Physiology & Behavior 84 (2005) 715–724

PHYSIOLOGY & BEHAVIOR

Effect of driving duration and partial sleep deprivation on subsequent alertness and performance of car drivers

Sarah Otmani*, Thierry Pebayle, Joceline Roge, Alain Muzet

Centre d'Etudes de Physiologie Appliquée (CEPA-CNRS), UPS 858, 21 rue Becquerel, 67087 Strasbourg, France

Received 21 September 2004; received in revised form 20 January 2005; accepted 21 February 2005

Abstract

The effect of partial sleep deprivation and driving duration on subsequent alertness and performance in car drivers was investigated. Twenty healthy male subjects, between 25 and 55 years of age, free from any sleep disorder, took part in two simulated driving sessions carried out between 2 p.m. and 4 p.m. Before one session, subjects were sleep deprived as they were allowed to sleep only between 3 a.m. and 7 a.m. during the preceding night. Throughout the driving task, the subjects' driving performance, electroencephalogram and Karolinska Sleepiness Scale (KSS) score were recorded. The results revealed that sleep deprivation had an effect on KSS score but not on the (alpha + theta) spectral power, while driving duration had an effect on these two parameters. This effect was also influenced by sleep restriction. Time on driving task alone had a significant effect on driving performance; the sleep restriction having only an effect on one of the performances indices studied: the number of right edge-line crossings. These results are interpreted in terms of the relationship between level of alertness and performance impairment.

Keywords: Partial sleep deprivation; Alertness; Karolinska Sleepiness Scale (KSS); Electroencephalogram (EEG); Driving performance

1. Introduction

Our alertness level, or more precisely our arousal level, is subject to diurnal variation. This level of alertness is controlled by a circadian pacemaker and also by the process of sleep homeostasis [1–4]. Decline of alertness constitutes a normal physiological phenomenon but its importance depends on many factors (individual characteristics, sleep, drugs, alcohol...) [5,6]. It occurs primarily at two times of the day between 1 p.m. and 4 p.m. and between 4 a.m. and 6 a.m. This decrease in alertness is mainly characterized by a strong propensity to sleep, causing the occurrence of sleepiness and "microsleep" episodes. These fluctuations of alertness level bring into play change in oscillatory brain activity [7–9], which is observable on the electroencephalogram (EEG). The increase in appearance of alpha and theta rhythms is thus often associated with the development of sleepiness [10–13].

Variations of the level of alertness across the day are also accompanied by fluctuations in performance [14]. We could understand, therefore, why a low level of alertness could cause deterioration in performance to a level which is incompatible with safety [15–17]. Driving is a complex task requiring an optimum level of alertness to guarantee the security of the driver and the other road users. Statistics suggest that low-alertness is the cause, each year, of many road accidents. The number of sleep related accidents ranges from 10% to 30%, depending on the year of the reported study and the country [15,18–23]. These accidents generally occur at two different times of the day, coinciding with periods of minimum alertness and mainly involve a single vehicle coming off the road [19,24–26]. Indeed, various studies on simulators show that deterioration in driver's alertness level is accompanied primarily by a difficulty in maintaining the vehicle's trajectory [27–31]. Finally, the sleep related accidents particularly involved younger drivers (20–30 years) [25].

Although sleepiness is known to be a serious risk factor in automobile driving, many drivers combine sleep deprivation

* Corresponding author. Tel.: +33 3 8810 6249; fax: +33 3 8810 6245.
E-mail address: sarah.otmani@c-strasbourg.fr (S. Otmani).

0031-9384/$ - see front matter © 2005 Elsevier Inc. All rights reserved.
doi:10.1016/j.physbeh.2005.02.021

and long driving [32]. The cardinal feature of sleep deprivation is diminished alertness and performance, which seems to be a function of the severity of sleep deprivation. Literature about the effect of sleep deprivation on alertness and performance is however difficult to analyse because of the many different protocols employed (partial or total sleep deprivation; acute, short term or long term sleep restriction; delayed or advanced bedtime) and the wide range of subjective, objective and performance measures. Our study involved partial sleep deprivation of 4 h, representing half of the length of a "normal" night. We have therefore concentrated our literature review on the effects of such partial sleep deprivation on alertness and driving performances.

