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Less effective executive functioning after one night's sleep deprivation

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SUMMARY The prefrontal cortex (PFC) is affected negatively by sleep deprivation (SD) and executive functioning is largely dependent on activity in the PFC. Earlier studies have focused on subsystems of executive functioning, and tests of executive functioning have shown both low reliability and low validity. In the present study, 11 healthy volunteers were sleep deprived and compared with 11 healthy controls in a study on effects of one night's SD on integrative executive functioning. Following SD, the performance of subjects on an ecologically valid test, the modified Six Elements Test, was significantly impaired. There were no group differences on psychomotor vigilance, verbal or visuo-spatial working memory. This extends previous knowledge of performance effects of SD, and may be of special importance for individuals with cognitive work tasks.

KEYWORDS executive function, performance, prefrontal cortex, six elements test, sleep deprivation, working memory

INTRODUCTION

Sleep deprivation (SD) is known to impair various aspects of cognitive performance of which monotonous, attention demanding, long, and machine-paced tasks are most sensitive (Dinges, 1992; Dinges and Barone Kribbs, 1992; Dinges and Kribbs, 1991; Gillberg and Åkerstedt, 1998; Hockey *et al.*, 1998; Wilkinson, 1961). Negative effects of SD have also been found during short-lasting reaction time tests (Gillberg and Åkerstedt, 1994) and with discernible effects after 5 min of a 10-min auditory reaction time task (Lisper and Kjellberg, 1972). Performance impairments have been found in speed, accuracy, and overall stability. The impairments also correlate with physiological sleepiness measures (Electroencephalography, EEG, Electrooculogram, EOG), slowed event-related potentials (ERP), and lower amplitude in ERP responses (Cajochen *et al.*, 1999; Smith *et al.*, 2002). Effects of task repetition, e.g. boredom and fatigue, could in some cases be additional causes, or interact 'positively' with sleepiness (Webb and Levy, 1984; Wilkinson, 1961, 1964).

It has been argued that higher level skills may be relatively unaffected by SD as sleepiness may be masked or overcome by the more activating and encouraging nature of these tasks and also that performance may be close to normal as a result of compensatory effort (Hockey *et al.*, 1998; Horne and Pettit, 1985; Kjellberg, 1977; Webb and Levy, 1984; Wilkinson, 1961). Binks *et al.* (1999) reported that short-term SD does not lead to detrimental effects selectively on higher cortical functioning, as measured with the Wisconsin Card Sorting Test and Stroop. However, the authors discussed both test sensitivity and circadian rhythm effects overriding a possible sleep loss effect on performance.

Although recent research has dealt with negative effects of sleep loss and mental fatigue on more complex and executive tasks, including impaired temporal memory and divergent thinking (Drummond and Brown, 2001; Harrison and Horne, 1999, 2000a,b; Horne, 1988; van der Linden *et al.*, 2003; Wimmer *et al.*, 1992), very little is known about the effects of SD on goal-directed behavior, based on integrative executive functioning and supervisory control. Earlier studies on more complex behavior have focused mainly on subcomponents of

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executive functioning. Problems with existing data include task difficulty, low reliability, and low validity of the tests (Burgess *et al*., 2000; Harrison and Horne, 1998; Jones and Harrison, 2001; Stuss and Alexander, 2000). In addition, data pertaining to the effects of SD on functions with high ecological validity and relevance for working life situations are scarce.

A suitable test of integrative executive function is the modified 'Six Elements' task (SET) (Burgess and Shallice, 1996). The test was originally developed for identifying impaired functioning among patients with frontal lobe damage. It can be used as a measure of supervisory control of executive functioning and everyday functioning. Test results on the original SET have been consistently related to performance in everyday planning and organization, providing clear support for its ecological validity (Burgess *et al*., 1998, 2000; Shallice and Burgess, 1996). The test requires aspects important for goal-directed behavior: prioritization, planning, self-organization, multitasking and monitoring of own behavior. A key characteristic of successful performance on the test is the ability to create and subsequently activate delayed intentions. A second characteristic is that the degree of adequate performance has to be decided by the subject herself (Burgess *et al*., 2000).

