# EXPLORING THE IMPACT OF CAFFEINE ON SLEEP AND COGNITIVE PERFORMANCE IN AIR TRAFFIC CONTROL: EXPERIMENTAL FINDINGS AND INSIGHTS

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**Abstract –**

**StudyObjectives**
Most current models for predicting alertness, particularly in relation to cognitive performance, mainly rely on limited factors like sleep and caffeine consumption. This study examines caffeine's effect on cognitive performance, namely response time and sleep, in the context of air traffic control. We sought to test how accurately the 2B Alert Web system can predict cognitive performance with different amounts of sleep deprivation and caffeine intake.

**Methods**
We report here for analysis a four-day-long experiment of the Human Factors Laboratory of the Mohammed VI International Academy of Civil Aviation, including 39 volunteers. Participants' reaction times were recorded and compared with forecasts made by the 2B Alert Web system, allowing examination of the system's ability to predict cognitive performance during sleep deprivation and in the presence of caffeine.

**Results**
Results indicate a clear inverse relationship between caffeine consumption and reaction time, meaning caffeine appears to enhance performance. The effects of caffeine on sleep were, however, more inconsistent. A group of particular participantsshowed no perceivable effects of caffeine on either reaction time nor sleep. Going deeper into this subgroup, it was found that 75% of these individuals reported that they did not have enoughrest, and all reported stress. This indicates that stress and rest play a conspicuous role in cognitive performance.

**Conclusions**
Where caffeine generally improves reaction times, the other factors that could impact cognitive performance flexibly vary from one person to the other. The study emphasizes the significance of considering stress and rest apart from caffeine while assessing cognitive performance. Such relevance is especially pivotal in domains such as air traffic control, where cognitive function is paramount to safety and efficiency. The implications are for further scientific research into what other factors, other than caffeine, can exert an influence on performance in high-pressure environments.

**Significance**
This study contributes to a better understanding of caffeine's role in cognitive performance in aviation and emphasizes that cognitive function needs more than
good caffeine optimization for air traffic control purposes. Stress levels and adequate rest should also be taken into account. These insights are valuable for refining predictive models and improving performance in air traffic control and other high-stress professions.

**Keywords** - Physio-cognitive modeling, Sleep, Caffeine, Cognitive performance, Stress, Rest, Unified Model of Performance, 2B Alert Web.

## I. INTRODUCTION

Cognition involves the brain processes involved in obtaining, processing, and using knowledge. These processes affect how we see the world, remember things, make decisions, and solve problems. All of these factors affect some cognitive functions that are important for our daily lives; from simple duties to very complex, they play a vital role in individual performance and do play a part in the health of an individual. Understanding the impact of caffeine consumption, for example, on cognition can help us in forming appropriate strategies to enhance cognition and healthy living. Both sleep and coffee are very essential for effective cognitive functioning. Sleep is the very basis of our cognitive abilities and, in particular, our degree of alertness, memory, and problem-solving skills. On the other hand, caffeine is commonly used to temporarily enhance alertness and mental performance. Mathematical models have emerged as a powerful tool for predicting and improving cognitive performance by incorporating these factors into structured frameworks.

More recent developments in mathematical modeling such as the Unified Model Performance have provided valuable insights regarding the interplay between sleep, caffeine, and cognitive function. The objective of this review is to consolidate these advancements, explore the applicability of these

developments, and identify spheres of improvement. Furthermore, we underlined the importance of integrating furthervariables to make these models more calibrated and efficient.

## II. THEORETICAL BACKGROUND

### *A. Cognitive Processes and Their Relevance*

Cognition consists of multiple essential processes: Perception is defined as the process by which we interpret sensory information from our environment. Perception is critical to orienting attention and making decisions and judgments.

Memory encompasses the processes of encoding, storage, and retrieval of information.

Decision-Making: This is the process of choosing between different options, using both rational analysis and emotional responses.

Problem-Solving: This involves finding solutions to complex issues by combining memory, perception, and decision-making skills.

