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Published in:
Journal of Sleep Research

DOI:
10.1046/j.1365-2869.2002.00290.x

Publication date:
2002

Citation for published version (APA):
de Bruin, E. A., Beersma, D. G. M., Daan, S., & Bruin, E. A. D. (2002). Sustained mental workload does not affect subsequent sleep intensity. Journal of Sleep Research, 11(2), 113-121. DOI: 10.1046/j.1365-2869.2002.00290.x

J. Sleep Res. (2002) **11,** 113–121

Sustained mental workload does not affect subsequent sleep intensity

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Accepted in revised form 8 January 2002; received 13 December 2000

SUMMARY Mental activity is a neglected factor in sleep research. The few investigations on sleep that manipulate prior mental activity are inconclusive with respect to the possible effects of mental activity on recovery. In the present study, the effects of two levels of mental activity on subsequent sleep were studied. Thirteen male subjects (range 18–28 years) participated in one lightly and two heavily mentally strenuous conditions in a counterbalanced order. Light mental activity included 8 h of relaxed video watching. The second condition consisted of performing computer tasks involving sustained attention, memory, logical thinking and calculations for eight consecutive hours. In the third condition, the same heavy mental workload was interspersed with breaks. Subjectively, the subjects rated the condition with heavy mental activity (without breaks) as mentally more strenuous than the condition with light mental activity. Subjects were significantly less awake shortly after sleep onset in the heavy-workload condition than in the light-workload condition. There were no differences between the conditions in any of the other visually scored sleep variables. The total amount of slow wave activity (SWA) and its discharge during the night was not affected by the level of mental activity or by the presence of breaks. These findings fail to support the proposition that SWA reflects a need for sleep that accumulates at a rate depending on mental activity during prior wakefulness.

KEYWORDS mental workload, recovery, sleep, slow wave activity

INTRODUCTION

Why we sleep is a complex question (Horne 1988). One of the functions of sleep may be to recover from activities during the waking period. The recovery hypothesis is supported by the dependence of propensity and intensity of sleep on the duration of prior wakefulness. Extending the duration of the waking period to 40 h increases the amount of slow wave activity (SWA) during recovery sleep (Borbély *et al.* 1981; Dijk *et al.* 1990), while reducing the standard 16-h wake interval leads to a reduction of SWA (Dijk *et al.* 1987). These relationships support the hypothesis that the human brain generates deep sleep to recover from prior wakefulness.

The duration of wakefulness is not the only factor influencing sleep depth. Even when the duration, and the timing of sleep and wakefulness are kept constant, the amount of SWA discharged per night differs considerably within individuals (Achermann and Borbély 1990). In addition, the *nature* of the activities that are performed during waking may also influence recovery processes during sleep. Indeed, acute physical activity has been reported to increase SWA in the sleep following that exercise (see Youngstedt *et al.* 1997 for a review). This increase in SWA may be related to the rise of body temperature, as both trained and untrained subjects respond to sitting in a hot bath with a rise in subsequent slow wave sleep (SWS) (Bunnel *et al.* 1988; Horne and Reid 1985).

The question arises whether the increase in SWA after physical activity is an indication that the central nervous system (CNS) needs more recovery because of greater nerve activity during physical activity (e.g. processing visual stimuli, motor planning, etc.), or whether it is a side-effect of body heating. To answer this question, SWA should be measured following a purely mental workload, avoiding body heating.

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A few studies have addressed the role of non-physical, or mental activity in determining subsequent sleep depth, and their results are contradictory. Horne and Minard (1985) investigated the effects of a novel and perceptually stimulating environment on sleep by letting their subjects walk around in a city they were unfamiliar with. Following this novelty condition, no change in total sleep duration was found. There was a significant increase in SWS in the second and third cycle, as compared with sleep following a day spent in the laboratory. However, as the novelty condition involved a considerable amount of physical activity, body heating may be a confounding factor in this study (Horne and Minard 1985; Horne 1992). In another study, Japanese students were asked to translate English texts into their own language. In the control condition, the students remained awake for the same time in a relaxed state. The translation task did not lead to more SWS during subsequent sleep in comparison with the control condition. On the contrary, in the first sleep cycle the SWA was found to be depressed after the cognitively demanding day as compared with the relaxed day (Takahashi and Arito 1994). A third study compared sleep following a relaxing day with sleep after a day filled with deskwork of unspecified nature and duration, and found no difference in the amount of SWS (Kobayashi *et al.* 1998).