Several processes related to the frontal lobes converge on the general concept of supervisory control. This supervisory attentional system is involved in adjustment to novel situations. The prefrontal cortex (PFC) is seen as the seat of higher level processes that interact with, and modulate lower level ones (Shallice and Burgess, 1996). Decreased brain metabolism has been found during SD, particularly in the PFC (Muzur *et al*., 2002; Thomas *et al*., 2000; Wu *et al*., 1991). Increased activity has been shown post-SD in specific PFC areas during divided attention tasks (Drummond *et al*., 2001), which might reflect compensatory mechanisms (Drummond *et al*., 2001; Horne, 2000). The PFC vulnerability hypothesis (Horne, 1993) states that the PFC benefits most from sleep, as total SD leads to PFC-related neuropsychological impairments, reversed by recovery sleep.

The objective of the present study was to investigate the acute effects of SD on integrative executive functioning when compared with subsystems such as memory and psychomotor vigilance, previously shown to be affected by SD and used as building blocks to accomplish goal-directed behavior.

METHODS

The present study was part of a larger project on the effects of SD on the immune system and was approved by the Ethical Committee of Karolinska Institutet. Twenty-two healthy subjects with normal sleep patterns, participated after providing written informed consent. They were recruited via posters displayed around Karolinska Institutet. Mean age for controls was 27.6 years (19–41), and 23.9 years (20–29) for the SD group. Subjects were compensated economically for participation.

The subjects were randomized into two groups, matched on gender and age: an SD group (31–32 h of SD at the start of the test battery) and a normal sleep (control) group. The subjects in the SD group arrived at the laboratory at 6.00 PM for a standardized meal and were monitored by an experimenter throughout the experiment. Sleep before the study was monitored with The Karolinska Sleep Diary (Åkerstedt *et al*., 1994) and with wrist actigraphy (Cambridge Neurotechnology®, Cambridge, UK). Actigraphy data were analyzed by the manufacturer's software algorithm in 30-s intervals for definition of sleep or non-sleep epochs. Actigraphy TST correlates significantly with TST derived from polysomnography (Kushida *et al*., 2001).

All subjects were instructed to maintain a regular sleep schedule (11.00 PM to 7.00 AM) without alcohol consumption for 3 weeks before the cognitive tests. The subjects (three to four per night) stayed in the laboratory facilities, watching video, reading, surfing on the Internet and interacting socially until after the tests the subsequent afternoon (ca 4.00 PM). The subjects were not allowed to drink coffee, tea or any other caffeinated beverage from arrival until the termination of the laboratory setting. All tests and ratings were given between 2.00 and 3.30 PM and lasted for 36–40 min for each subject.

The control group arrived at 1 PM, 1 h before the tests were administered. The cognitive tests were always carried out in the following order: a verbal memory test, Claeson-Dahl (CD, Psykologiförlaget AB, Sweden), visuo-spatial working memory test (vsWM) (Park *et al*., 1995), the modified Six Elements Test (SET) (Burgess and Shallice, 1996), and a serial reaction time test (RT) (Gamberale *et al*., 1989).

Test battery

The Claeson-Dahl (CD) test was used for testing verbal working memory and episodic memory. A list of 10 words was read to the subject. After a delay of 15 s, the subject was to repeat as many words as he/she remembered. The list was repeated, until the subjects correctly repeated all 10 words two times consecutively. The maximum number of trials was 10. A weighted score was computed based upon the number of trials and words recalled in each trial. The CD test lasted for 10–12 min.

In our version of the vsWM, we used a free delayed recall (16 presentations in total) in a two-dimensional space where a circle had been presented 15 or 30 s previously. During those intervals (randomized order) a distractor task was presented, during which the subject was instructed to press the left mouse button on a Kensington TurboBall mouse every time three-digit numbers were counted down by three instead of two. After the distractor sequence, the screen went blank for free recall. Completion time for the vsWM test was 9–10 min.