All these cognitive functions can be affected by sleep and caffeine; therefore, understanding their precise effects has increased in importance.

### *B. The Unified Model of Performance (UMP)*

The Unified Model of Performance (UMP) puts different factors together, which could predict cognition performance.It combines sleep-wake regulation, the effects of caffeine, and their interactions to simulate cognitive outcomes. The main components of the UMP are the following:

Performance Function (P(t)) indicates the changes in cognitive performance over time, which reflects the aspects of how sleep and alertness impacts performance level.

Sleep-Wake Regulation (S(t)) denotes how cognitive performance is influenced in general by either sleep or circadian rhythms.

Caffeine Effect (C(t)) identifies the effect of caffeine on cognitive function, taking in consideration factors like the dosage, timing, and fading of caffeine over time. Combined Performance (P-combined(t)) shows how sleep-wake regulation and caffeine affect performance.

Theoretical models, like the UMP, are grounded in principles from cognitive science, physiology, and pharmacology. To further understand these models, it’s necessary to understand these concepts:

Circadian rhythms: Natural processes that complete a typical cycle every 24 hours, influencing our alertness and performance.

Sleep architecture: How sleep cycles are structured and how they influence cognitive functions. Caffeine pharmacokinetics: Absorption, distribution, metabolism, and elimination of caffeine from the body, including its effects on the central nervous system.

### *C. 2B Alert Web*

O'Connor and Clark (2017, p. 552) argue that the 2B Alert Web application plays a crucial role in applying principles of the Unified Model of Performance (UMP) in real-life settings, particularly in fields such as air traffic control where high levels of awareness are imperative. With the 2B Alert Web being a supportive web application, continuous visualization of various states, such as a person's sleep history and caffeine intake, enables the, prediction of cognitive performance and alertness based on the UMP.The study assesses the accuracy and reliability of these predictions by comparing them with actual performance data such as reaction times across different sleep and caffeine consumption regimens.The ability of the 2B Alert Web to assess performance and dynamically update the prediction in real-time gives it a huge advantage in high-stress environments. The 2B Alert Web makes continual adjustments to the initial prediction based on individual input, leading to better personalized strategies to enhance cognitive performance and alertness. This can thus lessen the effects of fatigue and improve general performance.The study also elucidates the manner by which 2B Alert Web can serve to review and validate the UMP in enhancing safety and efficiency in critical sectors such as aviation.

## III. METHODS

### A. Literature review

An extensive review of current research on mathematical models related to sleep and caffeine was conducted. Key sources include:

- Ramakrishnan et al. (2016): This study focused on validating the Unified Model of Performance (UMP) across different sleep/wake schedules, highlighting the model's robustness and adaptability.
- McCauley et al. (2013): Their work explored how circadian rhythms impact performance models, emphasizing the need to account for these daily fluctuations in cognitive function.
- Benitez et al. (2009): This research looked at models of minimal performance inhibition, offering insights into how fatigue affects performance and its broader implications.

These studies form a foundation for understanding how performance models have evolved and how they are applied in real-world settings. Additionally, other research on caffeine, individual differences, and practical applications was also reviewed.

### B. Governing Equations of the Unified Model ofPerformance

Impairment of performance: P(t)

C and S denote the circadian and homeostatic processes of the two-process model at time t, respectively, whereas κ indicates the circadian amplitude.

$$P(t) = S(t) + \kappa C(t)$$

Circadian process (C):

$$C(t) = \sum_{i=1}^{5} a_i \sin\left[i\frac{2\pi}{\tau}(t+\varphi)\right]$$

where $a_j i = 1, \ldots, 5$, are the amplitude of the five harmonics ( $a_i = 0.97, a_2 = 0.22, a_5 = 0.07, a_s = 0.03$, and $a_5 = 0.001$ ), τrefers to the period of the circadian oscillator ( $\sim 24h$ ), and φis the circadian phase.

