SHORT NOTE

Sleep Deprivation and Time-Based Prospective Memory

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Study Objectives: To evaluate the effect of sleep deprivation on time-based prospective memory performance, that is, realizing delayed intentions at an appropriate time in the future (e.g., to take a medicine in 30 minutes).

Design: Between-subjects experimental design. The experimental group underwent 24 h of total sleep deprivation, and the control group had a regular sleep-wake cycle. Participants were tested at 08:00.

Settings: Laboratory.

Participants: Fifty healthy young adults (mean age 22 ± 2.1, 31 female).

Interventions: 24 h of total sleep deprivation.

Measurements and Results: Participants were monitored by wrist actigraphy for 3 days before the experimental session. The following cognitive tasks were administered: one time-based prospective memory task and 3 reasoning tasks as ongoing activity. Objective and subjective vigilance was assessed by the psychomotor vigilance task and a visual analog scale, respectively. To measure the time-based prospective memory task we assessed compliance and clock checking behavior (time monitoring). Sleep deprivation negatively affected time-based prospective memory compliance ($P < 0.001$), objective vigilance (mean RT: $P < 0.001$; slowest 10% RT: $P < 0.001$; lapses: $P < 0.005$), and subjective vigilance ($P < 0.0001$). Performance on reasoning tasks and time monitoring behavior did not differ between groups.

Conclusions: The results highlight the potential dangerous effects of total sleep deprivation on human behavior, particularly the ability to perform an intended action after a few minutes. Sleep deprivation strongly compromises time-based prospective memory compliance but does not affect time check frequency. Sleep deprivation may impair the mechanism that allows the integration of information related to time monitoring with the prospective intention.

Keywords: total sleep deprivation, prospective memory, time monitoring, reasoning tasks.

Citation: Esposito MJ, Occhionero M, Cicogna P. Sleep deprivation and time-based prospective memory. *SLEEP* 2015;38(11):1823–1826.

INTRODUCTION

Sally is a nurse, and she is sleep deprived because she has not slept for 24 hours because of very noisy neighbors. It's 7:30 am, and Sally is updating patient data and therapies as well as providing patient assistance. Suddenly, a colleague asks her to do an Oral Glucose Tolerance Test (OGTT) with patient number 41 in 20 minutes. From that time, Sally continues to perform her previous activities, and she checks her watch to monitor the OGTT deadline. Sally is sleep deprived; will she remember to perform the OGTT at the proper time? The previous example shows salient aspects that specify a time-based prospective memory task: performing an intended action at a specific time, performing the current activity while waiting for the target time, clock checking (i.e., time monitoring), and interrupting an ongoing activity when the target time of the prospective task arrives.[1] Time-based prospective memory tasks differ from event-based prospective memory tasks since in the latter case the delayed intention has to be put into action when a specific event occurs, and so the recall of intention is triggered by an external cue (i.e., give a message to your colleague when you meet him).[1] Time-based prospective memory tasks have been argued to rely on top-down control mechanisms because, assuming that no external trigger aid is available, the use of time cues depends on self-initiated mental processes, such as active time monitoring.[2] From a neurocognitive point of view, these tasks heavily rely on executive functions,[3,4] and they require the engagement of prefrontal areas.[5–7] The effect of a short total sleep deprivation (TSD) on cognitive variables has been explained by three main hypotheses.[8] The "neuropsychological" hypothesis[9] proposes that TSD effects on cognitive performance mirror a reversible functional impairment on the prefrontal cortex. The "controlled attention" hypothesis[10] suggests that tasks needing internally motivated top-down control would be more greatly affected by TSD. The "vigilance" hypothesis[11,12] sustains that poor cognitive performances following TSD are mainly explained by a low level of arousal and vigilance. To our knowledge, only two studies have investigated the effect of TSD on prospective memory.[13,14] Both studies, however, focused on event-based prospective memory tasks. One study reported a detrimental effect of TSD on event-based prospective memory tasks performance independently of their resources demanding levels (i.e., whether they were supposed to strongly rely on frontal-executive functioning), thus supporting the "vigilance" hypothesis.[13] The other one, (Experiment 1)[14] reported the beneficial effect of sleep, compared with TSD, on event-based prospective memory tasks by the facilitation of the spontaneous-associative retrieval processes, which allows us to remember the association between the appearance of the external stimulus and the associated intention at the proper time.