Thus, the evidence for effects of pure mental activity on SWA is inconclusive. In the present study, we set out to investigate potential effects of heavy mental activity on SWA during subsequent sleep in comparison with the effects of light mental activity, avoiding physical activity. The effect of a continuous 8 h block of mental workload was also compared with the effect of 8 h of mental workload interspersed with pauses, in order to investigate potential recovery from mental workload during relaxed wakefulness.

METHODS

Subjects

Thirteen male students (mean age 22.6 years, range 18–28 years) were paid to participate in this study. Subjects who applied for participation in the experiment were sent a questionnaire about their physical and mental health. Exclusion criteria were: physical or medical complaints for which a medical doctor had been contacted, medication, drug use or smoking and excessive caffeine, tobacco or alcohol use. Only subjects with the following self-reported sleep characteristics were included: sleep onset between 22:00 and 00:00 h, sleep offset between 06:00 and 08:00 h and a sleep duration of about 8 h, during weekdays as well as in the weekend. Subjects were instructed to maintain these sleep schedules in the week prior to the experiment. They were neither extreme morning nor extreme evening types as assessed by the Horne–Östberg Morningness–Eveningness scale (i.e. no scores over 70 or below 30; Horne and Östberg 1976). Subjects reporting waking up more than once per night or daytime napping were not entered in the study.

Experimental design

Subjects participated in every condition with at least 1 week between the conditions. The order in which the subjects passed through the conditions was counterbalanced.

Each condition consisted of one night of sleep in the laboratory, followed by light or heavy mental activity during the day, and a second night of sleep. As previous studies agree that mental activity does not affect sleep duration, sleep times were fixed from 00:00 until 07:00 h the next morning. During the day, the isolation unit was brightly lit by fluorescent tubes at a level of about 300 lux. Between 00:00 and 07:00 h, the lights were off, resulting in a luminance level of less than 0.1 lux. Breakfast was taken at 08:15 h, and a hot meal was served at 13:30 h. Bread and (non-alcoholic) drinks were freely available during the waking period. Hot and/or caffeine-containing beverages were not available.

In the condition of light mental activity (condition A) subjects started with an adaptation night. After sleeping from 00:00 until 07:00 h, they were free to spend their time in the isolation unit until 15:30 h, provided that they did not engage in physical activity. After 15:30 h, the subjects sat in a chair and watched videos until 23:30 h. The video session consisted of two non-violent movies they had already seen on television or at the cinema, interspersed with nature documentaries. At 23:30 h, the subjects were immediately prepared for sleeping.

In the condition of heavy mental activity (condition B) subjects also had an adaptation night first. From 07:00 until 15:30 h, they were again free to spend their time in the isolation unit. From 15:30 until 23:30 h, the subjects continuously had to perform computerized cognitive tasks. These tasks involved sustained attention, memory, logical thinking, decision making and calculating (for a description see below).

In the condition of heavy mental activity interspersed with breaks (condition C) subjects again started with an adaptation night. The next day, they had to perform the same computer tasks as in condition B. These tasks had the same total duration, but were, however, evenly spread over the day between 08:00 and 23:30 h. The periods of heavy mental load were alternated with breaks of 30 or 50 min. For an overview of the time schedule for the three conditions, see Table 1.

To investigate whether different levels of mental activity influence subsequent sleep differentially, the data of conditions A and B were tested by means of paired *t*-tests. To assess whether breaks result in recovery during wakefulness, thus influencing subsequent recovery during sleep, the data of conditions B and C were compared by paired *t*-tests. As more than one parameter differs between the light condition and heavy-with-breaks condition (namely heaviness *and* the presence of breaks), they were not combined in one statistical analysis.

The subjects were supervised by the experimenters while executing computer tasks or watching videos. In this way, it was ensured that they continuously performed the tasks without a pause (except for toilet reasons). Also, naps were prevented. After the last video or computer task, subjects had