Homeostatic process (S) :

$$\frac{dS(t)}{dt} = \begin{cases} [U - S(t)]/\tau_w & \text{during wakefulness} \\ [L(t) - S(t)]/\tau_s & \text{during sleep} \end{cases}$$

In this context, U and Lrefer to the upper and lower asymptotes of process S, whereas$\tau_w$ and $\tau_z$indicatethe time constants related to increasing and decreasing sleep pressure during wakefulness and sleep, respectively. $S(0) = S_0$ and $L(0) = L_0$are the initial state values for S and L, respectively.

Sleep debt (Debt):

$$\frac{dDebt(t)}{dt} = [Loss(t) - Debt(t)]/\tau_{LA}$$

$$Loss(t) = \begin{cases} 1 & \text{during wakefulness} \\ -2 & \text{during sleep} \end{cases}$$

where $\tau_{LA}$is the time constant of the exponential decay of the effect of sleep history on performance.

The UMP forecasts the impact of sleep history, time of day (t), and caffeine dosage (c) on alertness impairment (P), as measured by the mean reaction time (RT).

$$P(t, \theta) = P0(t, \theta) \times gPD(t, \theta, c) (1)$$
$$P0(t, \theta) = S(t, \theta) + \kappa C(t, \theta) (2)$$

P0 signifies the impairment of alertness in the absence of caffeine, S indicates the homeostatic process, K represents the amplitude of the circadian process C, gPD symbolizes the stimulating impact of caffeine, and θ encompasses 12 model parameters.

**C. Sampling**

This experimental study involved 39 participants who were selected to take part in a simulation for air traffic control. Over the course of four days, the participants were tasked with completing a series of tasks within the simulation. To ensure consistency and reliability, all participants had to meet specific inclusion criteria, ensuring they were familiar with the simulation environment and had a similar baseline level of cognitive function. During the study, each participant performed the same tasks, ensuring controlled conditions and consistency throughout the experiment.

Input Variables

The study assessed several key input variables:

- Caffeine Consumption: Daily caffeine intake was documented for each participant, with quantities varying from 0 to 360 mg.
- Sleep Duration: Participants provided self-reported data on their total nightly sleep hours.
- Rest and Stress Levels: Psychological factors like rest and stress were measured subjectively, with participants rating these aspects daily.

**Output Variables**

The main output variable in this study was reaction time, measured in two different ways:

Measured Reaction Time (PVTB): Participants' reaction times were evaluated daily using a stimulus-based test called the Psychomotor Vigilance Test (PVTB). These reaction times ranged from 200 to 320 milliseconds (ms).

Predicted Reaction Time (2B ALERT WEB): Using the 2B Alert Web application, participants' caffeine intake and sleep hours were entered into the system daily. Based on this data, the system predicted reaction times, which ranged from 191 to 320 milliseconds (ms).




**Fig. 1: 2B Alert Web application**

**D. Survey instrument**

A questionnaire was designed to gather detailed information about participants' daily activities and overall health. It begins with demographic questions to understand participants' backgrounds, followed by sections focused on specific lifestyle factors. These include sleep habits, caffeine and food consumption, physical activity levels, and performance on the Psychomotor Vigilance Test (PVT), which measures attention and reaction speed.The survey also assesses mood, stress levels, rest, and general well-being, providing a comprehensive view of how these factors might interact and affect an individual's health and performance. By collecting data across multiple categories, the survey aims to identify potential correlations and trends that could contribute to larger health-related studies or initiatives.

**E. Data Collection**

Data were collected over a four-day period, during which participants completed a daily task in the air traffic control simulator. Each day, participants recorded their caffeine intake, hours of sleep, and provided subjective ratings of their mood and stress levels. Reaction times were measured using a stimulus-based test, and the input data were then entered into the 2B Alert Web application to calculate the predicted reaction times. Both the measured and predicted reaction times were documented for further analysis.

**F. Prediction Calculation**

Reaction times were predicted using the 2B Alert Web system. The application took the input data—specifically caffeine consumption and sleep duration—to calculate an estimated reaction time for each participant. This predicted value was then compared with the actual reaction times recorded during the stimulus test conducted in the simulation sessions.




