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Effects of sleep reduction on the phonological and visuospatial components of working memory



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ABSTRACT

Sleep reduction impairs the performance of many tasks, so it may affect a basic cognitive process, such as working memory, crucial for the execution of a broad range of activities. Working memory has two storage components: a phonological and a visuospatial component. The objective of this study was to analyze the effects of sleep reduction for 5 days on the storage components of working memory. Thirteen undergraduate students (18.77 ± 2.20 years of age), 5 men and 8 women, responded two N-Back tasks (auditory and visual), with three sections each (0-Back, 1-Back, and 2-Back). These tasks were performed at 13:00 h under the following conditions: before sleep reduction (control; C); on the first (SR1), fourth (SR4), and fifth (SR5) days of sleep reduction (4 h of sleep per night); and one day after they slept freely (recovery, R). Sleep reduction produced a decrement in accuracy on the auditory 2-Back section the fifth day of sleep reduction ($C=87.86 \pm 13.35\%$; $SR5=74.76 \pm 16.37\%$; $F=14.57$, $p<0.01$). In the visual 2-Back section accuracy decreased ($C=88.10 \pm 9.95\%$; $SR1=82.45 \pm 11.57\%$; $SR5=77.76 \pm 14.14\%$; $F=10.80$, $p<0.05$), and reaction time increased ($C=810.02 \pm 173.96$ ms; $SR1=913.51 \pm 172.25$ ms; $SR5=874.78 \pm 172.27$ ms; $F=10.80$, $p<0.05$) on the first and fifth day of sleep reduction. In conclusion, five days of sleep reduction produces a decrease in the phonological and visuospatial storage components of working memory, which may interfere with processing verbal information and solving problems that require spatial analysis.

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Introduction

People who sleep well, based on their own needs and in free conditions (weekends, vacation), feel alert during the day, rested, and in an optimal state to perform their daily activities. However, when they suffer a reduction of sleep due to work, school or social activities, physiological and cognitive changes occur that affect their physical and mental health [1,2]. Currently, the majority of the population suffers from chronic partial sleep

deprivation [3], so it is important to analyze the effects of sleep reduction on human performance [4,5].

Laboratory studies have shown that total sleep deprivation for 24–72 h impairs the performance of many tasks [1,6,7]. So, it is possible that the lack of sleep may affect a basic cognitive process, such as attention, working memory or executive functions, crucial for the execution of a broad range of activities. Some studies have provided evidence of an effect of total sleep deprivation on attention [8], while others have documented and

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effect on executive functions [9]. However, conflicting results about the effects of total sleep deprivation on working memory have been found, since a reduction in this cognitive process has been observed in some studies, while no effect has been observed in other papers [10,11]. Several papers have demonstrated that total sleep deprivation affects verbal working memory, while other papers have failed to demonstrate an effect on visuospatial working memory [1]. Nevertheless, sleep deprivation affects performance on verbal and visuospatial tasks, which require the participation of phonological and visuospatial components of working memory [12].

On the other hand, partial sleep deprivation is a reduction in the number of hours a person normally sleeps at night, and this condition becomes chronic when it occurs over the course of several consecutive days [13,14]. This condition occurs commonly during weekdays in people working or studying on a morning shift, because they have to wake up early to go to work or school, but they tend to go to bed late due to occupational, social or recreational activities [1,2,14]. This chronic sleep reduction produces subjective feelings of sleepiness, tiredness, irritability, and lack of concentration [15,16]. Although many people are exposed to chronic partial sleep deprivation, its effects on basic cognitive processes are less known. An effect of sleep reduction on attention has been observed [8,17,18], but there are few studies documenting effects on working memory [19,20].

Working memory is a basic cognitive process that maintains a limited amount of information during a brief period, in order to organize, differentiate, and use this information [21,22]. Working memory has several components: phonological storage, visuospatial storage, an episodic component, and a central executive. The first two components are involved in storing information, while the last two components are related to the regulation and use of the stored information. The phonological component focuses on processing auditory information related to speech, reading, language comprehension, and vocabulary acquisition [23,24]. The visuospatial component is responsible for processing visual information, including both images and the location and placement of objects in space [23–25]. The episodic component is involved in the integration and transfer of information between the other stores of working memory [23,26,27]. The central executive is a component that selects relevant information and directs it to each memory subsystem [28].