Table 1 Time schedule of mental workload

	Mental workload		
Time (h)	*A: Light*	*B: Heavy*	*C: Heavy with breaks*
00:00	Sleep	Sleep	Sleep
07:00	Rise	Rise	Rise
08:00	Tiredness tests	Tiredness tests	Tiredness tests
08:10			SWITCH TASK
08:30	Breakfast	Breakfast	Breakfast
09:00			COFFEE TASK
09:30			
10:00			COFFEE TASK
10:30	Tiredness tests	Tiredness tests	Tiredness tests
11:00			
11:30			NETWORK TASK
12:00			
12:30			NETWORK TASK
13:00	Tiredness tests	Tiredness tests	Tiredness tests
13:10			SWITCH TASK
13:30	Meal	Meal	Meal
14:00			SYNWORK TASK
14:30			
15:00			SYNWORK
15:30	Tiredness tests	Tiredness tests	Tiredness tests
15:40	Video	SWITCH TASK	
16:00	Video	COFFEE TASK	
16:30	Video	COFFEE TASK	SYNWORK TASK
17:00	Video	NETWORK TASK	
17:30	Video	NETWORK TASK	SYNWORK TASK
18:00	Tiredness tests	Tiredness tests	Tiredness tests
18:10	Video	SWITCH TASK	SWITCH TASK
18:30	Video	SYNWORK TASK	
19:00	Video	SYNWORK TASK	COFFEE TASK
19:30	Video	SYNWORK TASK	
20:00	Video	SYNWORK TASK	COFFEE TASK
20:30	Tiredness tests	Tiredness tests	Tiredness tests
20:40	Video	SWITCH TASK	
21:00	Video	COFFEE TASK	
21:30	Video	COFFEE TASK	NETWORK TASK
22:00	Video	NETWORK TASK	
22:30	Video	NETWORK TASK	NETWORK TASK
23:00	Tiredness tests	Tiredness Tests	Tiredness Tests
23:10	Video	SWITCH TASK	SWITCH TASK
23:30	Bed	Bed	Bed
00:00	Sleep	Sleep	Sleep
07:00	Rise	Rise	Rise
08:00	Tiredness tests	Tiredness tests	Tiredness tests
08:10	Breakfast	Breakfast	Breakfast

10 min for undressing and tooth brushing. Then the electrodes were checked, and the subjects went to bed. Lights went off 25 min after termination of the tasks or video.

Tiredness

In all three conditions, mental tiredness was measured on the experimental day every 2.5 h by a 5 min test block. In this block, the Letter Cancellation Task (based on the digit span by Wechsler 1939) and the Activation–Deactivation Adjective Checklist (AD-ACL; Thayer 1986) were presented. In the Letter Cancellation Task, subjects had to remember a set of seven consonants and mark these in a 23 × 39 letter field as fast and as accurately as possible. In the AD-ACL, the subjects had to indicate to what extent 20 adjectives corresponded with their feelings at that particular moment. Directly following blocks of mental load (at 18:00 h, 20:30 h and 23:00 h in conditions A and B, and from 10:30 to 23:00 h at 2.5 h intervals in condition C) subjects had to fill out the Rating Scale Mental Effort (RSME; Zijlstra 1993). The RSME is a list of seven statements related to tiredness, such as ‘I have difficulty focussing attention’. Subjects were asked to indicate whether these statements applied to their feeling of tiredness at that moment on a scale ranging from 0 (not at all) to 150 (very much so). The scores were normalized per subject with regard to the grand average score over all conditions.

Workload

In conditions B and C, the heavy mental load consisted of four computer tasks developed by the Psychology Department of the University of Groningen: the Switch task, Coffee task, Network task and Synwork task. In the Switch task, red or blue letters are presented in one of the quadrants of a square. If the letter is presented in one of the upper quadrants, the subject has to react to the colour of the letters as fast as possible. If the letter is presented in one of the lower quadrants, the subject has to react to the nature of the letter (vowel or consonant) as fast as possible (Rodgers and Monsell 1995). The Coffee task is based on the choice-of-probability/effort (COPE) task as described by Shingledecker and Holding (1974). In each trial, the subject is presented with three scales, on top of which are one, two or three packages with coffee. By clicking on a scale the weight of the scale plus the package(s) is displayed. The task is to find out which package has the same weight as the scale it stands on by selectively taking packages off the scales. The Network task is an adapted version of the fault diagnosis task (Rouse 1978). In every trial, the goal is to track down a defected knob in a logical 7 × 7 network. The subject has to solve as many networks and make as few mistakes as possible in a certain time span. In the Synwork task, four tests are run simultaneously. The computer screen is divided into four quadrants. In the upper left quadrant, a memory set of five letters is presented for a few seconds. After this set has disappeared, the subject has to decide whether a newly presented letter had been present in the previously presented set. In the upper right quadrant, a summation task of two numbers with four digits is presented. In the left lower quadrant, the subject has to prevent a moving dash from 'falling' off a line. During these three tasks, low and high tones are presented. The subject has to click in the right lower quadrant whenever a high tone is presented (Kane and Reeves 1997).

Table 1 presents the load schedule for the three conditions.

EEG recording

In both the first (adaptation) and second (experimental) night, the electroencephalogram (EEG) was derived from C3–A2 and C4–A1. Electrodes were not removed between sleep episodes within a condition. EEG, electromyogram (EMG) and electrooculogram (EOG) signals were low-pass filtered at 30 Hz (24 dB/oct) and digitized at a sample rate of 128 Hz. EOG and EMG were downsampled offline to 64 Hz.