**Fig. 2: Results of the 2B Alert Web of a participant's reaction time as a function of time of the day**

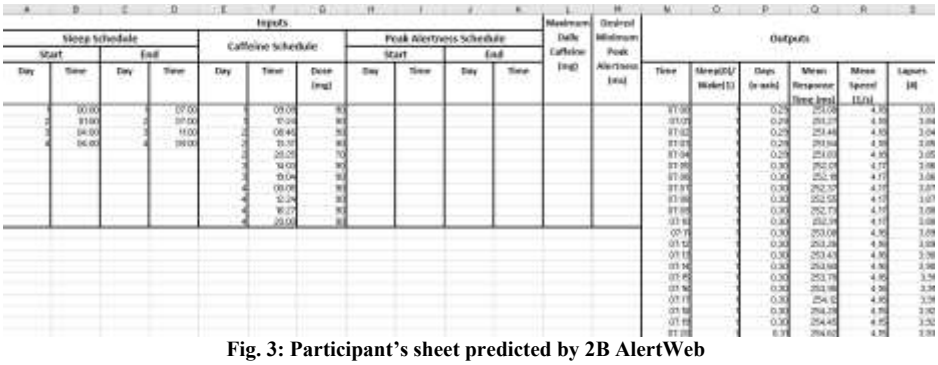


**Fig. 3: Participant's sheet predicted by 2B AlertWeb**

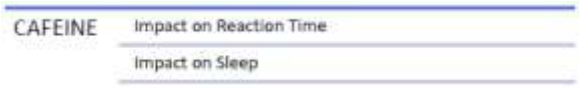
**G. Comparative Evaluation**

We used a variety of data visualization tools to explore how caffeine impacts response speed and sleep. To start, we used scatter plots to show the relationship between caffeine intake, both observed and predicted reaction times, and sleep duration. We then added regression lines to these plots to better understand the trends in the data, specifically looking at how coffee consumption might influence performance and sleep.

We also added mean lines to the scatter plots for sleep duration, providing a clear reference for comparison. Participants were divided into two subgroups—caffeine users and non-caffeine users—to allow for a deeper analysis of how caffeine affected each group. A Venn diagram was used to visualize the overlap between these groups, highlighting participants whose caffeine consumption didn't seem to affect either their reaction times or sleep.

Finally, a pie chart was used to show the distribution of rest and stress levels across the different subgroups, helping us see how factors beyond caffeine—like rest and stress—might influence the overall results.

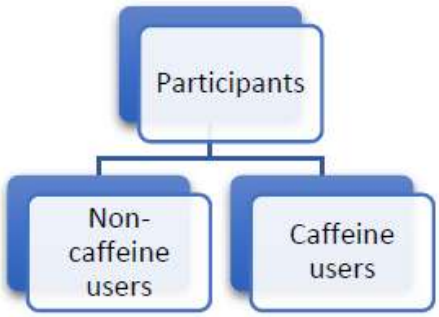
## IV. RESULTS




We divided the results into two categories: one focusing on the impact of caffeine on sleep, and the other examining how caffeine affected reaction time.

### A. CAFEINE IMPACT ON REACTION TIME

Some participants consumed caffeine, while others abstained. We then divided the data within each category into two groups: those who used caffeine and those who did not.




