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Effects of Acute Sleep Deprivation on Working Memory Capacity in Undergraduate Students

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Sleep is a necessary staple in our everyday lives but with advancements in society and an increase in day to day commitments it feels as though there is not enough time in the day. One of the first things to be forsaken in the hopes of maintaining a work schedule or routine is sleep. While the lack of sleep is disproportionate in most demographics, in university students in particular, a lack of sleep is a common, consistent, and necessary plague. Students can be under the impression that the effects of sleep deprivation have mostly long-term repercussions; however, prior literature has indicated that sleep deprivation impacts not just long-term consolidation but also significantly affects memory in the short-term, specifically the working memory (Xie et al. 2019; Chee et al., 2006). In this investigation, we seek to understand the effects that acute sleep deprivation has on the working memory capacity of individuals using a 2-back spatial test. A sample of convenience of upper-class undergraduate students was chosen and the participants were asked to take a specific 2-back spatial test - twice on a day that they subjectively felt as having a regular sleep schedule and twice on a day that they subjectively felt as having sleep deprivation. The team predicted that working memory 2-back task scores will be adversely affected by sleep deprivation. While there was a statistically significant difference in the working memory scores on the full sample level, this was not reflected on the individual level. This indicates that the effects of sleep deprivation are not generalizable to a full population and that they must be reviewed on a case-by-case basis. Furthermore, since greater variation was observed in the sleep deprived scores in all individuals, it implies that sleep deprivation may indirectly affect the consistency of working memory by affecting attention span and concentration.

Citation

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Introduction

With the recent advancements within society and increased competition in the workplace, one of the most neglected aspects of the working individual's health is sleep. This holds especially true in the case of university students who are always short on time and are subject to a large number of stressors [1]. As a consequence of overloaded schedules, many students consider sleep a luxury rather than a necessity. However, sleep is necessary for proper brain function not just for its restorative properties but also for its effect on memory cognitive function. Past literature has confirmed that offline reprocessing of memories is crucial in the consolidation of information and long-term memory storage [2]. However, this speaks to the long-term effects of sleep deprivation on long-term memory storage. While sleep can impact many aspects of long-term storage of information, this investigation seeks to understand how sleep deprivation affects short-term memory- specifically, working memory. Working memory is a function that is necessary in everyday tasks and is indirectly related to attention span and the ability to focus on a task [3]. As such, working memory plays a crucial role in students' lives as it may directly influence their academic performance by impacting their ability to focus or process information required for class participation, homework exercises, and test-taking [4,5]. Sleep deprivation is a phenomenon that has been known to influence an individual's mood, cognitive ability, and work performance. Furthermore, previous research has indicated that sleep deprivation severely limited working memory capacity [6,7]. In this study, we will assess the effects of acute sleep deprivation on working memory capacity in university undergraduate students utilizing a 2-back spatial memory test.

Working Memory and Sleep Deprivation

The working memory refers to a subset of short-term memory that involves the managing and applying short-term memory to cognitive tasks as well as manipulating information in the short-term [8]. It is a category of information storage in the human brain that holds temporary and relevant information to a given task and is responsible for incorporating this new information with older long-term information, to produce a unified cohesive idea. Working memory is what allows for the proper functionality of language comprehension, analysis of behavior, learning from patterns, and reasoning strategies, as it allows for old ideas to be analyzed and changed to incorporate new information [9]. Sleep deprivation has been proven in literature and in numerous studies to have a profound effect on overall brain performance, and more specifically on memory functionality, with a general negative trend [3]. Based on a study conducted in 1988 and subsequent replications sleep deprivation primarily manifests its effects on the prefrontal cortex and its respective functions in that locality where the function of working memory is primarily processed [10,11]. Moreover, previous literature shows that sleep deprivation also impacts non-executive processes such as vigilance and attention which play a significant role in retaining information which affects the encoding of information in the short-term [12,13]. Lastly, the impact of sleep deprivation on working memory can be explained by the fact that inadequate sleep reduces metabolic activity and activates the default network of the brain which mainly impacts information processing [14]. Researchers hypothesize that the lack of sleep increases the connectivity between the hippocampus, thalamus, and default network which leads to automatic processing rather than attention-based processing, adversely affecting the working memory.