In the case of partial sleep deprivation, the relationship between sleep duration and sleep propensity (multiple sleep latency test (MSLT) scores) is linear according to Devoto et al. [33] and to Rosenthal et al. [34]. Gillberg and Akerstedt [35] found that restricting sleep to 4 h (3–7 a.m.) affected the subjective feeling of being well-rested and reduced the MSLT latency as compared to an 8 h baseline sleep condition. On the subjective level, Jewett et al. [36] established that the relationship between Standford Sleepiness Scale (SSS) score and sleep duration is a linear function or a saturating exponential function. After a sleep deprivation of 4.5 h, the subjective sleepiness measured by the SSS increased in the study of De Valck and Cluydts [37]. In their study, Lenne et al. [38] observed, that following sleep deprivation of 5 h, subjective alertness was lower and sleepiness ratings were higher. Lastly, Fairclough and Graham [30], found that subjective sleepiness measured by the Karolinska Sleepiness Scale (KSS) was significantly higher after a 4 h sleep deprivation. In conclusion, one night of partial sleep deprivation seems to impair subjective and objective alertness (measured by MSLT), but to our knowledge, no study analysed the waking EEG of partially sleep-deprived subjects. Sleep deprivation, however, has been shown to affect EEG during wakefulness. Brunner et al. [39] found a significant decrease in the alpha range after the second night of 4 h partial sleep deprivation. After a night without sleep, subjects in the study by Dijk et al. [40] presented an increase in the power density of the theta and delta frequencies. To conclude, partial sleep deprivation affects alertness of the day after, as seen by the increase in KSS and SSS scores and in the low frequency spectral power.

The changes in driving performance reported after partial sleep deprivation are less consistent. After a 4.5 h sleep deprivation, De Valck and Cluydts [37] showed a significant increase in accident liability (defined by whether or not the subject came off the road or hit another vehicle at least once during the driving task) and lane drifting. Fairclough and Graham [30] observed that after a sleep deprivation of 4 h, the frequency of near-crossings increased but the frequency of lane crossings did not change. Moreover, the steering wheel reversal rate reduced. Some authors noticed no change in driving performance after a partial sleep deprivation. Thorne et al. [41] found no change in accident rate (number of vehicular collisions and running off the road per run) after a 3 h sleep deprivation and Peters et al. [42] as well Roehrs et al. [43] found no increase in lateral deviation after a 4 h sleep deprivation. No hypothesis has been found to explain these differences; these studies differing by numerous aspects: gender and age of the subjects, delayed or advanced bedtime, and finally type of road scene used (motorway, inter-city roads. . .). As the effect of partial sleep deprivation on driving performance is not clear, the first aim of our study is to examine, on a simulated monotonous motorway, the effect of a 4 h sleep deprivation on driving performances and on both subjective and objective alertness. The innovation characteristic of this experiment resides in this fact: we have analysed the effect of a partial sleep deprivation, simultaneously, on subjective data (KSS score), EEG data and on driving performance, with a simulated driving task, which combined realism and long duration.

Increased driving time is also a factor which decreases alertness and performance particularly when the driving environment is monotonous [44,45]. In fact, Harris [46] showed an increased accident rate (accidents that resulted in death, injury or damage to property in excess of $2,000) with increased driving time for truck drivers on real roads. Riemersma et al. [27] noted that standard deviations of lane position and speed both increased during a night of real road driving. Brookhuis and de Waard [28] showed that the time spent on a simulated driving task on task increases the standard deviation of lateral position and of steering wheel movements. Thiffault and Bergeron [45] found that the duration of the task increases the mean amplitude of steering wheel movements and their standard deviation. Van der Hulst et al. [29] noticed that task length has a significant amplifying effect on sleepiness ratings (SSS) and on the standard deviation of lateral position. Kecklund and Akerstedt [47] showed that rated sleepiness and bursts of alpha and theta power density, increased with hours driven. Ranney et al. [48] found that time on task increases subjective sleepiness (SSS) and (mean) speed and decreases the capacity of detection (pedestrian detection task) during a simulated driving task. Finally, Phillip et al. [49] showed an increase of 3.4 ms on a reaction time test per additional hour of driving. It is now well established that driving time impairs alertness and driving performance. In a total sleep deprivation schedule, Hack et al. [50] found that sleep deprivation caused progressive deterioration of the steering performance (calculated by the standard deviation of lateral position). Consequently, we made the hypothesis that sleep deprivation together with the duration of driving, would accentuate not only the impairment in driving performance, but also the deterioration in subjective and objective alertness.