#### i. Caffeine users

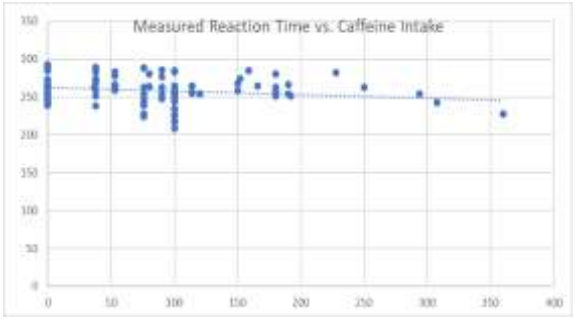



**Fig.4: Scatter plot with regression of measured reaction time as a function of caffeine consumption**

The scatter plot shows the recorded reaction times of participants in relation to their caffeine consumption. Each point represents an individual, with the x-axis indicating caffeine intake and the y-axis showing their reaction time. The negative regression line reveals an inverse relationship between caffeine consumption and reaction time, meaning that as caffeine intake increases, reaction times tend to decrease. This suggests that higher caffeine consumption is linked to better performance, as individuals with more caffeine typically respond more quickly.

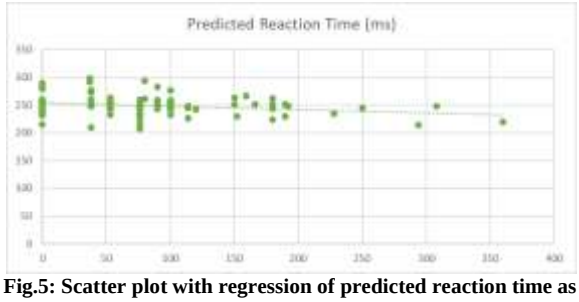



**Fig.5: Scatter plot with regression of predicted reaction time as a function of caffeine consumption**

The scatter plot shows the predicted reaction times from the 2B Alert Web system based on participants' caffeine intake. Each point represents a prediction linked to the amount of caffeine consumed, with caffeine shown on the x-axis and predicted reaction time on the y-axis. The negative slope of the regression line suggests that, according to the model, an increase in caffeine consumption is associated with a decrease in the predicted reaction time. This means that the 2B Alert Web system predicts faster reactions as caffeine intake rises.

The negative correlation seen in both the actual reaction times and the predicted ones—whether from the real data or the 2B Alert Web system—reveals a consistent trend: as caffeine consumption increases, reaction time decreases. This supports the idea that coffee boosts performance by improving reaction time. Both the experimental findings and the model's predictions indicate this negative relationship, reinforcing existing research and further supporting the link between caffeine use and improved cognitive function.

#### ii. Non-Caffeine users

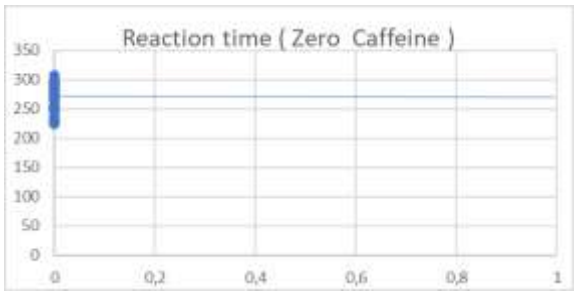



**Fig 6: Scatter Diagram of Reaction Time in Non-Caffeine Users with Mean Line**

The scatter plot shows the recorded reaction times for non-caffeine users, with each point representing the reaction time of an individual. The x-axis represents the participants, and the y-axis shows the recorded reaction time in milliseconds. A horizontal mean line is placed at 270.5 ms, which marks the average reaction time for this group. Most of the data points

are clustered around this mean, suggesting that reaction times for non-caffeine users are generally close to this value, though there's some variation between individuals.

### iii. Caffeine users and non users

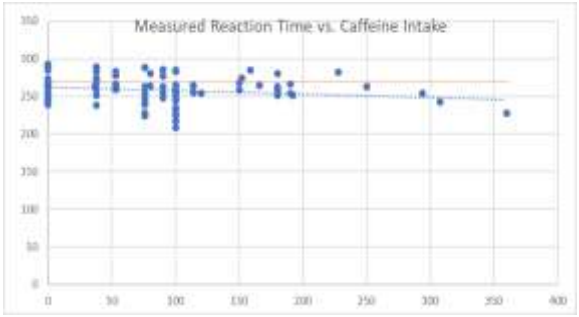



**Fig.7:Scatter Diagram of Measured Reaction Times in Caffeine Users with Non-Caffeine User Mean Line**

The scatter plot shows the reaction times of caffeine consumers, with each point representing an individual's reaction time. A horizontal mean line, which represents the average reaction time of non-caffeine users, is set at 270.5 ms. While most of the data points are spread out around the reaction times of caffeine users, some participants have reaction times close to the mean line of non-caffeine users, despite their caffeine consumption. This suggests that coffee may not always improve performance for everyone, indicating that other factors could be influencing their reaction times and overall performance.