The aim of the present study was to investigate for the first time the effect of TSD on time-based prospective memory. First, this study sets out to describe the effect of sleep loss on a crucial human behavior, time-based prospective remembering, which humans perform daily. In order to obtain such

Submitted for publication December, 2014
Submitted in final revised form April, 2015
Accepted for publication April, 2015

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ecological validity, we employed an experimental paradigm which was able to mimic a time-based prospective task similar to those that occur in everyday life, such as the one described in the opening episode. Second, given the highly demanding executive functions of time-based prospective memory tasks mediated by prefrontal areas[5–7] and the need for internally motivated top-down control,[2] this study aims to increase the knowledge about the effects of TSD on cognitive variables, testing respectively the "neuropsychological"[9] and the "controlled attention"[10] hypotheses. For this purpose, we developed an experimental design in which we compared performance collected after TSD and under normal sleep conditions using the following measures: (a) objective and subjective vigilance; (b) reasoning tasks; (c) time-based prospective task compliance; and (d) time monitoring. From a behavioral perspective, the results would support whether the effect of TSD on cognitive performance is better explained by one of the previous described main hypotheses proposed on this issue.

METHODS

Participants

Fifty healthy young adults took part in the study (mean age 22 ± 2.1 years; 31 females). Volunteers were screened for the absence of psychiatric and sleep disorders. All participants were neither type[15,16] and were drug-free at the time of the study. They were not involved in shift-work nor had they travelled between more than 3 time zones in the previous 3 months. The participants included in the study reported that they had regular sleep habits, and were not short or long sleepers (i.e., > 6 h; < 10 h per night). This study was approved by the local ethics committee, and informed consent was obtained from participants.

Materials and Procedures

Participants were randomly assigned to one of the following 2 conditions: (1) total sleep deprivation condition (TSD); (2) normal sleep condition (NSC). They were requested to maintain regular sleep schedules during the entire study period (i.e., lights off time not later than 23:30; wake up time not earlier than 06:30). To check the sleep-wake cycle in the entire sample and the effectiveness of the TSD procedure, participants were monitored by wrist actigraphy (Basic Mini-Motionlogger; Ambulatory Monitoring Inc., Ardsley, New York, USA) for 3 days, and they were also asked to complete a daily sleep log. All participants were requested to abstain from caffeine beverages after breakfast on the day before the experimental testing session. Volunteers in the TSD condition arrived at the Laboratory at 22:00. They spent the night under the supervision of 4 experimenters, and they were engaged in watching movies, playing board games, or other non-arousing activities. They were allowed to have caffeine-free drinks and chocolate-free light snacks. Participants in the NSC condition arrived at the Laboratory at 07:45. The experimental testing session began at 08:00, and it included: (1) 5-min version of the psychomotor vigilance task[17]; (2) a visual analogue scale assessing subjective vigilance[18]; and (3) a cognitive tasks session, including the time-based prospective memory task, preceded by a brief training phase. The order of vigilance levels assessment and cognitive tasks administration was counterbalanced among volunteers. Each participant was tested individually in a soundproof room, in a constant light condition (~100 lux). In the cognitive task session, participants were administered 3 reasoning tasks (syllogistic reasoning, spatial reasoning, crypto-arithmetic problems) and a time-based prospective memory task (Press the "A" key on the keyboard 20 min after the beginning of the reasoning tasks). Participants were asked to remove their watch so they could check elapsing time by pressing a specific key on the keyboard. To successfully perform the time-based prospective task, participants were supposed to interrupt their ongoing activity (solving crypto-arithmetic problems) and press the "A" key on the keyboard 20 min after the beginning of the cognitive task session. All experimental details about the cognitive task session are published elsewhere (Experiment 1, experimental discontinuous condition).[19] The cognitive task session lasted 24 minutes.

Data Analyses

Statistical analyses were performed by IBM SPSS Statistic 21.0. The time-based prospective memory performance was scored as *successful* (the intention was executed within 1 minute from the target time) or *unsuccessful* (the intention was executed out of time or was not executed at all), and was analyzed by applying the χ^2 test. The following data were analyzed using a 2-tailed Student t-test for independent samples: all of the reasoning task dependent variables (i.e., accuracy and response time), total number of time checks, and objective and subjective vigilance levels. To analyze the differences between the 2 experimental conditions in time check distribution throughout the cognitive task session, a 2 × 24 mixed ANOVA was applied (Condition × Minutes lasting the cognitive task session).

RESULTS

Sleep-Wake Cycle

The actigraphic recordings and sleep logs showed that all participants maintained regular sleep habits during the study period. Regarding the TSD procedure, post hoc actigraphic data revealed that none had sleep episodes (5 consecutive minutes of no motor activity) during the night of total sleep deprivation, so the TSD manipulation was effective.

Vigilance Levels

Participants in TSD showed a significantly lower subjective vigilance level (298.24 ± 161.298) than volunteers who had a regular night of sleep (757.01 ± 102.06) (t_{48} = 12.01, P < 0.0001). All PVT measures were significantly different between the 2 groups, except the fastest 10% reaction time. In participants who underwent the TSD, we observed a slower mean reaction time (443.80 ± 56.16), slower slowest 10% reaction time (640.28 ± 114.23), and more lapses (10.76 ± 9.13) than in participants in the normal sleep condition (respectively: 334.68 ± 47.44; 509.80 ± 97.56; 3.24 ± 6.49) (Mean RT: t_{48} = 7.42, P < 0.001; Slowest 10% RT: t_{48} = 4.34, P < 0.001; Lapses: t_{48} = 3.36, P < 0.005).

