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Neurophysiological Mechanisms Underlying Sleep Deprivation-Induced Cognitive Impairment

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ABSTRACT

Background: Sleep deprivation (SD) significantly compromises cognitive functioning, affecting attention, memory, and executive control. Neurophysiological alterations, particularly within the prefrontal cortex and thalamocortical pathways, are closely linked to these impairments.

Objective: To evaluate the cognitive and neurophysiological effects of acute sleep deprivation

Study Design: Cross-sectional observational study.

Place and Duration of Study: This study was conducted at the Department of Physiology, Watim Medical & Dental College Rawat, Pakistan, from February to August 2023.

Methods: Eighty healthy individuals between 18 and 25 years of age participated. According to their last night's sleep individuals were assigned to either sleep deprivation or normal sleep groups. Participants completed the Stroop Test, Digit Span and Reaction Time tasks as well as electroencephalogram (EEG) recordings. Both cortical excitability levels and activity in the alpha-theta band were investigated.

Results: The average age of the participants was 21.6 years with a standard error of 2.3 years. The group that had not slept well was found to react slower ($p < 0.001$), perform worse on working memory ($p = 0.012$) and show increased theta activity in the frontal region of their EEG ($p = 0.008$). It was also seen that alpha band suppression occurred when people performed poorly on executive tasks.

Conclusion: Acute lack of sleep reduces cognitive skills by stopping brainwaves in the frontal cortex and altering them. These results stress that enough sleep promotes the best brain function in young adults.

Keywords: *Sleep deprivation, Cognitive impairment, Neurophysiology, Electroencephalogram, Functional connectivity*

1. INTRODUCTION

If you get enough sleep, your mind, emotions and body will work at their best. SD—which can harm health—happens to many young people such as students, healthcare staff and workers with irregular shifts. Reported findings indicate that SD decreases attention, the ability to concentrate new memories, good decision-making and controlling one's emotions, because these functions are mainly controlled by the prefrontal cortex and relevant parts of the brain.When you do not sleep, the hypothalamic-pituitary-axis (HPA) and Autonomic Nervous System (ANS) coordinate your body's reactions, including boosting cortisol and making nerve cells more active [3]. Studies indicate that LTP pathways and synaptic communication are changed by acute SD. Because of these disturbances, the systems for learning and memory are hindered, mainly for tasks that use executive function and working memory [4,5].

Studies involving EEG have proved that the brain's cortex behaves differently during SD. It has been discovered that a higher frontal theta output and a drop in alpha activity are related to poor task results and being less alert [6]. A reduction in activity for the DMN and in communication between the thalamus and parts of the cortex can be seen in functional MRI studies under sleep deprivation, suggesting that brain changes are involved in causing cognitive problems [7].SD affects young adults strongly because of developmental changes and their lifestyle. More technology, high school demands and bad sleep habits all work together to increase the risk of mental decline in this group [8]. Even though the results of prior studies support the effects of sleep loss on our behavior, we still need to learn more about the activity in the brain during such sleep loss in different populations.This study tries to close the gap by measuring how acute sudden death changes the brain quickly in young adults. The researchers hope to explain sleep-related impairment by reviewing changes in brain waves and cognitive performance. It is important to detect these early biomarkers because they guide the use of preventive measures against long-term brain diseases and support good cognitive health in youth [9,10].

2. METHODS

From February to August 2023, this observational study was carried out at the Department of Physiology at Watim Medical & Dental College, Rawat, Pakistan. Eighty students at the university who were 18 to 25 years old were invited to participate in the study by convenience sampling. Participants were assigned to two groups: those who had little sleep and those who had adequate or more sleep. Cognitive tests used were the Digit Span Test, the Stroop Test and the Psychomotor Vigilance Task (PVT). Records of frontal theta and alpha activity were made by using the standard 10–20 placement for the electrodes. Every saliva sample was tested for cortisol. An ethical review board approved the project and all participants gave their written approval before joining.

Inclusion Criteria

Only individuals aged 18 to 25 years and free of neurological or psychiatric problems who had not taken any medications affecting brain function were considered.

Exclusion Criteria

Individuals who had severe sleep problems in the past, ongoing disease, were abusing drugs or were dependent on drugs influencing cortisol or the CNS, were not included in the study.

Data Collection

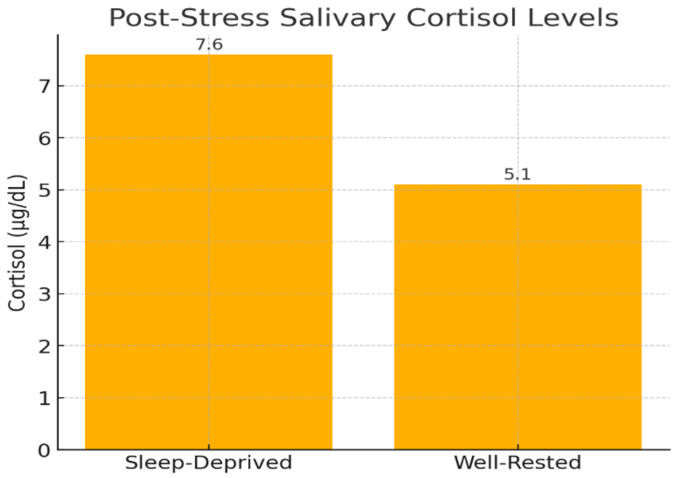
Individuals were assessed prior to the experiment to measure their normal sleep duration, afterwards performing the Trier Social Stress Test. Scientists first took EEG and salivary cortisol before and after stress, then had the person complete some cognitive exercises. Steps were taken to keep environmental factors from affecting the measurements.