The 30 s EEG epochs were visually scored following the criteria of Rechtschaffen and Kales (1968) to discriminate between wakefulness, rapid eye movement (REM) sleep, non-rapid eye movement (NREM) sleep and movement artefacts. Scoring was facilitated by Vitagraph Paperless Sleep Scoring Software (TEMEC Instruments, Kerkrade, the Netherlands). Sleep latency was defined as the time from lights off until stage 1 and/or 2 was scored, with a minimum of two consecutive minutes of stage 1 or 2. REM latency is the time from sleep onset until the first REM sleep epoch. NREM sleep includes stages 1–4. Movement artefacts are the number of 30 s epochs with muscle artefacts in more than 50% of the time. Total sleep time (TST) includes NREM sleep, REM sleep and movements during sleep. Sleep efficiency is the percentage of sleep during the period that the lights were off. As SWA analysis provides an objective and robust quantification of sleep intensity, differentiation of NREM sleep with respect to the duration of the stages 1–4 was not evaluated.

Spectral analysis was performed on 4 s epochs using a fast Fourier Transform and a cosine tapered window. As a result of the tapering, the effective width of the analysed interval was 3 s. Therefore, the 4 s epochs were taken to overlap by 1 s. The data were integrated over 30 s epochs per 0.25 Hz bin for the SWA range (0.5–4.0 Hz), as provided by Vitagraph Paperless Sleep Scoring Software. Outliers were detected automatically and replaced per 4 s epoch by the mean SWA value of the remaining 4 s epochs in that 30 s period. Additionally, movement artefacts were scored when muscle tension obscured the EEG in more than half of the 30 s epoch (according to Rechtschaffen and Kales 1968). The accompanying SWA value was interpolated by averaging the two adjacent values. The remaining outlying SWA peaks (i.e. twice as high as the value of the adjacent epochs) were also interpolated.

RESULTS

Comparison of condition A (light mental activity) with condition B (heavy mental activity)

Subjective measures

After completion of the experiment, the subjects retrospectively indicated that they had felt more fatigued during the heavy condition than during the light condition. The results of the test blocks measuring subjective fatigue throughout the experimental day reflected this experience. When analysed per test block, there was an overall trend in the RSME that subjects felt more fatigued in the heavy condition than in the light condition [t (1, 12) = 2.11; $P = 0.056$ at 18:00 h, and $t(1, 12) = -2.20$; $P = 0.052$ at 20:30 h] (see Fig. 1). On average, subjects felt more tired in the heavy condition as compared with the light condition according to the RSME [t (1, 12) = -2.28; $P = 0.042$].

The Letter Cancellation task and AD-ACL did not show significant differences between the conditions.

Visually scored sleep variables

Subjects were significantly less awake after sleep onset in the heavy-workload condition than in the light-workload condition [t (1,12) = 2.19; $P = 0.049$]. This differentiation mainly concerned wakefulness shortly after sleep onset, as analyses excluding stage 1 did not reveal significant differences. Other sleep stage variables did not differ between the conditions (see Table 2).

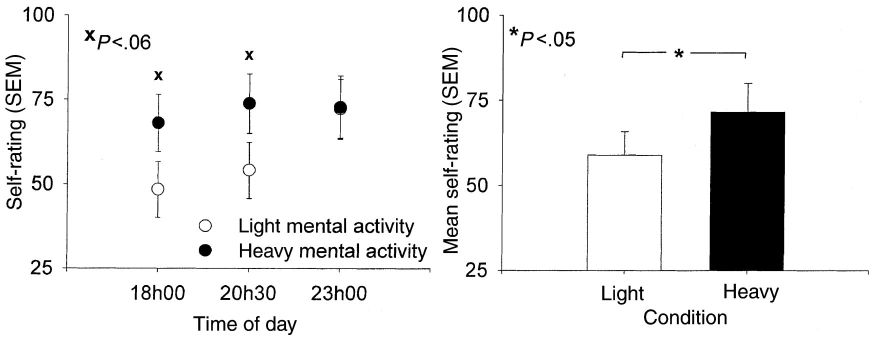

Figure 1. Self-rating of mental tiredness on Rating Scale Mental Effort for condition A (light mental activity) and B (heavy mental activity).

Slow-wave activity

The SWA accumulated over the TST from 00:00 until 07:00 h was 9.02 ± 0.9 h · 10^6 μV^2 (mean ± SEM) for condition A, and 8.82 ± 0.9 h · 10^6 μV^2 for condition B. A paired *t*-test between the experimental nights did not reveal a significant difference between A and B [t (1, 12) = 0.40; $P = 0.700$]. One subject was excluded from further analyses because of REM sleep onset in condition B (and C).