Working Memory and n-back test

Working memory functionality and capacity can be empirically tested by a multitude of different sources. One of the most frequent types of testing performed for measuring the capacity of working memory is known as n-back working memory paradigm. Individuals are tasked with determining whether the verbal or non-verbal stimuli matches the stimuli n-turns ago and it challenges not only ones' attention span but their ability to manipulate short-term memory, or working memory [15]. Although there has been debate on whether n-back test is a true measure of the working memory, there is evidence that n-back test stimulates prefrontal and parietal regions which is consistent with the physiological basis of working memory [16]. Furthermore, prior neuroimaging studies have indicated that the effects of sleep deprivation extend to visuospatial processing ability [17]. As such, this study will utilize the 2-back spatial working memory paradigm which involves matching a visual stimuli to that of 2 turns previous.

Conclusions

There are several risk factors that may play a role in affecting memory performance, which may influence the effects of sleep deprivation on the working memory. The most common of these factors include age, gender, caffeine or alcohol consumption, exercise levels, and stress and other outlying mental factors [18,19]. To determine the exact response that sleep deprivation has on working memory function, these factors must be properly accounted for or controlled. A common demographic that is impacted by sleep deprivation is college students. Researchers have confirmed that up to sixty percent of all university students suffer with poor sleep quality [20]. While students justify sacrificing sleep by deeming it a necessity for success, they underestimate the impact on their cognition and their ability to function during the day. The law of diminishing returns plays a huge role in this phenomenon as the loss of sleep does not equate to the same proportional amount of productivity lost. In this study, we aim to confirm that the act of losing sleep can produce a tangible change in cognition testing. Using a within-subject experimental design, we will conduct a group case-study in which participants will undergo a 2-back spatial working memory test in hopes of showing that sleep deprivation adversely impacts each individuals' working memory.

Methodology

Participants

We recruited a sample of convenience of upper-class undergraduate students with diverse sleeping patterns, but within normal variation of natural sleeping patterns. Of the seven participants, four were male and three were female. Participants were solicited using both social media and by individual requests from the members of the research team. The average age of the participants was 21. In the two weeks leading up to the experiment, participants were not restricted to following a strict 8-hour sleep schedule nor forced to alter their lifestyle for the study in any way, shape, or form. For the duration of the experiment, the participants were controlled for their exercise level, caffeine and alcohol consumption, and stress levels, to ensure that these variables did not impact their scores from one day to another. Lastly, participants were not provided with an incentive to participate in this study. Participants were allowed to conduct the study on their own time and their results were not monitored by the research team. The instructions that the participants were asked to follow for the duration of the experiment can be seen in the Appendix. Participants were fully briefed on the intent and purpose of this study and were asked to contact the research team with any further questions throughout the duration of the experiment.

Experimental Design

The research paradigm of this study consists of a group case study in which participants participated in a within-subject experiment. Prior to the study, participants were asked to fill out a questionnaire regarding their sleep habits and other major factors that affect sleep quality, such as exercise levels, estimated screen time, alcohol consumption, quantity of sleep, and normal hydration levels. Caffeine consumption, being a common factor among the target demographic of the study, was controlled for, as any potential participant with regular consumption of caffeine was not included in the study. To study the effect of subjective sleep deprivation on working memory capacity, each participant was asked to take the 2-back spatial memory test four times total: twice on a day when the participant feels they have received adequate sleep and twice on a day that they subjectively valued as having inadequate sleep. The test analyzed the participants' performance for how accurately they could recall a stimulus, by correctly matching a stimulus to another that occurred two turns before.