Each component of working memory require the participation of different brain structures; the phonological component is related to the posterior parietal cortex of the left hemisphere [29], the visuospatial component is related to the medial frontal gyrus, the superior frontal sulcus and the intraparietal sulcus [29,30], and the central executive is related to the ventrolateral prefrontal cortex [31].

Different tasks have been used to evaluate working memory. One of these is the N-Back task, in which participants are presented with a stream of stimuli, and they have to decide for each event whether it matches the one presented N items before. This task has been used in many studies to evaluate working memory, because its design fits well with the working memory concept as expressed by Baddeley [22]. Also, this task has been used extensively in the fields of neuroscience, clinical and aging research [32–34]. Some concerns have been raised about the validity of the N-Back task as a working memory test, because it has low correlations ($r=0.20$) with other working

memory tasks [35]. Nevertheless, high correlations ($r=0.67$, $r=0.80$) between N-Back and other working memory tasks have been found when a confirmatory factor analysis is used, that includes hierarchical latent factors that model task-specific, paradigm-specific and construct variance [36,37].

Sleep reduction for 5 days produces a decrease in the performance of verbal working memory tasks [19], while other studies did not find differences [18,38]. To our knowledge there are no studies documenting the effects of sleep reduction on visuospatial memory tasks.

Therefore, it is necessary to analyze what specific components of working memory are affected by sleep reduction. The objective of this study was to analyze the effects of 5 days of sleep reduction on the phonological and visuospatial components of working memory. The hypothesis of this study was that sleep reduction for 5 days affects both components of working memory.

Method

Participants

Participants in the study included 13 volunteer university students with an age of 18.77 ± 2.20 (average \pm standard deviation), range = 17–20 years, 5 men and 8 women, who attended morning classes (start time: between 07:00 h and 10:00 h; finish time: between 12:00 h and 14:00 h), from Monday to Friday. None of the participants had any physical or psychological condition or sleep disorder, none were under medical treatment, and none consumed drugs or substances that alter the functions of the nervous system. At the beginning of the study the participants signed a letter of informed consent. In the case of minors, their parents or guardians also signed a letter of informed consent. The study was approved by an academic committee at the university and was conducted in accordance with the ethical standards established in the Declaration of Helsinki.

Instruments

The following questionnaires were used:

- (1) General information questionnaire: this questionnaire obtains information on personal data, class schedules, extra-curricular activities, menstrual period, physical and cognitive health, as well as consumption of drugs, diseases, disorders, or accidents that affect the nervous system [39].
- (2) Morningness–Eveningness Questionnaire: this questionnaire allows identifying the hours during which individuals prefer to perform their activities. These preferences are classified in three categories: morning type (people who tend to perform their activities during the early hours of the morning); evening type (people who prefer to perform their activities at night); and intermediates [40,41].
- (3) Sleep disorder questionnaire: this questionnaire is used to detect sleep disorders, such as insomnia, excessive sleepiness, or parasomnias. This questionnaire allows identifying the presence of sleep disorders in participants

[40,42].

(4) Sleep diary: this questionnaire allows for daily recording of information related to sleeping habits and schedules. It includes questions on bedtime and wake up time, naps, and daily consumption of caffeinated beverages and tobacco [39].

(5) Visual analog scales to assess sleepiness and tiredness: the participant indicates their level of sleepiness or tiredness by drawing a mark on a 10 cm-long horizontal line. The left end corresponds to the minimum level of sleepiness or tiredness, while the right end corresponds to the maximum level [43,44].

For the presentation of stimuli and recording of participant responses during the working memory tasks, a desktop computer was used with a 17-in., 800 × 600-pixel monitor placed 60 cm in front of the participant. Auditory stimuli were presented using Sony MDR-ZX100 headphones. Each speaker has a diameter of 30 mm, a response frequency of 12 at 22,000 c/s, and maximum power of 1000 mW.

Task

Two N-Back tasks were used to assess each component of working memory, an auditory N-Back task for the phonological component, and a visual N-Back task for the visuospatial component [45,46] (Figs. 1 and 2). The first task consists of presenting a series of auditory stimuli, while for the second task visual stimuli in a certain position or location were presented. Each N-Back task contains three sections: 0-Back, 1-Back, and 2-Back. In the 0-Back section, the participant must indicate whether the presented stimulus at each event

is the same as or different from the first stimulus presented at the beginning of the section. The 1-Back section consists of answering whether each event presented is the same as or different from the one appeared immediately prior. The 2-Back section consists of indicating whether each event presented is the same as or different from the one appeared two events prior. The 0-Back section depends on attention while 1-Back and 2-Back sections require working memory with two levels of difficulty.