SWA discharge decreases exponentially in consecutive NREM sleep episodes over the night (see, for example, Borbély *et al.* 1981), so that most SWA is discharged during the first part of the night. Therefore, accumulating SWA over the first 120 min of pure NREM sleep, skipping REM and other sleep stages, reduces the variance (Beersma and Achermann 1995). For both conditions A and B, the mean SWA power accumulated over 120 min was 4.7 ± 0.5 · 10^6 μV^2 [mean ± SEM; t (1, 12) = 0.11; $P = 0.915$].

By simply adding power over a fixed time span, possible subtle effects of the preceding workload may be obscured. Therefore, all records were studied in more detail. First, paired *t*-tests were performed on cycle duration, but this did not reveal significant differences. As cycle length did not vary systematically between the conditions, all records were made to fit into a mould of the average duration of the NREM and REM periods. This procedure was first introduced as a way to analyse EMGs (Brunner *et al.* 1990), and later elaborated for EEGs (Achermann *et al.* 1993). To control for interindividual differences in power, SWA was standardized for each individual with respect to the mean SWA power in the first 120 min over both experimental nights for that individual. Then, the time course of SWA was rescaled per condition by subdividing each NREM and REM period into equal intervals, taking the diminishing duration of NREM periods and the increasing duration of REM periods over the night into account. By calculating the mean SWA per interval per condition, Fig. 2 was generated.

This figure shows the regular pattern of alternating high and low SWA, corresponding with NREM and REM bouts, respectively. The SWA during NREM periods decreases during the night. These findings reflect the normal course of sleep, as documented before (e.g. Achermann *et al.* 1993).

Table 2 Visually scored sleep variables. Sleep latency is time from lights off until stage 1 and/or 2 (at least two consecutive minutes). Non-rapid eye movement (NREM) sleep includes stages 1–4. Rapid eye movement (REM) latency is time from sleep onset until the first REM sleep epoch. Total sleep time (TST) includes NREM sleep, REM sleep and movements during sleep. Sleep efficiency is the percentage of sleep during the period that the lights were off. All sleep variables are reported in minutes (except for sleep efficiency in percentage) and standard error in brackets

	Level of mental workload				
	A: Light	*Paired* t-*test A–B*	*B: Heavy*	*Paired* t-*test B–C*	*C: Heavy with breaks*
Sleep latency	19.08 (4.61)	t (1, 12) = −0.47 P = 0.648	20.84 (19.48)	t (1, 12) = 1.46 P = 0.171	16.42 (3.30)
Total NREM duration	278.62 (10.39)	t (1, 12) = −0.15 P = 0.886	279.62 (8.53)	t (1, 11) = 1.52 P = 0.157	274.67 (6.58)
REM latency	94.73 (5.88)	t (1, 12) = 0.28 P = 0.786	91.75 (11.08)	t (1, 12) = 0.90 P = 0.385	83.96 (6.32)
Total REM duration	104.42 (11.27)	t (1, 12) = 0.34 P = 0.740	102.08 (8.37)	t (1, 11) = −1.92 P = 0.081	111.25 (7.17)
Movement artefact	12.62 (1.45)	t (1, 12) = −1.45 P = 0.173	14.88 (1.62)	t (1, 11) = 0.25 P = 0.810	14.71 (1.84)
Wakefulness after sleep onset	4.96 (1.87)	*t (1, 12) = 2.19* *P = 0.049*	2.27 (0.84)	t (1, 11) = −1.86 P = 0.091	3.54 (1.33)
TST	395.65 (5.51)	t (1, 12) = −0.22 P = 0.829	398.58 (4.30)	t (1, 11) = −1.05 P = 0.318	400.63 (4.28)
Sleep efficiency	94.27 (1.32)	t (1, 12) = −0.08 P = 0.938	94.35 (0.97)	t (1, 11) = −1.33 P = 0.211	95.39 (1.02)

