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Original Article

Topographic electroencephalogram changes associated with psychomotor vigilance task performance after sleep deprivation

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ABSTRACT

Objectives: The psychomotor vigilance task (PVT) is a widely used method for the assessment of vigilance after sleep deprivation (SDEP). However, the neural basis of PVT performance during SDEP has not been fully understood. In particular, no studies have investigated the possible relation between EEG topographical changes after sleep loss and PVT performance. The aim of the present study is to assess the EEG topographic correlates of PVT performance after SDEP.
Methods: During 40 h of SDEP, 16 healthy male subjects were evaluated in four sessions performed at the same time (11:00 a.m. and 11:00 p.m.) of the first and second day with: (a) subjective sleepiness recordings by means of the Karolinska Sleepiness Scale (KSS); (b) EEG recordings (5 min eyes-open condition); and (c) PVT.
Results: SDEP induced a slowing of PVT reaction times (RTs), higher level of subjective sleepiness and an increase of delta, theta, alpha and beta 1 EEG activity. Only slowest PVT RTs were influenced by circadian factors, with longer RTs in the morning. Both fastest PVT RTs and KSS scores were positively correlated with post-SDEP changes in EEG theta activity, mainly in centro-posterior areas, but not with other EEG frequencies. KSS scores and PVT measures were also positively correlated.
Conclusions: These findings suggest that SDEP differently affects PVT variables, and that an increase in theta activity may be the principal EEG basis of the post-SDEP slowing of fastest PVT RTs. Similar neural mechanisms seem to underlie both performance deterioration to PVT and the increase of subjective sleepiness.

1. Introduction

Sleepiness is a widespread condition in modern society that represents a significant problem, being a major risk factor for accidents [1,2]. Sleep deprivation (SDEP) induces a severe deficit in alertness, as indicated by subjective and objective measures of sleepiness [3]. Sleep loss has degrading effects on simple task performance, indexed by reaction times (RTs), attention, and vigilance [4], as well as on complex task performance involving frontal lobes or executive functions [5].

The psychomotor vigilance task (PVT) [6] is a computerized simple cued RT task that provides a valid measure of sustained attention [7]. Due to its sensitivity to SDEP [8–10] and chronic sleep restriction [11], the PVT has become one of the most widely used methods to assess the effect of sleep loss on vigilance [7]. Nevertheless, only few studies have investigated the neural basis of PVT performance. From functional magnetic resonance imaging (fMRI) data recorded during the execution of the PVT [12], it has been observed that higher activity in a cortical sustain attention network and in the cortical and in subcortical motor regions was related to optimal PVT performance, whereas the slowest RTs, particularly during SDEP, were related to higher activation of the 'default

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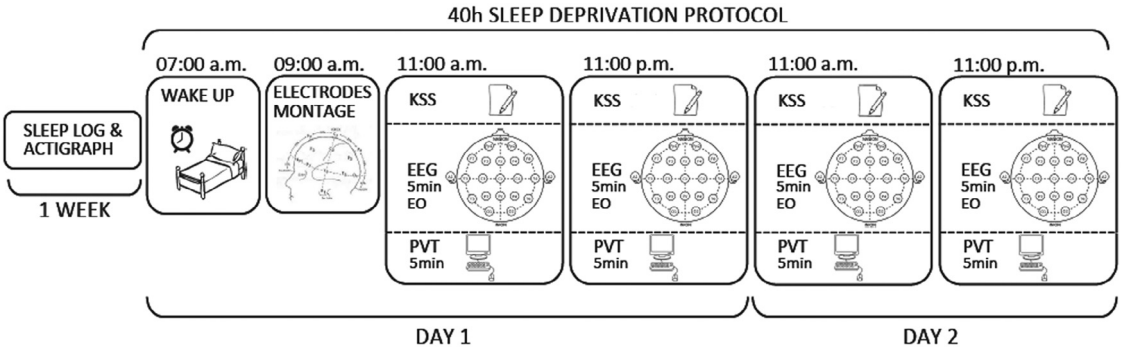

Fig. 1. Timeline of the experimental protocol. During the week preceding the beginning of the sleep deprivation (SDEP) period, subjects were monitored by actigraphic recording and sleep log. On the morning of the experiment subjects on average woke up at 07:00 (mean ± SE 6.54 ± 0.13 based on sleep log) and entered the laboratory at 09:00 for the electrode montage. Experimental procedure started at 11:00. Subjects were evaluated in four different sessions carried out at the same time (11:00 and 23:00) of the first and second day, each conducted in the following sequence: (a) subjective sleepiness recordings (Karolinska Sleepiness Scale); (b) electroencephalographic recordings (5 min eyes-open condition); (c) behavioral sleepiness recordings (5 min psychomotor vigilance task).

mode network', a brain network consisting of different frontal and posterior midline regions that are more active during resting wake than during cognitive task engagement [13]. However, these results are limited by the intrinsic difficulties of administering the PVT in the fMRI environment.