The SET consists of three main tasks: story-telling, simple arithmetic calculations and object naming. Each task consists of two subtasks: A and B. For 10 min, the subjects were instructed to do something from each of the six tasks, and to follow one rule: not to do the two subtasks consecutively. The maximum raw score is 6 (all tasks started, no rule broken) and it is then subtracted with the number of rules broken (maximum 3 rule breaks). Another score reduction criterion is applied if a subject spends more than 271 s on one of the six tasks in total. After the instruction, the subjects should describe the test procedure, so understanding of the test could be established. Including the test instruction, SET lasted for 12–13 min.

A 5-min RT was carried out using a PSION Organizer. A black square was shown on the screen until the subject responded by pressing a button. The interstimulus interval varied from 2 to 7 s. The total time for the test battery ranged from 36 to 40 min.

To avoid learning effects, the subjects had a training session on vsWM and RT 24 h before the test battery, but not on the SET, as it relys on task novelty, nor on the CD, where the learning curve is an essential outcome of the test.

Subjective ratings

Before the test battery and after each test, subjective ratings were collected: Karolinska Sleepiness Scale (KSS) (Åkerstedt and Gillberg, 1990), ranging from 1: 'very alert' to 9: 'extremely sleepy, fighting sleep, an effort to stay awake'; level of stress, from 1: 'no stress at all' to 9: 'maximum level of stress'; mental fatigue (MF), from 1: 'very slow, inefficient' to 9: 'very fast, efficient'; and effort, 1: 'no effort at all' to 5: 'maximum level of effort'.

Statistical analyses

Data from SET was analyzed with chi-squared test for error versus no error on the test, as no subjects failed on SET in the control group. One-sided *t*-tests were used for mean distance from target in pixels during vsWM, and the weighted score in CD. The median RT, the standard deviation, number of lapses and the fastest and slowest 10% were analyzed with a repeated measures ANOVA, with group and time on task (1–5 min) as independent variables. Subjective ratings were analyzed with repeated measures ANOVA, with group and test as independent variables.

RESULTS

The sleep deprived subjects performed significantly worse than the control group on the executive test SET ($\chi^2 = 4.9$, $P = 0.027$). Four subjects in the SD group broke at least one of the rules, while none from the controls did so. Two subjects from the SD group had an *extra* reduction of the score because of the >271 s criteria.

Subjects in the SD condition did not differ from controls with respect to the vsWM task on the mean distance (in pixels) from target center, regardless of distractor length (see Table 1 for summary of test results and the subjective ratings).

There were no differences with respect to the mean weighted score on the CD verbal memory test, or number of trials to learn all 10 words. Moreover, the groups did not differ on *any* of the RT-parameters.

The main effect of group on KSS was significant ($P < 0.03$). The SD group was significantly sleepier than the controls. The main effect of test on subjective sleepiness was also significant ($P < 0.0001$). The subjects were most sleepy after the RT and most alert after SET, but no interaction was found between group and test.

Ratings of stress levels did not differ between the groups, but there was a main effect of test ($P < 0.0001$). Highest ratings were obtained after SET, and lowest after RT. No interaction was found between group and test.

The SD group was significantly more mentally fatigued than the control group ($P < 0.01$). The main effect of test was also significant ($P < 0.001$), where the ratings were highest after RT and lowest after SET. No interaction was found between group and test.

Effort ratings showed no significant main effect of group. The main effect of test was significant ($P < 0.001$), with highest effort during vsWM and lowest during RT. No interaction effect was found.

Mean actigraphy total sleep time (TST) for the controls the night before the tests was 7.57 h (6.15–9.33 h), all with good or very good subjective quality of sleep.

DISCUSSION

Sleep deprivation was associated with less effective executive functioning, without affecting the working memory subsystem, or psychomotor vigilance. The current study does not address the issue of which subprocess of the supervisory attentional system that is affected by SD, or whether the effect is global. It does, however, address the issue of whether the effect is because of visuo-spatial/verbal working memory or vigilance deficits, as tested by specific tests.