Introducing a link between alertness and performance is not a recent idea but dates from the sixties with attempts to correlate observations made on the EEG and performance in vigilance tasks. As far as driving task is concerned, few authors have attempted to correlate physiological EEG data and driving performances indices. Brookhuis and de Waard [28] found that correlation between averages of standard deviation of lateral position and (alpha + theta)/beta energy is moderately low but significant across subjects. Risser et al. [51] found correlations between the frequency and duration of attentional lapses (alpha or theta activity lasting 3 s or longer), the lane position variability and the crash frequency in obstructive sleep apnoea patient and normal subjects. Campagne et al. [52] established correlations between lower frequency EEG (i.e., alpha or theta) and driving errors (running-off-the road index and large speed variations), but these correlations depend on the driver's age. Khardi and Vallet [53] claimed that the number of steering wheel reversals correlated positively and significantly with the amount of theta and alpha activity of the EEG. Finally, Horne and Baulk [54] found correlations between (alpha + theta) power and incidents (a car wheel crossing the lateral lane marking) across 15-min intervals on a 2 h simulated driving task performed after a 5 h of sleep deprivation. Another aim of this study is to investigate correlations between numerous performance indices and a physiological brain index of sleepiness obtained from the EEG.

2. Method

2.1. Subjects

The sample consisted of 10 young men with an age of 29.6 ± 2.62 (mean ± S.D.) years and 10 middle-aged men with an age of 49.6 ± 3.06 (mean ± S.D.) years. The younger drivers had held their driving licence for 11.2 ± 2.04 (mean ± S.D.) years on average. The older people had held their driving licence for 30.05 ± 3.4 (mean ± S.D.) years. All the drivers drove more than 10,000 km/year. All subjects were medically evaluated prior to the study and were found to be in good physical condition. They were free of any sleep disorder, simulator sickness (checked after a 15 min simulator familiarization test) and on no medication. Subjects did not have extreme score when typed for fluctuations in morning or evening alertness (14 Intermediate types, 4 Morning types and 2 Evening types) [55]. Their vision was compatible with the driving act. Each subject signed an informed consent agreement prior to his participation and was paid for his participation. This investigation has received approval from local ethics committee and then submitted to the ministry of health, in accord with French law on biomedical research on healthy human volunteers.

Participants wore wrist actimeters 36 h before the driving session to evaluate their rest/activity rhythm. Subjects were asked to have a usual activity the day before the test and have a habitual amount of sleep (average of 8 h 01 ± 54 min) the night without sleep deprivation. No difference was found for the average sleep length between young (7 h 58 ± 66 min) and middle-aged groups (8 h 05 ± 43 min). No nap was allowed prior to the driving test. Subjects were asked to abstain from alcohol, and to restrict their tea and caffeine consumption 36 h before the test.

2.2. Experimental procedure

Each subject took part in two driving simulation sessions, carried out during the afternoon post lunch dip period (between 2 and 4 p.m.). One test day (control condition) was conducted after a normal night's sleep at home. The subject arrived at midday at the laboratory and took lunch with the scientific team. The other test day was conducted after a night of sleep deprivation. The subject arrived at 10 p.m. at the laboratory and was supervised to ensure he remained awake until 3 a.m. During this time, he could play games, watch films, read or talk with an experimenter but exercise was not permitted. After 3 a.m. he was allowed to sleep until 7 a.m. in a sleep chamber. The subject took his breakfast (coffee or chocolate, cereals or toast and juice) at 8 a.m., remaining under the supervision of an experimenter until lunch. The test days were conducted approximately 1 week apart, with half the subjects in each group performing the control day before the post-sleep deprivation day.