In the 0 and 1-Back sections, 65 stimuli were presented, while 66 in the 2-Back section. The stimuli from each section were presented in random sequences. Half of the stimuli presented in each section corresponded to the target stimulus. After the stimulus occurred, participants had an interval of 3000 ms (milliseconds) to make a response. The participant had to press the green button with the index finger of their dominant hand to indicate that the event matched the target stimulus. If it did not match, they had to press the red button with their middle finger. Fifty percent of events (32) matched with the corresponding target, while the other 50% mismatched.

In the N-Back auditory task, the stimuli were the Spanish syllables Ce, Che, Gue, Ke, Le, Pe, Re, and Ye, recorded in stereo and emitted through the headphones. Each syllable had a maximum duration of 300 ms (Fig. 1). In the visual N-Back task the stimuli were black text boxes (font, Wingding 37), appearing in one of eight different positions around the center of the screen. The box could be located at 45°, 135°, 225°, or 315° from the vertical axis, at either 4 or 8 cm from the center (Fig. 2).

Procedure

At the beginning of the study, the participants completed the Morningness-Eveningness Questionnaire and the general

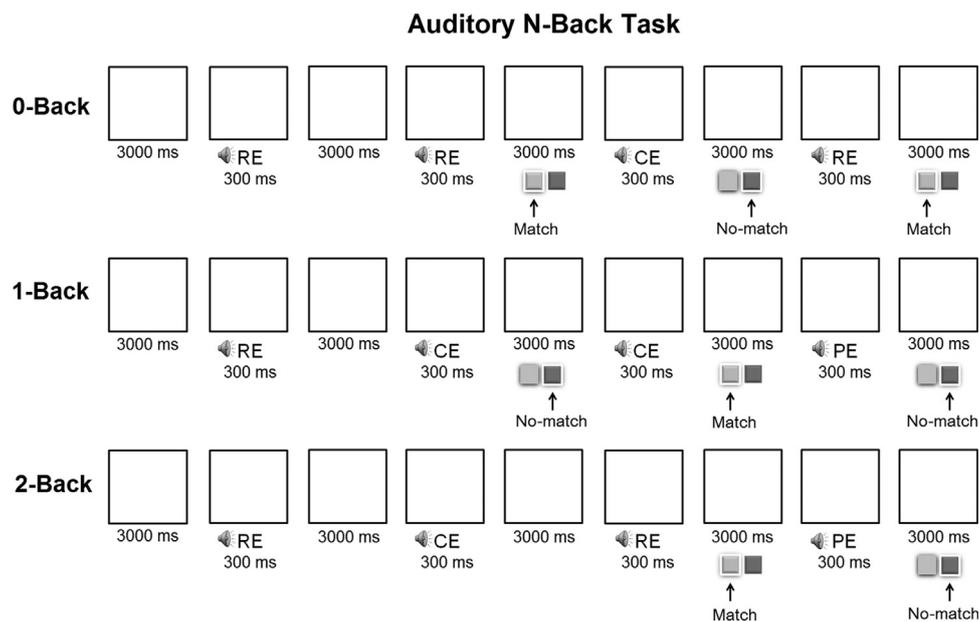


Fig. 1 – Auditory N-Back task. This task consists of presenting a series of auditory stimuli (syllables). It includes three sections: 0-Back, 1-Back, and 2-Back. During the 0-Back section, the participant must indicate whether each syllable presented is the same as the syllable presented at the beginning of the section. During the 1-Back section, the participant must indicate whether each syllable presented is the same as the one presented immediately prior. During the 2-Back section, the participant must indicate whether each syllable presented is the same as the syllable that appeared two events prior.