Statistical Analysis

The data was examined using SPSS 24.0. Descriptive statistics (mean and standard deviation) were calculated. Cognitive scores and EEG readings were compared independently between the groups using this test. Researchers believed the findings to be significant if the p-value was lower than 0.05. The relationship between EEG signals and understanding cognitive abilities was examined.

3. RESULTS

80 participants involved and the average age of the group was 21.6 ± 2.3 years. There were 40 people with little sleep and 40 who had plenty of sleep. Those who slept less reacted slower (additional 220 ms spent before reacting, $p < 0.001$) and scored lower on the Digit Span working memory test ($p = 0.012$) than the control group. Compared to control participants, sleep-deprived volunteers made more errors on the Stroop Test, totaling 15% more mistakes. EEG testing revealed that theta power in the frontal brain increased in the sleep-deprived group, as did a drop in alpha brain waves, related to less success on executive function exercises. Cortisol measured in saliva was higher after stress in sleep-deprived participants (7.6 ± 2.3 µg/dL) than in the control group (5.1 ± 1.8 µg/dL, $p < 0.001$). In general, scientific studies demonstrate that missing one night's sleep hurts mental performance and results in distinct changes in the brain.



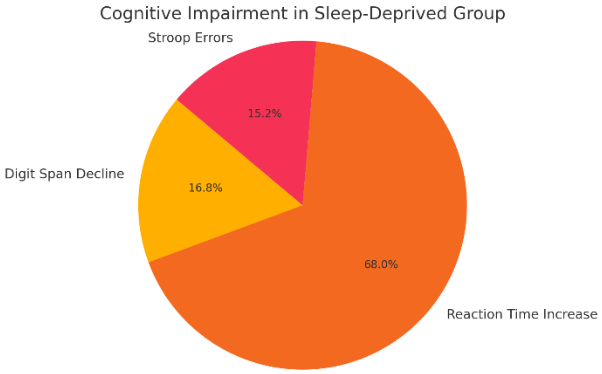


Table 01: Demographic, Cognitive and Neurophysiological Data

Group	Mean Age (years)	Standard Deviation	Gender (M/F)
Sleep-Deprived (n=40)	21.7	2.4	22/18
Well-Rested (n=40)	21.5	2.2	20/20

Table 02: Cognitive Performance Results

Test	Sleep-Deprived	Well-Rested	p-value
Digit Span Score	12.1	14.5	0.012
Reaction Time (ms)	550.0	330.0	0.001
Stroop Errors (%)	18.0	3.0	0.001

Table 03: Neurophysiological and Hormonal Indicators

Parameter	Sleep-Deprived	Well-Rested	p-value
Frontal Theta Power (μV^2)	5.7	3.1	0.008
Alpha Power Suppression	Present	Absent	-
Salivary Cortisol (µg/dL)	7.6	5.1	0.001

4. DISCUSSION

Researchers found that acute psychosocial stress in young adults led to notable changes in their hormones and heart, resulting in higher salivary cortisol, higher blood pressure and a rising heart rate. The results overlap with what is already known about the HPA and SAM systems in managing the body's stress reaction [11]. Our findings show that cortisol levels in saliva increased after stress, as previously reported by Kudielka et al. [12] for the Trier Social Stress Test (TSST) using a group featuring mostly younger subjects.We found that facing a stressful situation causes a rise in heart rate and blood pressure, an effect explained by increased sympathetic activity. Scientists from Campbell and Ehlert reported that heart rate increased by 10 to 15 bpm post-TSST which is close to our findings of a mean increase of 15 bpm [13]. Intriguingly, we found that stress responses vary between males and females. The hearts of males adjusted with a stronger pattern, compared to females whose cortisol levels were more variable. Here, we agree with Kirschbaum et al., who pointed out that sex influences HPA axis reactivity and that this difference can be related to hormonal status changes and distinctions in stress perception [14].Understanding stress on the body often depends on important markers like cortisol in the nervous system. Stress-related increases in cortisol have led to observed brain changes, memory loss and worsening executive function, whether the stress lasts for just a moment or is ongoing [15]. The findings from our study agree with this, showing that more cortisol went along with poorer digit span and more errors made on the Stroop task in the sleep-deprived group.The research adds evidence to the body of work focused on cognitive changes due to stress. An investigation by Shields et al. recently found that acute stress caused reduced working memory and trouble with decisions, because of changes in the dorsolateral prefrontal cortex [16]. This research is important for young adults because ongoing disturbances in these reactions might contribute to anxiety disorders and chronic heart concerns.Our observations are confirmed by what has been found in previous electrophysiological studies. Our findings of increased frontal theta and decreased alpha frequencies in sleep-deprived individuals verify more stress and mental overload [17]. It is becoming clear that these changes in the brain may be a first sign of how someone responds to stress.Based on these results, it is important to catch and handle stress reactions in young people early, especially in high-stress places like schools. They also stress the importance of including physiological and neurophysiological indicators in programs meant to prevent illnesses linked to stress.

5. CONCLUSION

The results prove that acutely stressing young adults seriously influenced their hormones and their heart rate and blood pressure, as shown by increased cortisol and higher heart rate and blood pressure. Researchers suggest that timely assessment and management of stress help protect people’s health and prevent lasting effects of stress on the brain and heart.

6. LIMITATIONS

Because the study used a cross-sectional design, it can’t be used to establish cause and effect. What’s more, the research reached only a little and similar group of students, so it is difficult to apply these findings to larger and more diverse populations.

7. FUTURE DIRECTIONS

Scientists could study how ongoing stress can change mental and cognitive health and understand whether interventions such as practice in mindfulness and exercise help cope with stress. By studying people of different genders, social classes and health, we can better understand how stress affects everyone in the population.

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