2.3. Driving task

The driving task took place in our driving simulator PAVCAS ("Poste d'Analyse de la Vigilance en Conduite Automobile Simulée"). It consists of a front car cabin (with all controls and commands) placed on a mobile base that enables longitudinal, vertical, pitching and rolling movements. The cabin was linked to three interactive display units (sampling frequency 60 Hz, delay in generation of picture 40 ms). The road image was placed 2.50 m away from the driver and covered 108° of horizontal (3 screens of 36°) and 24° of vertical visual field. The day driving scenario used for this study was a monotonous motorway (a lap = 50 km) yet realistic to maintain ecological validity. The roadway measured 10 m wide between the two edge-lines (2 lanes of 3.75 m and a hard shoulder for emergency use of 2.5 m). The crash barriers were located on both sides of the edge-lines at a distance of 0.5 m on the right and 2 m on the left (central reservation). The road was edged by a flat rural landscape and fog was present (visibility reduced to 150 m). Scenery was similar throughout the driving task and included road-signs (speed limits, emergency telephone, rest areas modeled by parking) and the vertical signage. There was no traffic light. The circuit was composed by straight and curved segments (per lap, 14 on the right, and 7 on the left with a radius between 500 and 3500 m), uphill and downhill (2 hillocks of 15 m and 2 of 25 m). The traffic used was light (per lap: 20 vehicles on the right lane at a constant speed of 90 km/h, requiring drivers to initiate an overtaking maneuver). The simulator is situated in a climatic chamber where humidity (ambient water vapor pressure = 14 ± 1 hPa), temperature (21 ± 1 °C), noise (68 dB at 3000 turn/min) and light (average of 10 lx) are regulated and maintained constant to avoid influence of one of these parameters on the physiological state of the driver. Furthermore, during the driving, all subjects were dressed with the same clothes (tee shirt, tracksuit and tennis shoes) to reproduce the same thermal conditions.

Subjects were asked to drive at their own pace observing the usual driving rules, that are to drive in the right lane except for overtake and to not exceed the motorway speed limit (in France: 130 km/h). They were also required to drive as much as possible in the center of the right lane and their speed was continuously controlled and should not be lower than 90 km/h. Each subject had to perform a motorway drive of 90 min. Every 10 min during the driving, subjects were invited to evaluate their level of alertness on the Karolinska Sleepiness Scale [56]. We also collected the subjects KSS score before the driving task to ensure that there was no difference between them at baseline. The scale and the descriptors were located near the speedometer, within easy view.

2.4. Driving measures

Performance measures included standard deviation of lateral position (in metres), mean amplitude of steering wheel movements (in degrees), frequency per minute of steering wheel movements and number of right edge-line crossings. We choose to study only the right edge-line crossings because studies have shown that most of the trajectory deviation occurred on the right side of the road [25–27]. Lateral position was defined by a zero position (which correspond to the driver's position when the car is in the middle of the right lane) and by the left line (+1.5 m) and the right line (−2.3 m) position. Standard deviation of lateral position was computed only when the car remained in the right lane, to avoid effects of the few overtakings. In fact, including overtaking periods in the calculation of the standard deviation of lateral position would make this index not representative of driver's capacity to maintain the trajectory. This is why, by concern of simplification of data treatment, we only took into account standard deviation of lateral position when driver's car remained in the right lane and have not calculated the deviation when the car was in the left lane. To eliminate the effect of lane changes, we took into account only small steering wheel movements (between 0.5° and 5°) needed to adjust lateral position within the lane. An edge-line crossing was counted whenever a car wheel encroached the right edge-line. All these measures were averaged each 10-min period.

2.5. Electroencephalographic measures

Physiological recordings were performed on a digital data acquisition ("Neuroscan", Neurosoft Inc., USA) continuously during the driving test. This activity was measured through four silver electrodes (F3, C3, P3, O1), referenced to A2 [57]. In addition before the driving, a baseline 5-min period "eyes open" was recorded, with the subject sitting quietly in the car. Monopolar recording was preferred to bipolar. The digital EEG, sampled at 250 Hz, was submitted to visual artefact rejection. Power spectra with 0.5 Hz resolution, on C3 lead, were computed using "Brain Vision Analyzer" (Brain Product GmbH, Germany) after applying a Hanning window (10%) to data epoch of 2 s. These EEG power data were then averaged in 10-min periods and log-transformed [58]. This allowed temporal correlation with the KSS scores. We measured EEG (3.9–12.7 Hz) absolute power, which correspond to theta and alpha absolute power combined and which is positively associated with increasing sleepiness.