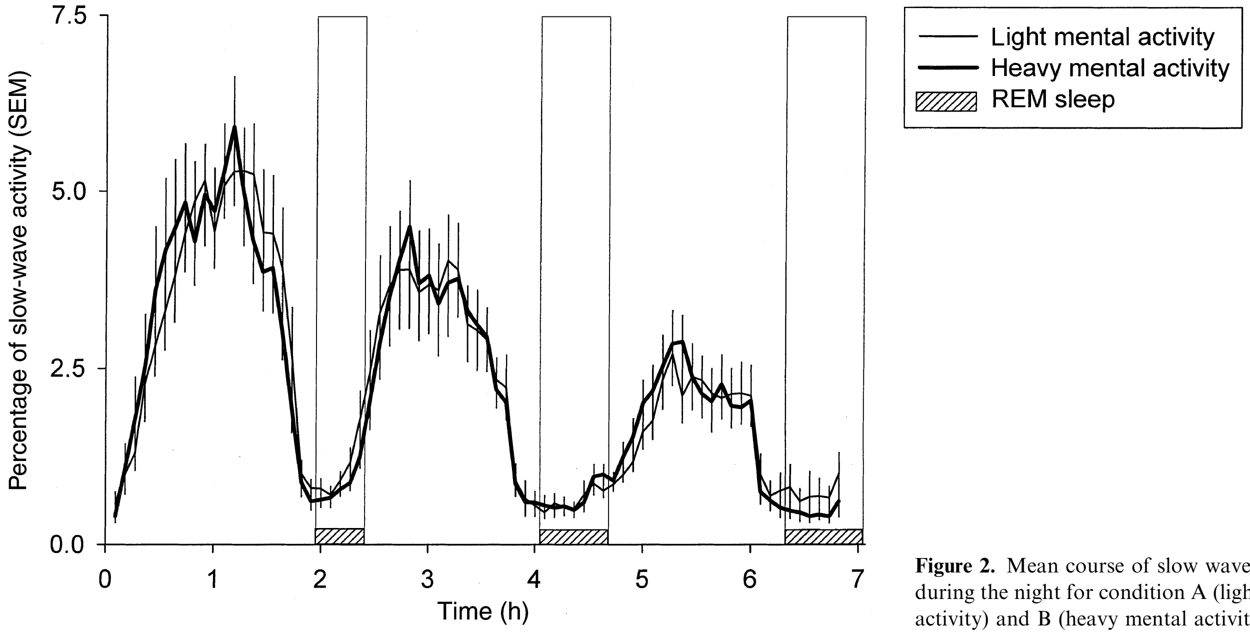

Figure 2. Mean course of slow wave activity during the night for condition A (light mental activity) and B (heavy mental activity).

Paired *t*-tests of the intervals did not reveal any significant differences between the conditions.

Comparison of condition B (heavy mental activity) with condition C (heavy mental activity with breaks)

Subjective measures

Paired *t*-tests of the Letter Cancellation task, AD-ACL and RSME (see Fig. 3) did not show any significant differences between condition B and C. Also, there was no significant difference between the mean self rating of the fatigue in condition B as compared with the mean rating in condition C averaged over the corresponding test blocks. Thus, there is no evidence that interspersed breaks alleviated subjective fatigue.

Visually scored sleep variables

In condition C, the EEG signal of one subject deteriorated after 176.5 min because of electrode fixation problems. This EEG was included only in the calculation of the mean sleep and REM latency. With respect to the visually scored sleep variables, paired *t*-tests did not show significant differences on any of the variables (see Table 2).

Slow-wave activity

As with the visually scored sleep variables, one subject was excluded from the analysis because of electrode fixation problems in condition C. The SWA accumulated over the period from 00.00 until 07.00 h was 8.82 ± 0.9 h · 10^6 μV^2 (mean ± SEM) for condition B, and 8.80 ± 0.7 h · 10^6 μV^2 for condition C (excluding one subject because of REM sleep onset in condition B and C). This difference was not statistically significant [t (1, 11) = 0.40; $P = 0.698$]. For the first 120 min of NREM, the mean SWA power accumulated was 4.7 ± 0.5 h · 10^6 μV^2 (mean ± SEM) for condition B, and 4.4 ± 0.4 h · 10^6 μV^2 for condition C [t (1, 11) = 0.72; $P = 0.485$].

To find out whether differences between B and C are present but subtle, SWA was rescaled. The condition that cycle length did not vary systematically between condition B and C was met. SWA was standardized with respect to the mean SWA power in the first 120 min per individual over both experi-

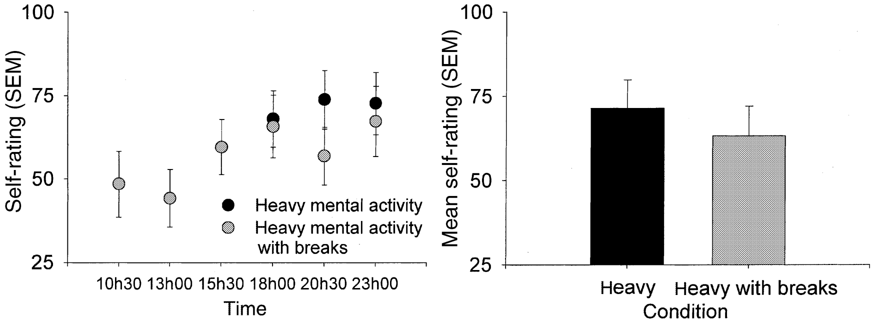

Figure 3. Self-rating of mental tiredness on Rating Scale Mental Effort for condition B (heavy mental activity in a continuous block) and C (heavy mental activity with breaks).