The effects on executive functioning in this study cannot be explained with mental fatigue, effort, or stress, as indicated by the subjective ratings. This indicates that the control group subjects were not affected negatively by their studies or work before the test battery. The effects can neither be explained in terms of monotony or length of the test battery, as duration of testing did not exceed 40 min in total (45 min including the subjective ratings). If monotony were an issue the reaction times would have been affected (Gillberg and Åkerstedt, 1998). Nor is task difficulty a cause, as the modified Six Elements has been adapted for individuals with low IQ using simpler tasks and reduced demands on retrospective memory and working memory load. The subject can see the written instructions at any time during the test. The test is also self-paced. This is a factor that could protect against performance decrement (Hockey *et al.*, 1998).

The SET is mainly a measure of supervisory control, a necessary aspect of adjusting to novel situations and multi-tasking, which makes it highly relevant to everyday, and work-related behavior. Ecological validity has been a major problem with tests of executive functioning (Burgess *et al.*, 1998; Jones and Harrison, 2001; Stuss and Alexander, 2000), but associations have been found between failure on SET and everyday

Table 1 Mean results for the serial reaction time test (RT), Claeson-Dahl (CD) verbal memory test, visuo-spatial working memory test (vsWM), as well as subjective ratings of sleepiness (KSS), stress, mental fatigue and effort

Test/Scale	*Mean ± SE sleep deprivation group*	*Mean ± SE controls*	*F-value, T-value*	*P-value*	*d.f.*
RT-median (ms)	265.0 ± 18.8	225.0 ± 13.1	2.38	NS	1, 19, 4
RT-SD	84.0 ± 41.1	53.9 ± 10.5	0.62	NS	1, 19, 4
RT-fastest 10%	200.9 ± 7.8	183.6 ± 9.0	2.73	NS	1, 19, 4
RT-slowest 10%	438.2 ± 89.5	349.4 ± 32.3	0.62	NS	1, 19, 4
CD-weighted score	43.1 ± 16.3	18.8 ± 6.0	−1.39	NS	1, 19, 4
CD# learning trials	5.81 ± 1.1	4.6 ± 0.7	−0.94	NS	1, 19, 4
vsWM (px from target center)	49.8 ± 4.0	51.1 ± 3.5	0.6	NS	1, 19, 4
KSS (1–9 high)					1, 20, 4
Group	5.5 ± 0.2	3.8 ± 0.2	6.4	0.02	
Test			6.1	< 0.001	
G × T			1.5	NS	
KSS ‘Pre’ battery	5.7 ± 0.5	4.1 ± 0.6			
KSS CD	5.0 ± 0.6	4.0 ± 0.5			
KSS vsWM	5.9 ± 0.6	3.8 ± 0.5			
KSS SET	4.6 ± 0.7	3.1 ± 0.3			
KSS RT	6.5 ± 0.6	4.1 ± 0.5			
Stress (1–5 high)					1, 20, 4
Group	2.8 ± 0.2	3.3 ± 0.2	1.04	NS	
Test			5.7	< 0.001	
G × T			1.7	NS	
‘Pre’ stress	3.0 ± 0.6	2.4 ± 0.5			
CD stress	2.4 ± 0.2	2.6 ± 0.4			
vsWM stress	2.4 ± 0.2	2.8 ± 0.4			
SET stress	3.5 ± 0.4	4.7 ± 0.7			
RT stress	2.5 ± 0.3	3.3 ± 0.6			
Mental fatigue (MF 9–1 high)					1, 20, 3
Group	4.4 ± 0.2	5.8 ± 0.2	9.2	0.01	
Test			10.3	0.001	
G × T			2.5	NS	
CD MF	4.3 ± 0.5	5.4 ± 0.5			
vsWM MF	4.0 ± 0.5	6.5 ± 0.5			
SET MF	5.4 ± 0.4	6.6 ± 0.4			
RT MF	3.8 ± 0.4	5.4 ± 0.4			
Effort (1–5 high)					1, 20, 3
Group	3.4 ± 0.1	3.2 ± 0.1	0.9	NS	
Test			9.9	0.0001	
G × T			1.7	NS	
CD effort	3.9 ± 0.2	3.3 ± 0.3			
vsWM effort	4.0 ± 0.2	3.5 ± 0.3			
SET effort	3.2 ± 0.3	3.2 ± 0.2			
RT effort	2.6 ± 0.2	2.8 ± 0.3			

SE, standard error of the mean; ‘Pre’, rating before the test battery; G, group; T, test; distractor length during vsWM or minute of the test (RT), G × T, interaction; the CD-weighted score = Number of learning trials to learn all 10 words and number of words learned per trial; SET, Six Elements Test; NS, non-significant.

planning and organization (Burgess *et al*., 2000; Shallice and Burgess, 1996).