Procedure and Materials

Procedure

Participants were given explicit instructions in how to perform the 2-back spatial memory task on themselves, and the full instructions that were given to the participants to access and properly set up the test can be seen in the Appendix. Participants were asked to select the options of "normal duration" (100 trails, 5 minutes) and "2-back spatial" before beginning the test. Participants were permitted to use the "train duration" test to acclimate themselves to the test and understand both the criteria and how to take the test. Each participant underwent four separate tests: two tests (back-to-back) on days with subjectively determined normal sleep and two tests (back-to-back) on days with subjectively determined insufficient sleep to ensure accurate measurement of their working memory. Participants were then asked to send a screenshot of their results after taking each series of tests, which were then used to run statistical analysis on. The average and variance values per individual and as a group were recorded, and paired two sample t-tests for means were performed on the individual results as well as the aggregate group results. The resulting p-values and t-stat values were also recorded for further statistical analysis. The results were analyzed on a case-by-case basis, taking into consideration the presence of other factors noted from the participants' survey responses, which asked specific questions about sleep pattern, daily supplement intake, exercise history, and other factors that can affect sleep quality and cognition, and relevant conclusions were drawn. Throughout the study, for all of these participants, the only variable factor was the quantity of sleep achieved (which measured the presence of sleep deprivation) with all other factors being held constant.

2-back spatial task

The 2-back spatial task refers to the working memory test designed for participants to keep track of location of the stimulus and the pattern of the firing pattern of the stimuli. Participants performed this test on their own hardware, which was not standardized. Participants were presented with a 3X3 grid of nine squares, in which one trial represents the random green flashing of one of the nine squares. For the "normal duration" 2-back spatial task used in this study, this process was repeated 100 times total. The participants were required to keep track of the flashing squares position. When the location of the flashing square matched the location of the flashing square two trials before, then participants were asked to press the "a" key on their keyboard. Failure to press "a" before the beginning of the next trial was counted as a miss. At the end of each test, the measure of their working memory capacity was reported as the percentage of correct indications recognized and recorded as a decimal over the total number of matches.

Results

Participant Number	Regular Sleep 2-back scores	Average and Variance for Regular Sleep 2-back scores	Sleep Deprived 2-back scores	Average and Variance for Sleep Deprived 2-back scores	One-tail Paired Two Sample t-test : t-stat	One-tail Paired Two Sample t-test : p-value
1	.85;.87	.86;.0002	.83;.70	.77;.00845	1.267	0.212
2	.77;.87	.82;.005	.73;.80	.765;.00245	3.667	0.085
3	.83;.83	.83;0	.79;.81	.80;.0002	3.000	0.102
4	.90;.96	.93;.0018	.70;.80	.75;.005	9.000	0.035
5	.90;.93	.915;.00045	.89;.84	.865;.00125	1.250	0.215
6	.69;.74	.715;.00125	.65;.68	.665;.00045	5.000	0.063
7	.88;.85	.865;.00045	.85;.78	.815;.00245	2.5	0.12112
Overall	.848;.005074	.776;.003862	3.756	0.00472		

Table 1. *Participant Number and Corresponding Non-Sleep Deprived and Sleep Deprived 2-back Spatial test results, with Paired Two-Sample T-Test results, for both Individual and Aggregate group results*