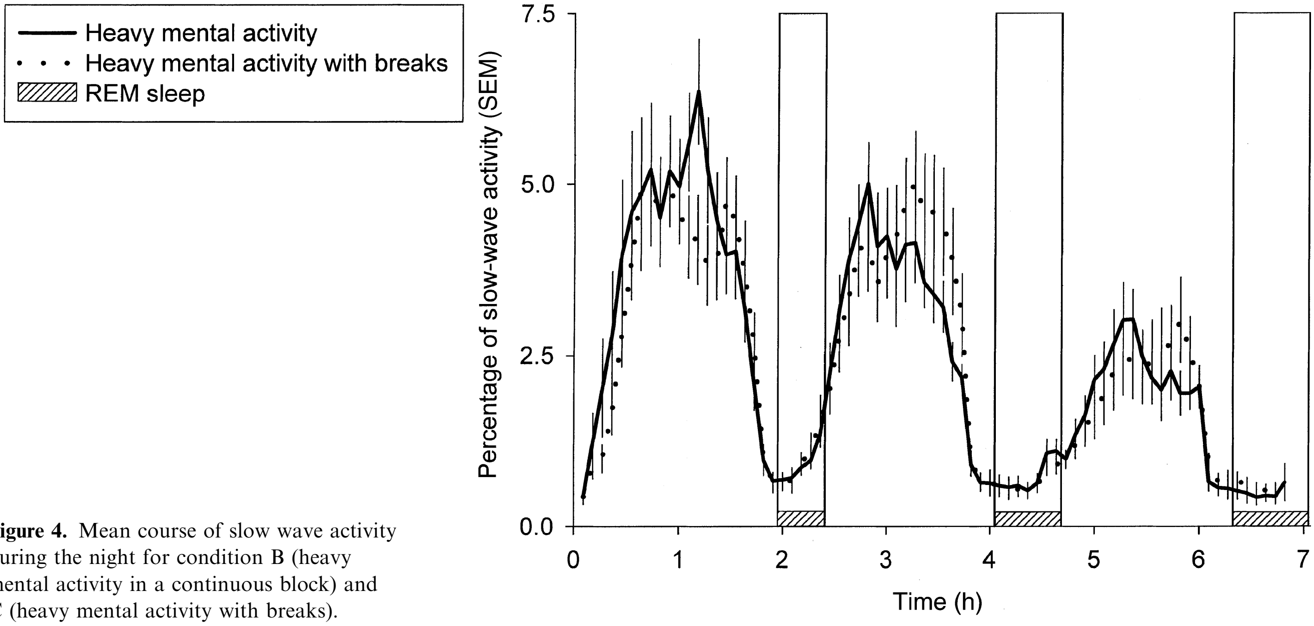

Figure 4. Mean course of slow wave activity during the night for condition B (heavy mental activity in a continuous block) and C (heavy mental activity with breaks).

mental nights. After subdividing each NREM and REM period into equal intervals, the mean SWA per interval per condition was calculated (see Fig. 4).

This figure also shows a regular alternating pattern of high and low SWA with a declining trend during the night. There were no differences between the conditions as shown by paired *t*-tests of the intervals.

DISCUSSION

Our experiments aimed to investigate whether different degrees of mental activity have a distinct effect on recovery processes during subsequent sleep. Sleep EEGs of 13 subjects, experiencing different degrees of mental activity, were scored visually. Also, the amount of SWA in the sleep EEG was calculated. The results indicate that light and heavy mental activity do not differentially affect sleep stages except for wakefulness after sleep onset. Subjects were less often awake shortly after sleep onset following heavy workload than after light mental activity. However, SWA, an indicator of sleep depth, did not reveal any difference between the light (A) and heavy condition (B). Neither the total amount of SWA expressed during the night, nor the amount of SWA in the first 120 min of NREM sleep, when recovery processes supposedly peak, showed a difference between the conditions. Even when the time course of SWA during sleep was studied in detail, the nights following light and heavy mental activity were strikingly similar. None of the intervals differed significantly between the two conditions. Hence, not only the total amount of SWA, but also the time course of SWA discharge was unaffected by behavioural conditions during prior waking.