2.6. Statistical analysis

KSS score and EEG data (spectral power in (alpha + theta) band) recorded before the driving were analysed with ANOVA using the "Statistica" program (Statsoft Inc, USA) taking into account the driver's age (young, middle-aged) and the sleep deprivation status (with or without). The analysis of KSS score, EEG data and driving performances (standard deviation of the lateral position adopted in the lane; the mean amplitude and frequency per minute of small steering wheels movements (0.5–5°) and the number of right edge-line crossings) during the driving task took considered the driver's age, the sleep deprivation and the driving time (sequential 10-min periods over 90 min). Post hoc analyses were performed using the Fisher's LSD test and the means were considered significantly different when probability of error was less or equal to 0.05. Product-moment correlation between EEG data and the performances indices (averages obtained on the 90 min (9*10-min periods) of driving across subjects) were made using the Pearson coefficient correlation for each session (with or without sleep deprivation).

3. Results

3.1. KSS score

Before the test, KSS score did not vary as a function of driver's age [$F(1,18) = 0.79$, n.s.] but with sleep deprivation [$F(1,18) = 8.22$, $p < 0.01$]. This score was higher in the condition with sleep deprivation (2.95 ± 1.36) than in the condition without sleep deprivation (2.30 ± 1.08). These analyses demonstrate that age was not a factor affecting the before driving KSS score but sleep deprivation had an impact on the driver's estimation of sleepiness level.

During the driving, KSS score did not vary as a function of driver's age [$F(1,18) = 0.24$, n.s.]. Sleep deprivation had a significant effect on KSS score [$F(1,18) = 12.26$, $p < 0.003$]. Without sleep deprivation, KSS score was

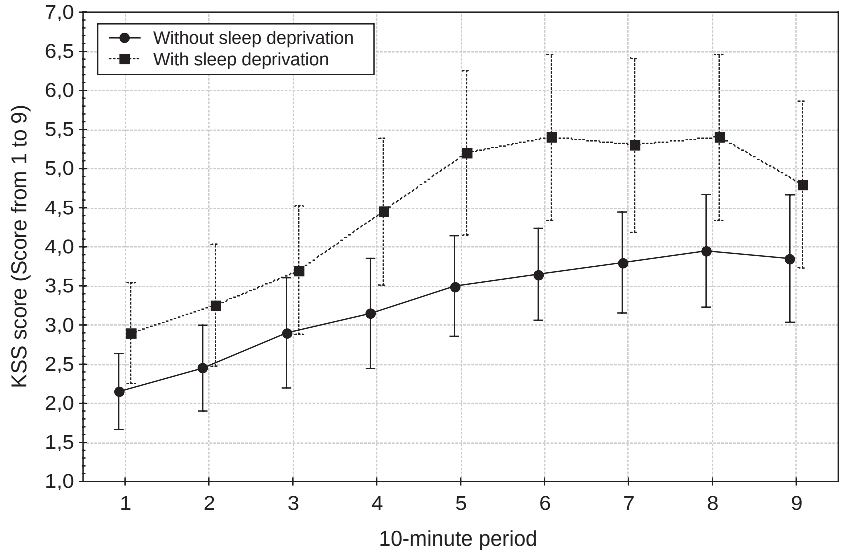

Fig. 1. KSS score as a function of sleep deprivation (with and without sleep deprivation) and of driving time (periods 1–9) (means ± standard errors).

3.27 ± 1.52 and with sleep deprivation 4.49 ± 2.21. KSS score varied significantly with driving time [$F(8,144) = 29.46$, $p < 0.0001$]. The mean comparison indicated that it increased significantly between the three first periods and the last five ($p < 0.0006$). Sleep deprivation interacted significantly with driving time on KSS score [$F(8,144) = 2.03$, $p < 0.05$]. After sleep deprivation, KSS score was significantly higher for all driving periods ($p < 0.009$) and increased more significantly with the driving time than without sleep deprivation (Fig. 1).

3.2. Spectral power in (alpha + theta) frequency band

Analysis of EEG data was available on 16 subjects, EEG data missing on four subjects due to technical problems during recording.

The analysis of the "5 min eyes open" period, recorded before the driving, showed that spectral power in (alpha + theta) band did not differ significantly with the driver's age [$F(1,14) = 0.32$, n.s.] or with sleep deprivation [$F(1,14) = 0.33$, n.s.]. These analyses demonstrate that, before the driving, spectral power in (alpha + theta) band was equivalent for the two age groups and for the two conditions.