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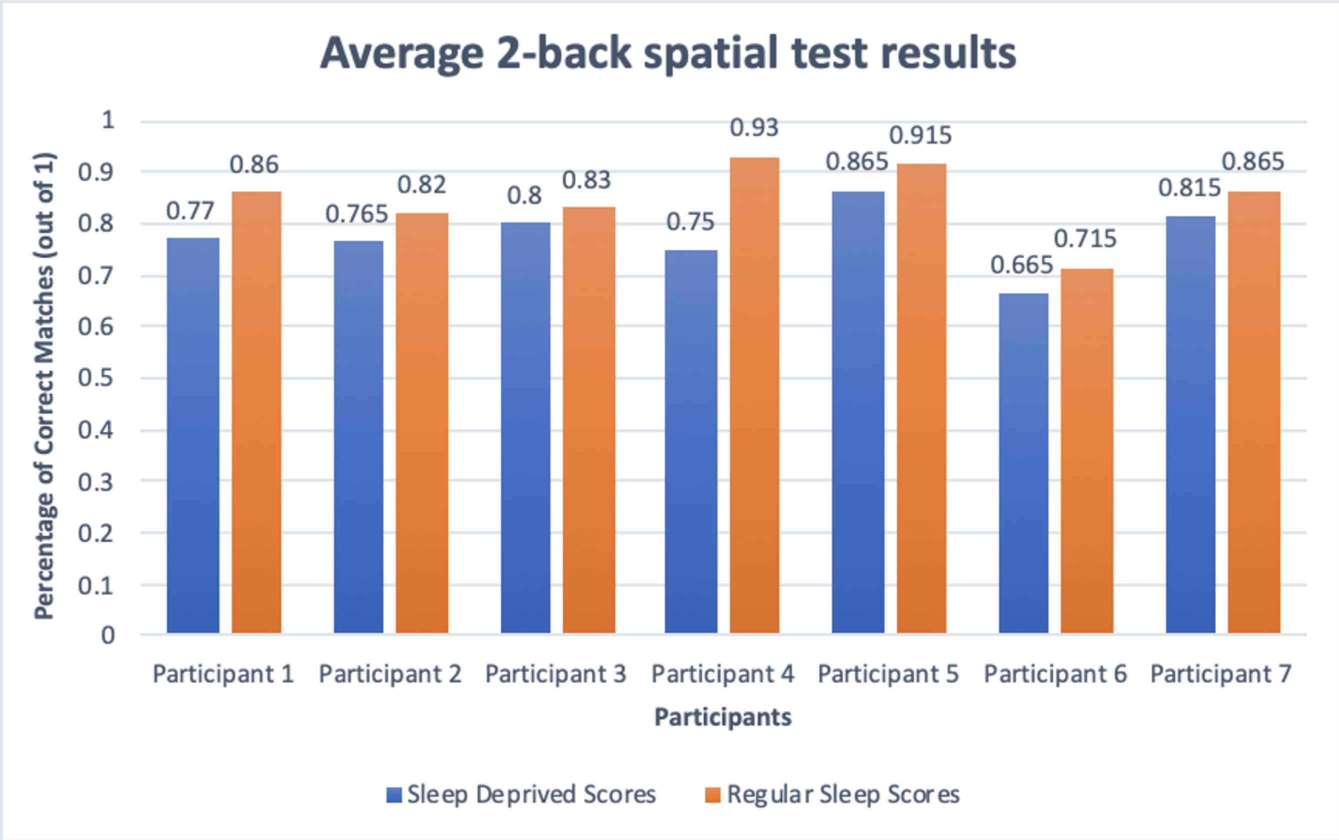

Figure 1. *Average 2-back Spatial Test Results Breakdown by Participant*

To determine the effect of sleep deprivation on working memory for the entire sample, a paired t-test with a significance value of 0.05 was conducted for each individual and for the aggregate group results. On the individual level, excluding the results of Participant 4, all recorded p-values were above the significance value threshold of 0.05 ($p > 0.05$). Participant 4 saw an individual recorded p-value of 0.035, which is less than the significance value threshold of 0.05 ($p < 0.05$). For the group aggregate scores, a p-value of 0.00472 was recorded, which is less than the significance value threshold of 0.05 ($p < 0.05$).

Discussion

Analysis of our results, on the sample level, yielded a significance value of 0.00472 ($p < 0.05$) which indicates the rejection of the null hypothesis that sleep deprivation has no measurable impact on working memory, in favor of the alternative hypothesis that sleep deprivation does adversely affect working memory. However, analysis on an individual level conflicted with this finding. With the exception of Participant 4, the remaining participants show no significant impact of sleep deprivation on their scores as their significance values were well above 0.05. This indicates that the effects of sleep deprivation are not generalizable across individuals and that the impact of sleep deprivation is specific to each individual. To ascertain how each individual was exactly impacted by sleep deprivation, we analyze their results in the context of both their normal sleep schedule as well as their lifestyle.