The second question addressed by the experiments concerned the possibility of recovery of mental activity during interspersed relaxed wakefulness. To investigate this, the condition in which the heavy mental activity was presented in a continuous 8-h block was compared with a condition in which the same total amount of mental activity was performed, but interspersed with breaks of 30–50 min. Again, there was no difference in neither sleep stages nor total amount of SWA, nor in the course of SWA discharge during the night.

In addressing the two questions stated above, the heavy-workload condition was first compared with the light-workload condition and subsequently with the heavy-workload-with-breaks condition, separately. As the data of the condition of heavy workload were re-used in this second comparison, the corresponding *t*-tests should have been corrected for interdependency. However, even without a statistical correction for this interdependence, which would decrease the chance to find a difference even more, condition B and C did not differ on any sleep variable. This demonstrates persuasively that breaks do not affect sleep propensity during the following sleep.

In the light of the well-established effects of physical activity on sleep depth (Youngstedt *et al.* 1997), our findings make it unlikely that these are attributable to the associated CNS activity. Presumably, the role of body heating on subsequent recovery processes during sleep is greater than the effects of mental activity associated with physical load.

It is surprising that the intensity of mental activity did not influence any aspect of subsequent SWA. In contrast to the expected SWA increase, an average reduction of 2% was found during sleep following heavy mental workload as compared with light mental workload. Given the standard error of about 10%, the increase of SWA after heavy workload should have been at least 20% to yield a significant difference. As lengthening the waking period is known to cause increases of SWA of sometimes even up to 40% as compared with baseline sleep (Borbély *et al.* 1981), the absence of an increase in SWA following mental workload cannot be the result of a ceiling effect. The insignificant small decrease we found fortifies our conclusion that mental workload does not predominate the need for SWA.

We have of course wondered whether our experimental manipulations have sufficiently differentiated between light and heavy workload. To maximize potential effects, a number of precautions had been taken. By supervising task performance, it was ensured that the subjects were continuously working, and the intervals between the last task session and going to bed was kept as brief as possible (25 min). In this way, 'unwinding' was minimalized, so that the increased recovery processes because of heavy mental workload – if present – would be confined to sleep. In spite of the great subjective difference between the experimental conditions as reported by the subjects after completion of the experiment (exhausting and easy for condition B and A, respectively), subjective fatigue ratings did not discriminate very strongly between conditions.

Several recent studies have suggested that finding differences in sleep may depend on the position of the electrodes. Kattler *et al.* (1994) reported that stimulation of one hemisphere resulted in local recovery processes during sleep in this hemisphere, and not in the contralateral hemisphere. After vibrating the right hand, the left hemisphere showed more SWA during subsequent sleep than the right hemisphere. However, the relative amount of SWA on C3 was only slightly higher than the relative amount of SWA during baseline, without prior stimulation. Stimulation of the left hand in fact reduced SWA in both hemispheres, and mostly so in the right hemisphere. This suggest that interhemispheric differences in recovery during sleep are small. Regarding the anterior–posterior axis, Werth *et al.* (1997) also found small regional differences in SWA power during NREM sleep. Their results show that SWA power was higher in bipolar derivations that surround a central lead (i.e. F3–C3 vs. C3–P3), than in derivations from electrodes surrounding a parietal lead (i.e. C3–P3 vs. P3–O1). A direct comparison between these derivations and those used in our study (i.e. C3–A2 and C4–A1) is difficult, but these findings are favourable to our choice to use C3 and C4 to measure SWA.

Cajochen *et al.* (1999) studied the topography of SWA in relation to sleep regulatory mechanisms. In their study, six volunteers were sleep deprived for 40 h. The sleep-deprivation induced increase of SWA was significantly larger in the more frontal derivations (i.e. Fz and Cz vs. linked mastoids) than in the more parietal derivations (Pz and Oz vs. linked mastoids). This anterior predominance was most pronounced during the first half hour of recovery sleep. The fact that our data do not even show the slightest difference between the conditions in the first 30 min of sleep indicates that the degree of mental activity may not influence recovery processes during sleep.

In summary, sleep debt as reflected by SWA does not accumulate at a different rate during wakefulness under sustained heavy mental workload vs. relaxed video watching or heavy mental workload with breaks.

ACKNOWLEDGEMENTS

This study was supported by NWO Grant no. 580-02-102 to D.G.M. Beersma and S. Daan. We are grateful to M. Gordijn, G. Overkamp and Ph. Duinisveld for helping with data acquisition, and to L. Jongman and M. Lorist for programming the computer tasks.

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