The electroencephalographic (EEG) correlates of the PVT after sleep loss are not well understood. An early study reports that the slowing of RTs after SDEP was associated with an increase in absolute EEG power (4–20 Hz), particularly in the left central cortex [14]. A positive correlation has been found after SDEP between PVT performance and frontal EEG power density in slow waves and theta bands [15]. More recently, decreased amplitude of the P1 component of event-related potentials (ERPs) and progressive reduction of theta and delta phase-locking index (PLI) have been observed over the course of SDEP by recording EEG hourly during PVT task performance [16]. However, Caldwell et al. [17] have found no correlation between EEG and PVT performance. To the best of our knowledge, however, the possible relation between topographic distribution of the EEG power after SDEP and performance on the PVT has never been investigated, despite the fact that there is a growing evidence of regional (cortical) differences in sleep and sleep need [18]. This may be relevant for understanding which areas and, presumably, which functions are affected by SDEP as assessed by the most-used task for measuring behavioral consequences of sleepiness. EEG measures have indeed indicated that the increase of low-frequency bands with time spent awake, considered as the main EEG marker of sleepiness, is particularly evident in fronto-central areas [19–21]. A significant increase in theta activity after sleep loss has also been observed in the occipital area [19]. Regarding the other EEG bands, both De Gennaro et al. [19] and Tinguely et al. [21] showed an increase in alpha and beta 1/sigma power, particularly in fronto-central areas (albeit secondary to the rise of theta power).

Hence, the main aim of the present work is to evaluate the EEG correlates of PVT performance during ~40 h of prolonged wakefulness. In particular, we have investigated the possible relation between performance at the PVT and the topographic distribution of delta, theta, alpha, beta 1 and beta 2 frequencies. Since the increase in low-frequency bands is considered the principal EEG marker of sleepiness, we hypothesized that SDEP would induce a generalized increase in EEG delta and theta waves, and that this phenomenon should be positively correlated with a slowing of RTs at PVT performance and an increase in subjective sleepiness.

2. Methods

2.1. Subjects

Sixteen healthy male volunteers took part in the experiment (mean age ± SE, 23.3 ± 0.64 years). All subjects reported themselves as right-handed and had no history of central or peripheral neurological impairments. In particular, exclusion criteria were: brain injury, alcohol abuse, diabetes, or drug addiction. Further requirements for inclusion were: normal sleep duration (habitual sleep time: 24:00–8:00 ± 1 h) and schedule, no daytime nap habits, no excessive daytime sleepiness, no other sleep, medical or psychiatric disorders, as assessed by a 1-week (7 ± 0.3 days) sleep log, administration of the Italian version of the Pittsburgh Sleep Quality Index (PSQI) [22], and a clinical interview. Participants were required to avoid napping; actigraphic recordings (AMI Mini motion logger) were collected for about 1 week (7 ± 0.3 days) before the beginning of the experimental procedure to control subjects' compliance.

All subjects gave their written informed consent. The study was approved by the Institutional Ethics Committee of the Department of Psychology of the University of Rome "Sapienza", and was conducted in accordance with the Declaration of Helsinki.

2.2. Procedure

2.2.1. Study design

Fig. 1 shows the timeline of the experimental protocol. On the morning of the experiment, participants on average woke up at 07:00 (6:54 ± 00:13 based on sleep log), and arrived at the laboratory at 09:00 for the electrode montage. Experimental procedure started at 11:00. Subjects were evaluated in four different sessions carried out at the same time (11:00 and 23:00) on the first and second day, with the aim to control for potential circadian effects. Each session was conducted in the following sequence: (a) subjective sleepiness recordings; (b) EEG recordings (5 min eyes-open condition); (c) PVT. During the experimental sessions, participants were seated on a comfortable chair in a soundproof, electrically shielded room.

When not involved in testing sessions, subjects were allowed to carry out their own preferred activities, such as reading, writing, listening to music, watching TV, or playing games, always under the direct supervision of at least one experimenter. Lying down, sleeping and vigorous physical activity were not permitted. Meals were provided to subjects at 08:30, 14:30 and 07:30. Non-scheduled light