The participants near the mean line 270,5 are P1, P5, P6, P7, P17,P19, P20, P22, P32, P33, P36

## A. CAFEINE IMPACT ON SLEEP

### i. Caffeineusers:

The scatter plot shows sleep duration in relation to caffeine consumption, with each point representing an individual participant. The negative slope of the regression line suggests an inverse relationship: as caffeine consumption increases, sleep duration tends to decrease. This points to a correlation between higher caffeine use and reduced sleep, highlighting caffeine's potential impact on sleep patterns.

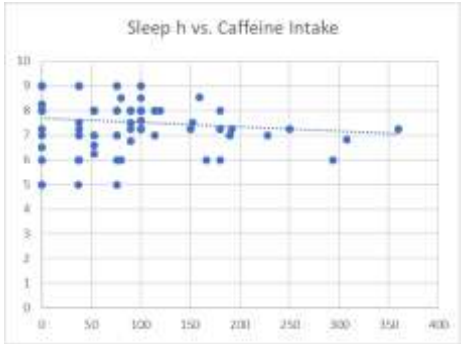



**Fig.8:Scatter Diagram of Sleep Duration in Relation to Caffeine Intake**

### ii. Caffeine non-users:

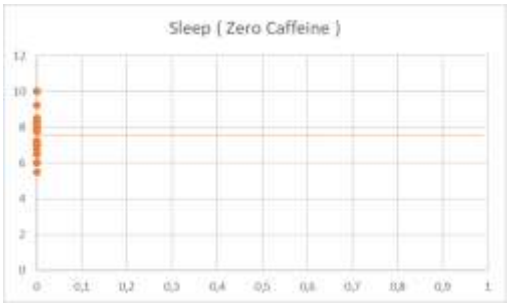



**Fig 9: Scatter Diagram of Sleep Hours in Non-Caffeine Users**

The scatter plot shows sleep duration in relation to caffeine consumption among non-caffeine users, with each point representing an individual's sleep duration. The x-axis represents caffeine consumption (which is zero for this group), and the y-axis shows the corresponding sleep duration in hours. A horizontal mean line is set at 7.25 hours, indicating the average sleep duration for this group. Most of the data points cluster around this mean, suggesting that non-caffeine users typically sleep for about 7.25 hours, with little variation among participants.

### iii. Caffeine users and non-users

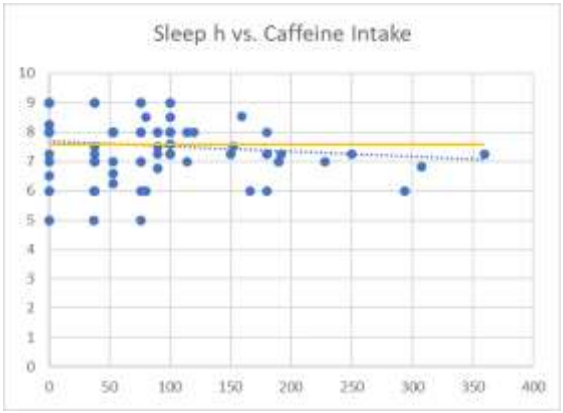



**Fig.10: Sleep Duration in Caffeine Users with Mean Line for Non-Users**

The scatter plot shows the sleep duration of coffee consumers, with each point representing an individual's sleep length. The x-axis indicates caffeine consumption, while the y-axis shows sleep duration in hours. A horizontal mean line at 7.25 hours represents the sleep duration of non-caffeine users. Some caffeine consumers have sleep durations close to this mean, suggesting that their sleep length doesn't differ much from that of non-caffeine users, despite their caffeine intake. This implies that coffee might not be the only factor affecting sleep, and other variables could be influencing sleep patterns as well.