Reasoning Tasks

Performance on reasoning tasks did not differ between groups. Response time and accuracy response levels on syllogistic and spatial reasoning tasks, as well as on crypto-arithmetic problems, were similar in participants who had a regular night of sleep and participants in TSD (respectively: $t_{48} = 0.41$, P = 0.684, $t_{48} = 0.65$, P = 0.515; $t_{48} = 0.29$, P = 0.773, $t_{48} = 0.87$, P = 0.390; $t_{48} = 0.37$, P = 0.715, $t_{48} = 1.38$, P = 0.175).

Time-Based Prospective Performance

Performance on the time-based prospective memory task showed a significant difference as a function of the experimental condition ($\chi^2_1 = 11.69$. P < 0.001). The 80% of participants in NSC successfully executed the intention, whereas only 32% of the participants in the TSD condition remembered to execute the delayed intention at the proper time. Regarding unsuccessful performance, 40% of sleep deprived volunteers did not execute the time-based prospective task at all, whereas TSD participants whose performance was out of time (28%) recorded a gap of 3 min 23 sec ± 1 min 31 sec from the target time. In NSC, the 12% of participants did not execute the time-based prospective task at all, while the mean gap for of out of time responses (8%) was 1 min 38 sec ± 9.89 sec.

Time Monitoring

The time checking behavior did not differ between groups. No significant differences emerged in the total number of clock checks (NSC 8.64 ± 5.57 *vs.* TSD 8.52 ± 7.91) ($t_{48} = 0.06$. P = 0.951). According to the 2×24 mixed ANOVA that we used to analyze time checking behavior throughout the retention interval period, only the within-subject factor gave a significant result ($F_{23} = 24.02$, P < 0.0001). This result shows how time checking behavior significantly changed over the experimental session; specifically, as soon as the proper time to execute the intention approached, the participants increased time checks. The interaction between the 2 factors was not significant ($F_{23} = 0.798$, P = 0.737). This finding means that the distribution of time checks over the retention interval period did not change between conditions.

DISCUSSION

In the present study, we investigated the effect of TSD on time-based prospective remembering. We documented a detrimental effect of sleep loss on the human ability to perform an intended action after a few minutes, which is a complex cognitive skill that is present in our daily activities, such as taking the cake out of the oven in 30 minutes or picking your son up from school at 4 pm. This ability is also important in safety and medical settings in which proper compliance is crucial (i.e., medication intake at the proper time). According to our results the probability that the nurse will perform the OGGT at the proper time is fairly low.

In our study, TSD negatively affected objective and subjective vigilance levels and compliance on the time-based prospective task, but it did not have any effect on time monitoring behavior and reasoning tasks. Adequate compliance on time-based prospective tasks is usually related to an increase in clock check frequency as soon the proper time to execute the intention approaches.[20,21] Nevertheless, in our sample, the time monitoring behavior did not differ as a function of TSD manipulation, whereas the time-based prospective compliance was dramatically different between the two groups. Therefore, we hypothesize that sleep deprivation compromised time-based prospective memory by affecting the mechanism that allows the integration of information related to time monitoring behavior with the prospective intention.[6] Although time checks were the same in both conditions, TSD likely affected the binding process between the target time and the intention representations and then shattered the time-based prospective performance. Sleep deprived participants check elapsing time as they know they are supposed to do something at a particular time in the future, but they do not seem able to successfully associate their time monitoring behavior with the recall of prospective intention at the right time. Missing differences between the two conditions on reasoning tasks performance were not surprising because of their "bottom-up," or "work-paced" nature, which is often not affected by TSD.[10,22,23] Considering the three main hypotheses proposed to explain the effect of a short TSD on cognitive variables,[21] our results are consistent with the "vigilance" hypothesis.[11,12] Because TSD affected time-based prospective compliance, but not the time monitoring behavior, and both were mediated by the activation of prefrontal areas[4–7] and are top-down internally motivated activities,[2,24] our data are less consistent with the "neuropsychological" [9] and the "controlled attention"[10] hypotheses. Furthermore, a recent study that focused on event-based prospective tasks, reported similar conclusions.[14]

The ability to remember to execute our intentions at the proper time in the future is very sensitive to sleep deprivation. Because time-based prospective memory is a basic component of daily life, further research is needed to investigate how sleep loss affects this skill.

ACKNOWLEDGMENTS

The authors are grateful to all participants in the study. A special thanks to the Department Laboratory Technician, Michele Marzocchi, for his precious technical assistance and data collection support.

DISCLOSURE STATEMENT

This was not an industry supported study. The study was funded by the Individual RFO 2012 of Maria José Esposito, PierCarla Cicogna and Miranda Occhionero. The authors have indicated no financial conflicts of interest.

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