Participant Breakdown

Participant Number	Age	Ethnicity	Sex	Average Sleep and

				Sleep Schedule
1	21	Asian American	Female	6 hours; 4AM- 10 AM
2	20	Indian American	Female	5 hours; 4AM- 9 AM
3	21	White	Male	6 hours; 4AM - 10AM
4	21	Indian American	Male	7 hours; 2AM - 9AM
5	21	Indian American	Male	6 hours; 4AM - 10AM
6	20	White	Female	8 hours; 12AM - 8AM
7	21	Indian American	Male	8 hours; 6AM- 2PM

Table 2. *Demographic Information Identifying the Participants*

Participant 1 is an Asian American Female who is 21 years old and is an Undergraduate Senior attending University. They average around 6 hours of sleep a day and typically sleep from the hours of 4AM to 10AM daily Table 2. They exercise daily for around two hours, have an estimated screen time of 10 hours a day, regularly consume alcohol about once a month, and drink an estimated 2 cups of water a day. They believe that they are regularly sleep deprived and do not regularly get enough sleep to feel rejuvenated. Their one-tailed paired two-sample t-test results (p-value and t-stat) did not show individual statistical significance between sleep deprivation and an effect on working memory. However, there is an increase in variance from the regular sleep to sleep deprived scores, suggesting that regular sleep may play a role in the consistency of the functionality of the working memory.

Participant 2 is an Indian American Female who is 21 years old and is an Undergraduate Senior attending University. They average around 5 hours of sleep a day and typically sleep from the hours of 4AM to 9AM daily Table 2. They do not exercise daily, have an estimated screen time of 10 hours a day, do not regularly consume alcohol, and drink an estimated 6 cups of water a day. They believe that they are regularly sleep deprived and do not regularly get enough sleep to feel rejuvenated. Their one-tailed paired two-sample t-test results (p-value) did not show individual statistical significance between sleep deprivation and an effect on working memory. Their t-stat value was significantly greater than 2, which does indicate a statistically significant correlation between sleep deprivation and working memory, but the null hypothesis is failed to be rejected because the p-value was found to be larger than the statistically significant value. Furthemore, there is a decrease in variance from regular sleep to sleep deprived scores which implies the possibility that participant 2 can be equally as high-functioning and consistent even under the effects of sleep deprivation.

Participant 3 is a White Male who is 21 years old and is an Undergraduate Senior attending University. They average around 6 hours of sleep a day and typically sleep from the hours of 4AM to 10AM daily Table 2. They do not exercise daily, have an estimated screen time of 13 hours a day, do not regularly consume alcohol, and drink an estimated 4 cups of water a day. They believe that they are regularly sleep deprived and do not regularly get enough sleep to feel rejuvenated. Their one-tailed paired two-sample t-test results (p-value) did not show individual statistical significance between sleep deprivation and an effect on working memory, but the t-stat value being greater than 2 does indicate statistical significance. However, the null hypothesis is failed to be rejected, so there is no statistical significance between sleep deprivation and an effect on working memory. This individual had the lowest variance between the scores of both regular sleep test scores and sleep deprived test scores. This shows that the individual is very consistent in their scoring despite the effects of sleep deprivation.

Participant 4 is an Indian American Male who is 21 years old and is an Undergraduate Senior attending University. They average around 7 hours of sleep a day and typically sleep from the hours of 2AM to 9AM daily Table 2. They do not exercise daily, have an estimated screen time of 8 hours a day, regularly consume alcohol around twice a month, and drink an estimated 8 cups of water a day. They do not believe that they are regularly sleep deprived and do regularly get enough sleep to feel rejuvenated. Their one-tailed paired two-sample t-test results (both p-value and t-stat) did show individual statistical significance between sleep deprivation and an effect on working memory. The reason for high statistical significance is likely that this individual does attain regular sleep so the effects of sleep deprivation are likely greater on this individual as compared to the effect of sleep deprivation on other individuals. This individual had higher variance in sleep deprived test scores which indicates less consistency in results as a result of sleep deprivation.

Participant 5 is an Indian American Male who is 21 years old and is an Undergraduate Senior attending University. They average around 6 hours of sleep a day and typically sleep from the hours of 4AM to 10AM daily Table 2. They exercise daily for around one hour, have an estimated screen time of 10 hours a day, regularly consume alcohol around once a month, and drink an estimated 6 cups of water a day. They believe that they are regularly sleep deprived and do not regularly get enough sleep to feel rejuvenated. Their one-tailed paired two-sample t-test results (both p-value and t-stat) did not show individual statistical significance between sleep deprivation and an effect on working memory. The individual did have lower overall sleep deprivation test scores than regular sleep test scores. Their variance for regular sleep test scores was lower than sleep deprivation test scores, which suggests that they perform more consistently when having adequate amounts of sleep as opposed to when they are sleep deprived. A likely reason that this participant had no statistical significance between sleep deprivation and working memory capacity is that this participant shows a history of regular inadequate sleep which may influence the effect of sleep deprivation on cognition.