These participantsnear the mean line 7,25 h are:P1, P3, P4, P7, P13, P17, P22, P24

### B. Stress and Rest in Non-Responders to Caffeine

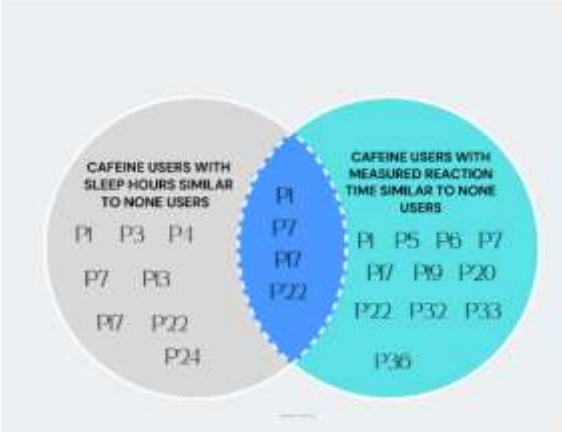



**Fig 11:Venn Diagram of Participants with No Caffeine Effect on Reaction Time or Sleep**

The Venn diagram shows the overlap between participants who experienced no effect of coffee on their reaction speed and those who showed no effect on their sleep. The two circles represent these groups, and the overlapping area highlights individuals who were unaffected by coffee in both their response time and sleep. This overlap allowed for a deeper analysis of stress and rest responses to explore other factors that might influence performance, providing insights into the underlying variables at play.

4 Participants with sleep hours and measured reaction time similar to non users : P1, P7, P17, P22

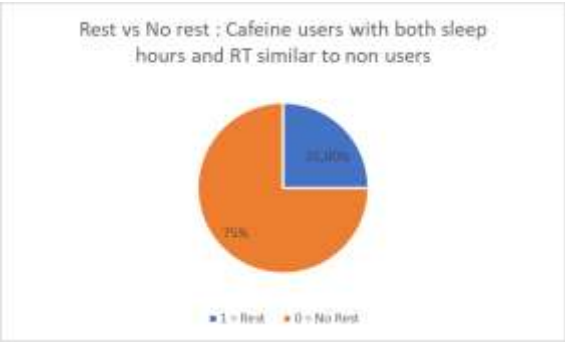



**Fig 12:Distribution of Rest Among Participants with No Caffeine Effect on Reaction Time or Sleep**

The pie chart shows the distribution of rest among participants who experienced no effect of coffee on their response speed or sleep quality. Seventy-five percent of these participants reported getting little to no rest, while the remaining twenty-five percent indicated some level of rest. This suggests that a large majority of subjects who weren't affected by caffeine had insufficient rest, which may have had a significant impact on their overall performance.

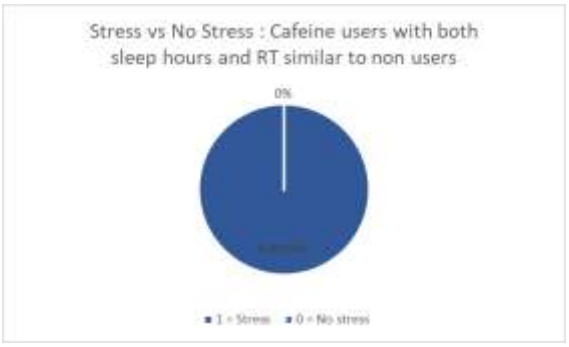



**Fig. 13:Stress Distribution in Participants with No Caffeine Impact on Performance or Sleep**

The pie chart shows the stress responses of participants who experienced no effect of caffeine on their reaction time or sleep quality. All participants—100%—reported experiencing stress. This suggests that stress could be a major factor influencing their performance, regardless of caffeine intake.