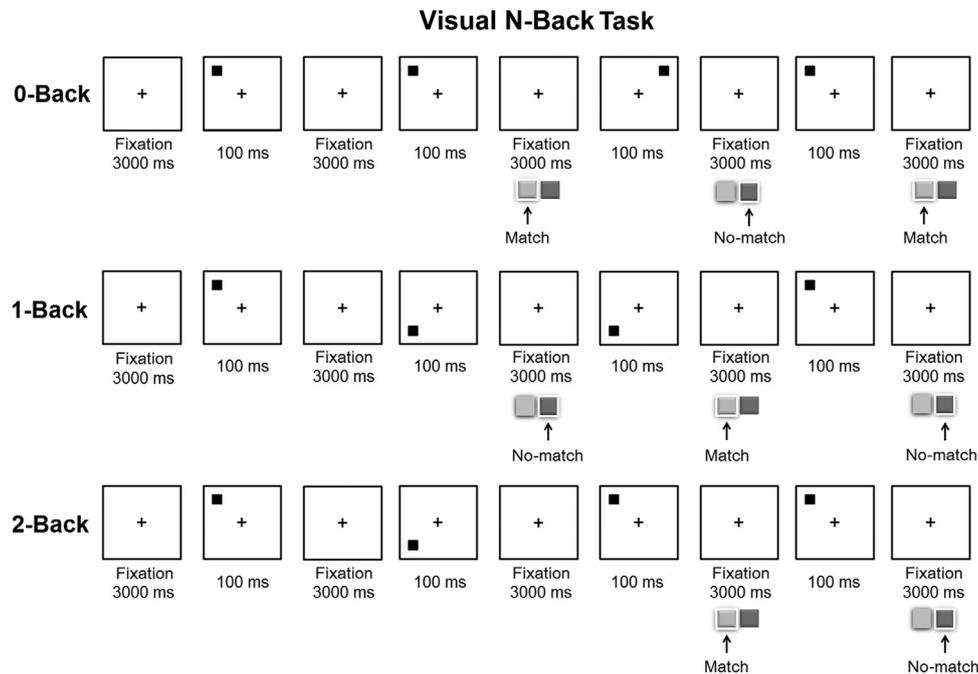


Fig. 2 – Visual N-Back task. This task consists of presenting a series of visual stimuli (black boxes) in a certain location on the screen. This task has three sections: 0-Back, 1-Back, and 2-Back. During the 0-Back section, the participant must indicate whether the location of each box presented is the same as the position of the box presented at the beginning of the section. During the 1-Back section, the participant must indicate whether the location of each box presented is the same as the location of the box presented immediately prior. During the 2-Back section, the participant must indicate whether the location of each box is the same as the location of the box presented two events prior.

information and sleep disorder questionnaires. They completed a sleep diary for 12 consecutive days, thereby recording their sleep habits, sleepiness and tiredness. During six of the 12 days, participants slept during normal hours and in normal conditions, from Tuesday to Sunday (control with no sleep reduction). During the next 5 days, participants were asked to sleep from 02:00 h to 06:00 h, meaning that their sleep was reduced to four hours per night, from Monday to Friday (5 days of sleep reduction). After the sleep reduction, they were allowed to sleep freely one night (recovery night). To ensure that participants adhered to the sleep reduction conditions, they were called via telephone every day prior to going to sleep and at the indicated waking time. The tasks were applied in the laboratory at 13:00 h in each condition: one day prior to sleep reduction (control condition with no sleep reduction, C); three days during sleep reduction: first (SR1), fourth (SR4), and fifth (SR5) day of sleep reduction; and one day after they slept freely (recovery, R). The laboratory recording began with application of the subjective sleepiness and tiredness scales, and then the auditory and visual N-Back tasks were administered.

Data analysis

Nonparametric statistical tests were used. A Friedman analysis of variance (F) was used to compare data from different days for each of the variables. A Wilcoxon T-test was used to compare performance on sleep reduction days and the day after the recovery night with the control condition (no sleep reduction). Analysis of the performance of the N-Back tasks after the

recovery night included only 12 participants, because data from one participant could not be measured due to a power failure.

Results

Participants had a score of 46.54 ± 5.03 points (range: 35–53) in the Morningness–Eveningness Questionnaire, 11 classifying as intermediates, and two as moderately evening type. Prior to sleep reduction, during weekdays the participants went to bed at $00:00 \pm 1:33$ h, woke up at $07:43 \pm 1:26$ h, and slept $7:43 \pm 1:01$ h, while during the weekend they went to bed at $00:36 \pm 1:38$ h, woke up at $09:16 \pm 0:17$ h, and slept $8:40 \pm 1:29$ h. During sleep reduction, participants complied with instructions, going to bed at $2:06 \pm 0:32$ h, waking up at $6:14 \pm 0:23$ h and sleeping $4:08 \pm 0:20$ h. During recovery, the participants went to bed at $23:46 \pm 2:24$ h, woke up at $9:02 \pm 1:03$ h, and slept $9:15 \pm 2:03$ h.