Horne (2000) comments on Drummond *et al*. (1999) that tests do not necessarily have to be monotonous and boring to be sensitive to sleep loss. Nevertheless, many studies focus on such tests only, missing potential effects on more integrative aspects of executive functioning. There are of course many problems associated with the issue of measuring executive functioning, such as task difficulty (too easy or too difficult), task novelty, reliability, ecological validity and repeatability, etc. (Jones and Harrison, 2001). These problems need to be further addressed.

It is not clear how the absence of impairment on psychomotor vigilance following SD should be interpreted. Slow reaction times might indeed lead to an overall impaired cognitive functioning, but performing well on a reaction time test or a working memory test does not imply that one will perform well on a ‘higher’ cognitive level. This is a rather paradoxical finding and it indicates that SD might have even more severe consequences than has been previously shown.

The clear effects of SD on psychomotor vigilance in other studies might be due to frequent repetition leading to an increased effort-related load that may interact with sleep loss. This, however, needs to be established experimentally. In the present study the short test length, absence of repetition and a between-group design with relatively small groups might have played a role. However, to minimize the effects of monotony and to keep the test battery shorter, RT was applied only once.

We cannot interpret the SD effect as acting completely on a global level of functioning, but the results in the present study indicate that the response of the PFC to SD is not merely task-specific. As the integrative capacity is thought to depend to a large extent on the PFC, we can further interpret data as supporting the PFC vulnerability hypothesis (Horne, 1993). Data might also be interpreted according to a cascade model of cognitive control (Koechlin *et al.*, 2003). In this model, lateral prefrontal cortex regions influence premotor or posterior associative cortices via top-down interaction and SD might impair that interaction. Most likely, the observed SD effects would have been even larger and more widespread had the tests been carried out at the circadian nadir when there is an interaction between time awake and circadian phase (Cajochen *et al.*, 1999; Waterhouse *et al.*, 2001). If an interaction between sleep loss and a potential afternoon increase in sleepiness would have been the case, a significant difference would have been observed in some of the other tests.

Interestingly, ratings of sleepiness differed significantly between tests. The effect of type of test on subjective ratings indicates that the latter need to be interpreted against the activity preceding the rating. It has, for example, been suggested that ratings of sleepiness show poor correlations with subsequent performance (Rogers and Dinges, 2003), suggesting that ratings may not reflect 'true' sleepiness. An alternative interpretation may be poor control of the context in which the rating was made. Yang *et al.* (2004) recently noted that a 1-min control situation before ratings (sitting quietly with eyes closed) increased correlations between Stanford Sleepiness Scale ratings and subsequent performance. The higher ratings of sleepiness post-RT for both groups are not because of mental fatigue of the test battery as both groups also scored lowest on the mental fatigue scale post-RT.

The higher ratings of stress after the SET are probably not related to effort, as the effort ratings did not increase. The rated stress is more likely associated with the issue of what is considered adequate performance. Thus, the subjects might have experienced uncertainty of whether they have performed well or not and this might have been somewhat distressing for them. This might not be the case for the other tests that were used in the study. Interestingly, the SET made controls slightly more stressed (but not significantly so) than the sleep-deprived group.

Important in future research is to use tests of executive functioning with high reliability and validity, although this may be difficult to achieve, as a result of the multi-factorial aspects of 'executive behavior.' Increased specificity of tests might lead to lost sensitivity, while increased sensitivity might cause impaired specificity (Stuss and Alexander, 2000).

In summary, the present study has demonstrated that one night of sleep loss impairs integrative executive functioning. This may be of special importance for individuals with cognitive work tasks.

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