Participant 6 is a White Female who is 20 years old and is an Undergraduate Sophomore attending University. They average around 8 hours of sleep a day and typically sleep from the hours of 12AM to 8AM daily Table 2. They exercise daily for around two hours, have an estimated screen time of 5 hours a day, do not regularly consume alcohol, and drink an estimated 8 cups of water a day. They believe that they are not regularly sleep deprived and do regularly get enough sleep to feel rejuvenated. Their one-tailed paired two-sample t-test results (p-value) did not show individual statistical significance between sleep deprivation and an effect on working memory. Their t-stat value was greater than 2, which does indicate a statistically significant correlation between sleep deprivation and working memory, but the null hypothesis is failed to be rejected because the p-value was found to be larger than the statistically significant value. The p-value obtained here is the closest of all the other participants, besides Participant 4, in indicating statistical significance.

Participant 7 is an Indian American Male who is 21 years old and is an Undergraduate Senior attending University. They average around 8 hours of sleep a day and typically sleep from the hours of 6AM to 2PM daily Table 2. They exercise daily for around two hours, have an estimated screen time of 12 hours a day, regularly consume alcohol around four times a month, and drink an estimated 3 cups of water a day. They do not believe that they are regularly sleep deprived and do regularly get enough sleep to feel rejuvenated. Their one-tailed paired two-sample t-test results (p-value) did not show individual statistical significance between sleep deprivation and an effect on working memory. Their t-stat value was greater than 2, which does indicate a statistically significant correlation between sleep deprivation and working memory, but the null hypothesis is failed to be rejected because the p-value was found to be larger than the statistically significant value. However, there is an increase in variance from the normal sleep to sleep deprived scores suggesting that sleep deprivation may play a role in consistency of working memory functioning. This participant did not have any regular sleep schedule and believes that they have indications of chronic insomnia. The patient does not have a set sleep routine for the full 8 hours but instead takes multiple naps in smaller lengths of time throughout the day to achieve the sleep needed. Any irregularities in expected behavior can be attributed to the irregular sleep schedule, which the effects of does not have a current proper and complete understanding in literature. The effects of chronic insomnia on the consistency of working memory are yet to be fully understood.

Implications

Prior research on the effects of sleep deprivation on working memory has indicated an adverse relationship between working memory performance and sleep deprivation. Generally, these experimental paradigms involved participants that were sleep deprived over the course of 36 hours [21]. Based on the conclusions of these studies, we predicted that individuals' working memory scores would plummet when they were faced with acute sleep deprivation. The results from this experiment indicated no overall statistically significant relationship between sleep deprivation and an effect on working memory function, on an individual level, contrary to the findings from past literature and past studies performed [22].

Though there was a lack of statistical significance, one phenomenon that was observed was the larger difference in regular sleep and sleep deprived 2-back scores in individuals that had a greater change in regular sleep pattern or a larger proportional amount of sleep deprivation. This can be seen in the results of Participants 4, who had more sleep on average than the other participants and a more regular sleep schedule than the other participants Table 1. Possible explanations of this phenomenon include the hypothesis that the effects of sleep deprivation have a larger impact on the working memory capacity of those that have not experienced it as regularly as others have. The effects of sleep deprivation could affect those individuals disproportionately more in the tested performance metric than the other individuals who experience sleep deprivation more regularly.

Another phenomenon that was observed was the tangible increase in the variation of sleep deprived scores for most participants of the study Table 1. For all but two of the participants in this study, the variance between each of the sleep deprived test results was greater than the variance between the regular sleep pattern test results. In these individuals, it is hypothesized that sleep deprivation could have manifested its effects in a more volatile overall attention span, or less concentration and focus in tasks. Whatever the case of the higher variance in sleep deprived test results, the results from the regular sleep test results have a lower variance for each individual which indicates more stability or consistency between trials. More in depth study on the implications of a consistent working memory as opposed to a volatile, accurate working memory needs to be done to understand the full context of the results.

