the effect of these substances on short-term cognitive ability. A negative difference would indicate improved performance on the final memory test, while a positive difference would indicate slower performance on the final memory test.

For our sample, we sampled individuals from Ironbard Island using public birth records to find individuals within our 2 age groups. Among those who met the criteria, 64 individuals were randomly selected, asked for consent to be in our study, and then randomly assigned to treatment combinations to ensure unbiased assignment. Half of our participants were tested in the morning block and half were tested in the afternoon block to mitigate the effects of performance differences from daily fluctuations in cognitive ability. Within each time block, half of the participants were aged 20-30 and the other half were aged 40-50 to ensure balanced age distribution across the time blocks. To control pontential bias from the sequence of administration, the order in which nicotine and caffeine were administered was randomized. Our initial power analysis test indicated that a sample size of just 9 participants per block would be sufficient to achieve a power of 0.8. We estimated our effect size for this initial power test using statistics from our preliminary run of 32 participants. However, because we had access to additional resources and participants we expanded our sample to include 64 participants with 16 in each of the four treatment combinations. Increasing our sample size both allowed for a substantial improvement in the power of our design, raising the power to 0.998. With this additional power, we increased our likelihood of detecting meaningful main and interaction effects of nicotine and caffeine on short-term cognitive performance.

Results and interpretation

After running our experiment and collecting our data, we utilized R to statistically analyze the effects of nicotine and caffeine on short term cognitive ability in our 2^2 blocked factorial design. The initial model included all terms, to allow for predictions regarding what terms are significant. The estimated effects were estimated by doubling the coefficients of the model and are seen in figure 1.

Nicotine	Caffeine	Time	Age	Nicotine:Caffeine
-2.56875	1.30625	-0.23125	-0.47500	0.11250

Figure 1: Estimated Effects of Factors, Blocks, and Interaction

Based on these results, we can see that nicotine has the largest effect magnitude in the negative direction. This indicates that nicotine decreases the average response time in the memory game among participants, aligning with our hypothesis that nicotine improves short term memory. On the other hand, Caffeine has a small positive effect on our response variable. This indicates that caffeine may or may not increase the amount of time it takes for a participant to complete the memory game; however, we can perform a significance test to determine whether caffeine truly has a significant effect on short-term memory performance.

Accordingly, the results of our ANOVA table, seen in Figure 2, confirms our initial guesses we formed from our effect estimates. Nicotine is the only factor that has a statistically significant impact on short term memory recall, with a p-value of .0351. When analyzed at an alpha level of .05, all other factors are insignificant. The main effect of caffeine as well as the interaction between caffeine and nicotine is not significant. Additionally, the very small sum of squares observed in both the age block and the time of day block indicates that our two blocking variables may have been ineffective in controlling for additional variability.