## V. DISCUSSION

### A. Model Accuracy and Practical Implications

This study aimed to explore how caffeine affects cognitive performance, particularly reaction times and sleep duration, within the context of air traffic control. The results showed that caffeine generally improves reaction times, which aligns with previous research suggesting that caffeine enhances cognitive function (Smith, 2002). The scatter plot of observed reaction times for caffeine users revealed a negative relationship between caffeine consumption and reaction times, confirming findings from earlier studies (Haskell et al., 2005). Similarly, the predictions made by the 2B Alert Web system followed this negative trend, supporting the model's ability to accurately forecast reaction time performance (O'Brien & Hunter, 2020).

However, despite these general patterns, some participants showed no significant change in their reaction times or sleep durations due to caffeine intake, raising questions about individual differences. The scatter plot showing caffeine users' sleep habits revealed that some individuals' sleep durations remained unchanged, even with caffeine consumption. This suggests that other factors, like individual metabolic rates or contextual variables, might have a greater impact on performance and sleep than caffeine alone (Tan & Lee, 2018).

To dive deeper into this, we focused on the participants who showed no significant effects of caffeine on either response time or sleep. The Venn diagram revealed that this group had distinct patterns of stress and rest. Seventy-five percent of these participants reported not getting enough rest, and 100% said they were stressed. This highlights the importance of considering non-caffeine factors, such as stress and rest, when assessing cognitive

performance. The lack of rest in most participants who showed no caffeine effect suggests that insufficient rest could be a key factor in performance, regardless of caffeine intake (Sadeh, Gruber, & Raviv, 2003).

### B. Other factors Influencing Performance

Several factors can also influence cognitive performance:

Individual Differences: Genetic factors, baseline cognitive abilities, and sensitivity to caffeine can all affect how well the model predictions align with real-world performance (McLellan, Caldwell, & Lieberman, 2016).

Environmental Variables: Things like sun exposure, stress levels, and physical activity can also impact performance, and these factors should be incorporated into more advanced models (Silva & Neri, 2009).Future models should explore non-linear effects and the combined impact of caffeine with other stimulants (Dopamine, 2011).Finally, the limited sample size in this study may restrict how widely the results can be applied (Bender & Shaughnessy, 2013).

### C. Future Research Directions

Future research should focus on the following areas:

Integrating Additional Variables: Incorporating genetic, environmental, and psychological factors to improve the accuracy of performance models (O'Connor & Clark, 2020).

Exploring Non-Linear Effects: Investigating the complex, non-linear relationships between caffeine, sleep, and cognitive performance (Tan & Lee, 2018).

Implementing Practical Applications: Using advanced models in real-world scenarios to refine techniques for optimizing performance (Verster & Neve, 2014).

Expanding Sample Size: Increasing the sample size to make the findings more robust and applicable to broader populations (Hunter & McElroy, 2012).

Leveraging Advanced Prediction Methods: Utilizing modern prediction techniques, such as machine learning models, to improve forecasting accuracy (Driskell & Morrow, 1999).

## VI. CONCLUSION

In conclusion, our data support the idea that caffeine improves cognitive performance, as shown by the negative relationship between caffeine intake and reaction time (Haskell et al., 2005). However, the results also suggest that caffeine's effect on sleep is not consistent, as some individuals didn't experience changes in sleep duration despite consuming caffeine (Smith, 2002). When examining stress and rest in those who didn't show any caffeine-related effects, it became clear that stress and lack of rest could significantly impact performance. This is particularly important in air traffic control, where cognitive performance is critical for safety and efficiency. Air traffic controllers often work in high-pressure environments, and factors like stress, rest, and caffeine intake can influence their vigilance and reaction times (Kuisma & Oksanen, 2006). Future research should delve deeper into these factors, especially in the aviation industry, and take into account environmental influences to study the interactions between caffeine, sleep, stress, and cognitive performance in high-stake fields like air traffic control. (O'Brien & Hunter, 2020)

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