Limitations and Future Directions

While we did see statistically non-significant results, our findings allude to the potential effects of sleep deprivation on working memory. Furthermore, the non-significant results can be attributed to the limitations of our study one of which being the ongoing pandemic. COVID has an indisputable impact on the daily lives of everyone, specifically college students. With the movement towards online-classes and more flexible schedules, students have had to adapt not just to work from home but also an overload of assignments, which significantly impacts their sleep schedules. Many participants claimed to have low motivation levels and have subsequently mentioned that work has been piling up until the last minute. This behavior hints to a development of an adaptive mechanism allowing for short bouts of high-functioning cognition followed by longer, laxative, breaks in concentration. To account for this variation in concentration it would be wise to obtain more data points from each participant throughout the day.

Future replications of the study should obtain a larger group of participants chosen at random from a larger pool of undergraduate college students (as opposed to a sample of convenience) and attempt to gather more data points for each individual and should test over more than just two days of testing to gather more statistically significant results. In this study, to minimize the effect of day-to-day learning on the 2-back spatial test results, it was decided to have the test be performed on the least amount of days possible, which was two days. However, this limits the statistical power of the results because the overall results are more subject to day-to-day normal variance, and are not representative of the long-term effect of sleep deprivation on the individual. The balance between the effect of learning and the reduction in statistical significance needs to be defined before replicating the study in the future. The presence of a subjective indicator (being the feeling of sleep deprived) as the reason that the individual chose to perform the tests on a certain day should also be eliminated in future studies. Sleeping habits and duration should instead be closely monitored and the point of sleep deprivation should be empirically determined for each individual; both quantitative duration and quality of sleep thresholds for sleep deprivation should be found and used to determine the days of testing for the participants. For more statistically significant results, the study should be repeated under conditions where the other factors that affect the effects of sleep deprivation and quality of sleep can be completely controlled for. For example, participants should have a controlled and consistent amount of exercise time, supplement intake, and stress load throughout the experiment.

Conclusion

The findings of our study, while statistically non-significant, provide several implications that have the potential to further future research on the effects of acute sleep deprivation on working memory. For instance, we noticed that there was greater variability in the scores on the sleep deprived days in comparison to the normal sleep days per individual. Based on these results, it is possible that the effect of sleep deprivation might indirectly affect working memory by affecting concentration and attention span directly in the short-term. To understand the short-term implications of sleep deprivation on working memory, it is necessary to further investigate its effects on both attention span and concentration. While the conditions under which this investigation was conducted were less than ideal, this study reveals the impact of sleeping history on the effect of sleep deprivation in college students. Though we may not be able to conclusively say that the students with acute sleep deprivation will have a decreased working memory capacity, students should take into account both the short-term and long-term (chronic) effects of sleep deprivation and the different possible ways that the effects can manifest themselves in their productivity. To better understand the exact relationship or mechanism of action that sleep deprivation has in affecting working memory capacity, more in depth testing and analysis needs to be done.

Authors Note

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Appendix

2-back Spatial Test Instructions

Good Evening,

We have asked you to take an n-back test to demonstrate your working memory capacity. The n-back test you will be taking is the “2-back spatial test”. In an effort to study how irregular sleep affects working memory capacity, we would like you to take the n-back test on 2 days: one where you get regular sleep and one on a day when you are sleep deprived. Please take the test two times each of those days (for 4 tests total) in the morning after you wake up (before any caffeine consumption).

How does the test work?

You will see a series of patterns on a 3x3 grid and you will be asked to determine when a specific square flashes green in the same place as the square two trials ago. For example, if the bottom right corner flashes green for the first trial, and then again on the third trial, you would press “a” on your keyboard. Below is an example of what you will see during testing. Each square will flash green for one second followed by a two second period of rest.

Instructions

1. Open the testing website ()
2. Select the “Normal” duration (100 trials, 5 mins)
3. Select the 2-back Spatial test. The test will begin when you click on the “2-back” button.
4. Press “a” on the keyboard when the square flashes green in the same position as the square two trials before.
5. When the test is over, please record your results or take a picture of the scorecard

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