The visualization of our main effects of nicotine and caffeine supports our initial

```
                  Df Sum Sq Mean Sq F value Pr(>F)
nicotine           1  105.6  105.58   4.656 0.0351 *
caffeine           1   27.3   27.30   1.204 0.2771
time               1    0.9    0.86   0.038 0.8467
age                1    3.6    3.61   0.159 0.6914
nicotine:caffeine  1    0.2    0.20   0.009 0.9250
Residuals         58 1315.2   22.68
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure 2: Full Model Anova Output

interpretations from our effect estimates and full model. As they are set to the same scale, it is easy to compare the difference in effect significance. Visually we can see how nicotine and caffeine vary both in magnitude and direction, which is evident given the following graphs. The nicotine main effects plot shows a strong negative slope as the factor is changed from low, not present, to high, present. This further confirms that the presence of nicotine enhances short-term cognitive ability, decreasing the amount of time it takes individuals to complete the memory task. It is important to note that the main effect of caffeine is not statistically significant in our model. Additionally, the interaction plot in figure 4 shows two near parallel lines for the factors, indicating that there is no interaction between the caffeine and nicotine regarding short term memory. This confirms our previous finding from the ANOVA table that there is no significant interaction between these two variables.

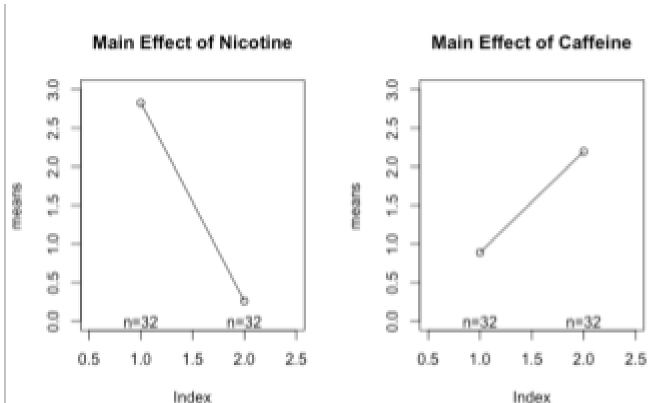

Figure 3: Main Effects Plots

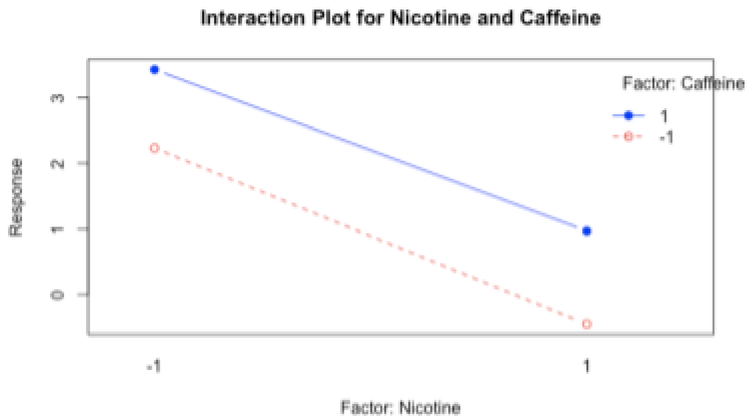

Figure 4: Interaction Plots

Following this analysis and visualization, the full model can be reduced in order to only include significant factors. For this experiment, nicotine is the only statistically significant factor. As a result, we can reduce our model and run a new ANOVA test on it to confirm our results. With the reduced model, nicotine has a p-value of .0312 as seen in figure 5, proving that it remains significant. There is a slight difference between the original model p-value and the reduced model p-value, which makes sense due to the removal of the insignificant factors as well as the blocking variables which did not explain a significant portion of the variability.

```
            Df Sum Sq Mean Sq F value Pr(>F)  
nicotine     1  105.6  105.58   4.859 0.0312 *
Residuals   62 1347.2   21.73                 
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Figure 5: Reduced Model Anova Output

As the final step in our analysis, we need to analyze the residual plots and the relationship between our residuals and fitted values. This will show the adequacy of our model, indicating the validity of our results. Our QQ Plot verifies that our assumption of normality is satisfied. The QQ plot specifically shows the linearity of our residuals, indicating a normal distribution. The Residual vs. Fitted plots also show that our assumption of constant variance is satisfied.