None of the participants consumed tobacco during the study. On the other hand, the consumption of caffeinated beverages was rare, only 4 participants reported intake of a cup of coffee in three or less occasions during the study.

Sleepiness and tiredness

Compared to the control condition with no sleep reduction, subjective sleepiness and tiredness increased during sleep reduction, though after recovery both decreased to levels similar to control (Sleepiness: C = 19.54 ± 20.15 mm; SR1 = 31.23 ± 22.41 mm; SR4 = 48.75 ± 22.15 mm; SR5 = 43.92 ± 20.94 mm; R = $21.45 \pm$

16.68 mm; $F=21.53$, $p<0.001$) (Tiredness: $C=11.54\pm 14.46$ mm; $SR1=25.46\pm 24.71$ mm; $SR4=34.67\pm 17.83$ mm; $SR5=36.08\pm 25.12$ mm; $R=19.17\pm 16.36$ mm; $F=14.91$, $p<0.01$).

Auditory N-Back task

In the auditory 0-Back section, a decrease was observed in the percentage of correct responses on the fifth day of sleep reduction, as compared to the control ($C=93.75\pm 7.79\%$; $SR1=95.07\pm 6.34\%$; $SR4=90.99\pm 6.38\%$; $SR5=87.02\pm 13.89\%$; $R=90.88\pm 5.76\%$; $F=13.00$, $p<0.05$) (Table 1).

In the auditory 1-Back section no differences were observed between the scores on the various days ($C=93.63\pm 5.54\%$; $SR1=90.87\pm 9.00\%$; $SR4=87.74\pm 8.12\%$; $SR5=81.97\pm 13.84\%$; $R=87.37\pm 8.15\%$; $F=6.43$, NS) (Table 1).

In the auditory 2-Back section, a decrease was observed in the percentage of correct responses on the fifth day of sleep reduction and on the day after the recovery night, as compared to the control ($C=87.86\pm 13.35\%$; $SR1=88.22\pm 6.17\%$; $SR4=80.53\pm 13.59\%$; $SR5=74.76\pm 16.37\%$; $R=78.52\pm 13.34\%$; $F=14.57$, $p<0.01$) (Table 1).

No significant differences were observed in reaction time in any of the three sections of the auditory N-Back task on any of the different days (Table 1).

Visual N-Back task

In the visual 0-Back and 1-Back section, no differences were observed in the percentage of correct responses or in reaction times between the scores from the different days (Table 1).

In the 2-Back section, the percentage of correct responses decreased on the first and fifth day of sleep reduction, as compared to the control ($C=88.10\pm 9.95\%$; $SR1=82.45\pm 11.57\%$; $SR4=82.57\pm 14.13\%$; $SR5=77.76\pm 14.14\%$; $R=79.95\pm 18.88\%$; $F=9.41$, $p=0.052$) (Table 1). In addition, an increase was observed in

reaction time in the visual 2-Back section on the first, fourth, and fifth day of sleep reduction, as compared to the control ($C=810.02\pm 173.96$ ms; $SR1=913.51\pm 172.25$ ms; $SR4=897.06\pm 153.51$ ms; $SR5=874.78\pm 172.27$ ms; $R=795.75\pm 154.42$ ms; $F=10.80$, $p<0.05$) (Table 1).

Discussion

According to the results of this study, a reduction to four hours of sleep per night for five consecutive days produces a gradual increase in sleepiness and tiredness. Other studies have also found a gradual increase in sleepiness with sleep reduction during several consecutive days [16–20,47,48]. The results of this study are similar to the data from Kopasz et al. (2010), who observed an increase in tiredness on the first night of partial sleep reduction [49].

Accuracy to respond to the auditory 0-Back diminished in the fifth day of sleep reduction. This section of the task depends mainly on attention, thus implying an effect of sleep reduction on this cognitive process. Other studies have also found that sleep reduction affects attention using other tasks that measure this process, such as a reaction time task: the Psychomotor Vigilance Task [8,17,18]. Attention is a central basic cognitive process, so a decrement in correct responses to the visual 0-Back section and a general decrease in reaction time should occur as a consequence of sleep reduction. But none of these results were observed, so sleep reduction may produce a weak effect on attention or only some aspects of attention are affected.