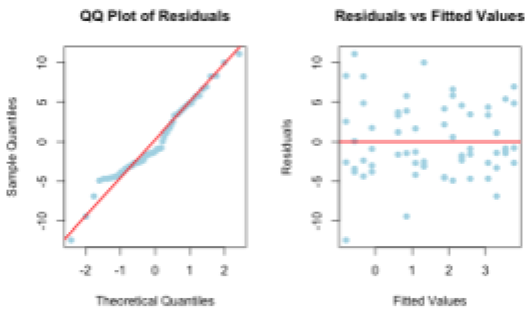

Figure 6: Full Model Assumption Checks

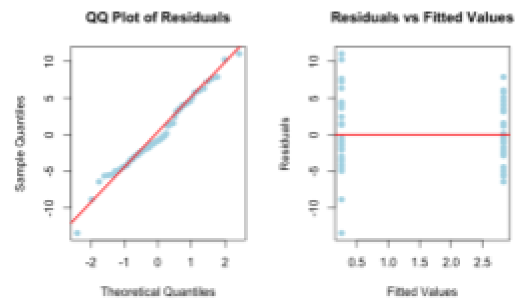

Figure 7: Reduced Model Assumption Checks

Overall, these results suggest that nicotine enhances short-term cognitive ability by significantly reducing memory task response time. Caffeine and the interaction between nicotine and caffeine had no statistically significant effect on response time in this experiment. The blocks of age and time explained little of the variability in our model. The overall analysis supports the conclusion that nicotine has a significant positive effect on short-term memory performance in this experiment.

Discussion

Our experiment explored the individual and interaction effects of nicotine and caffeine on short-term cognitive performance through a blocked 2^2 factorial design. Based on our analysis and ANOVA results, we found that nicotine has a statistically significant effect on short-term memory performance– with use of nicotine improving performance–while caffeine does not show a significant effect on performance. Furthermore, our analysis showed no evidence of interaction effect between the two substances on short-term cognitive ability. The blocks of age and time of day explained very little of the variability in our ANOVA model, suggesting these blocks were ineffective in helping draw clearer conclusions about the effects of caffeine and nicotine on short-term memory performance.

These findings have significant implications for real-world cognitive performance, especially for students who assume that turning to nicotine and caffeine will enhance their cognitive performance. Our findings indicate that nicotine does significantly improve short-term memory, which is consistent with previous research that found “Preclinical models and human studies have demonstrated that nicotine has cognitive-enhancing effects, including improvement of fine motor functions, attention, working memory, and episodic memory” (Valentine and Sofuoglu). It is important to note that while nicotine may offer short-term benefits, individuals should be cautious in using it as a cognitive supplement due to the substance's addictive abilities and potential health risks. Additionally, our study specifically measures the working memory aspect of short term memory– most academic tasks such as studying involve other forms of memory which was not the focus of our experiment.

In contrast, caffeine lacked significant effects in our study which opposes many published studies. Generally speaking, caffeine is consumed in order to increase brain function in the short term. This has been verified, at least with regards to short term memory. A study from 2021 found “caffeine having significant positive effects on both short- and long-term memory in the adult and elderly populations, but not in children" (Fiana, Zhu, et. al.). Although the study suggested more research to confirm these conclusions, caffeine benefiting short term memory was a strong result. While our study did not reach the same conclusion, it could be due to the nature of the memory game implemented, or an alternative, unknown confounding variable. Regardless, it is crucial to conduct many experiments or studies before reaching a final conclusion regarding the true effect of caffeine on short term memory.

While significant conclusions were able to be drawn from the study, the limitations of the study must be noted. Firstly, the study only captures the short-term effects of these substances and does not account for long-term or repeated exposure. Additionally, the use of a nicotine inhaler, which was used in this experiment, may not accurately represent common methods of nicotine intake. Furthermore, the memory game used to test short-term cognitive ability does not resemble the difficulty or duration of learning and studying in a classroom setting– we cannot generalize the results of this study to academic performance more generally. Overall, addressing these limitations in further research would help to expand the scope of this study and strengthen the validity of conclusions regarding the cognitive effects of these substances.

Works Cited

Fiani, B., Zhu, L., Musch, B. L., Briceno, S., Andel, R., Sadeq, N., & Ansari, A. Z. (2021). The neurophysiology of caffeine as a central nervous system stimulant and the resultant effects on cognitive function. Cureus, 13(5), e15032. https://doi.org/10.7759/cureus.15032

Valentine, Gerald, and Mehmet Sofuoglu. “Cognitive Effects of Nicotine: Recent Progress.” *Current neuropharmacology* vol. 16,4 (2018): 403-414. doi:10.2174/1570159X15666171103152136