In this study we observed that the phonological component of working memory (correct responses in the 2-Back section) decreased on the fifth day of partial sleep reduction and remained at a low level even after the recovery night. The phonological component of working memory may require more time to recover; unfortunately we only recorded performance

Table 1 – Phonological (auditory N-Back task performance) and visuospatial (visual N-Back task performance) storage components of working memory before (control), during and after (recovery) sleep reduction.

Task	Section	C	SR1	SR4	SR5	R	F
Auditory N-Back (% correct responses)	0-Back	93.75 ± 7.79	95.07 ± 6.34	90.99 ± 6.38	87.02 ± 13.89**	90.88 ± 5.76	13.00**
	1-Back	93.63 ± 5.54	90.87 ± 9.00	87.74 ± 8.12	81.97 ± 13.84	87.37 ± 8.15	6.43
	2-Back	87.86 ± 13.35	88.22 ± 6.17	80.53 ± 13.59	74.76 ± 16.37**	78.52 ± 13.34**	14.57***
Auditory N-Back (reaction time)	0-Back	698.01 ± 163.93	696.73 ± 106.25	743.54 ± 159.75	729.87 ± 191.55	784.03 ± 238.15	8.13
	1-Back	783.52 ± 152.14	879.40 ± 108.79	902.13 ± 145.98	881.79 ± 205.87	924.72 ± 266.91	7.13
	2-Back	831.20 ± 212.04	924.29 ± 197.33	925.42 ± 211.77	902.68 ± 213.83	915.76 ± 318.91	4.07
Visual N-Back (% correct responses)	0-Back	92.19 ± 9.57	94.23 ± 3.63	91.95 ± 6.56	92.19 ± 8.19	93.88 ± 8.09	1.25
	1-Back	88.82 ± 9.88	86.06 ± 13.19	86.78 ± 8.38	86.90 ± 10.70	88.41 ± 11.22	4.14
	2-Back	88.10 ± 9.95	82.45 ± 11.57**	82.57 ± 14.13	77.76 ± 14.14*	79.95 ± 18.88	9.41*
Visual N-Back (reaction time)	0-Back	688.00 ± 98.93	714.57 ± 77.97	706.08 ± 67.54	687.40 ± 102.64	640.85 ± 115.61	7.27
	1-Back	797.38 ± 168.72	771.51 ± 83.36	822.41 ± 79.88	809.41 ± 96.64	747.92 ± 155.23	5.73
	2-Back	810.02 ± 173.96	913.51 ± 172.25*	897.06 ± 153.51**	874.78 ± 172.27**	795.75 ± 154.42	10.80**

Values are mean ± standard deviation. F=Friedman. Bold values were significantly different from control with Wilcoxon T test. C=control (no sleep reduction), SR1=sleep reduction day 1, SR4=sleep reduction day 4, SR5=sleep reduction day 5, R=recovery.

* $p=0.05$.

** $p<0.05$.

*** $p<0.01$.

after a single recovery night. This decline in the phonological component of working memory can affect verbal skills. Therefore, these results are consistent with the data from Lo et al. (2012) [18] and Jiang et al. (2011) [19], who observed that a restriction of four hours daily over the course of several days reduces the ability to respond to verbal stimuli. The decline in the phonological component of working memory can affect the ability to process verbal information. This implies difficulties in processing and understanding written text, as well as in solving problems that require verbal analysis.

Furthermore, in this study we observed that five days of sleep reduction produce a decrease in the percentage of correct responses and an increase in reaction time in the visuospatial component of working memory (2-Back section). A decrease in correct responses together with an increase in reaction time in this section of the visual task, means an additional effort to process, store and use spatial stimuli. These results suggest that sleep reduction has a stronger effect on visuospatial than phonological working memory. Moreover, the decline in the visuospatial component of working memory may affect the ability to process images, locate objects in space, and solve problems that require spatial analysis. In addition, the decline in both components of working memory may cause problems in the acquisition of new knowledge.

One limitation of the study was the small number of participants. Other limitation is the lack of objective measurements of sleep parameters, so future studies may benefit of a larger number of participants as well as using objective measures of sleep parameters, such as polysomnography.

In conclusion, the results of this study indicate that five days of sleep reduction affects both the phonological and visuospatial storage components of working memory. At present, it is frequently observed that adolescents and adults sleep less during the week, due to social obligations, work, school, recreation activities, and even the use of electronic devices, such as computers and videogames. This sleep reduction during weekdays generates sleepiness and tiredness, as well as a reduction in working memory, which interferes with a person's performance during academic or work activities.

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