During the driving task, spectral power in (alpha + theta) band did not vary as a function of the driver's age [$F(1,14) = 2.06$, n.s.] and sleep deprivation [$F(1,14) = 2.20$, n.s.]. Spectral power in (alpha + theta) band was significantly affected by driving time [$F(8,112) = 7.85$, $p < 0.0001$]. Spectral power in (alpha + theta) band increased significantly between the three first periods and the last four ($p < 0.01$). Sleep deprivation significantly impacted on effects of driving time on spectral power in (alpha + theta)

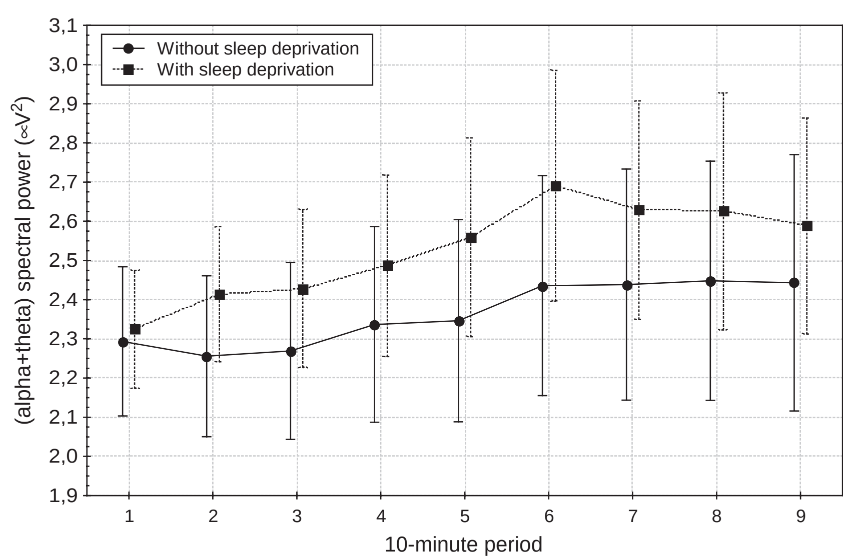

Fig. 2. Spectral power in (alpha + theta) band as a function of sleep deprivation (with and without sleep deprivation) and of driving time (period 1–9) (means ± standard errors).

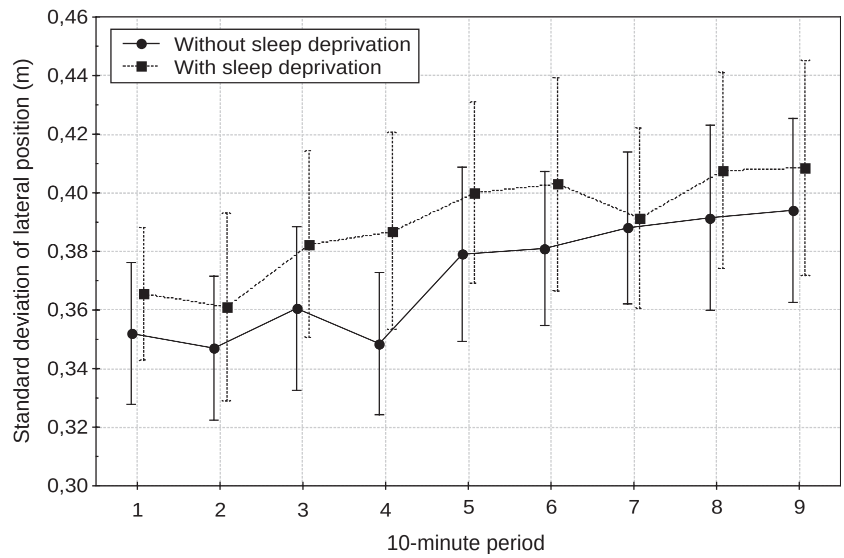

Fig. 3. Standard deviation of lateral position as a function of sleep deprivation (with and without sleep deprivation) and of driving time (period 1–9) (means ± standard errors).

band [$F(8,112)=2.50$, $p<0.02$]. After sleep deprivation, spectral power in (alpha + theta) was significantly higher between the second period and the last one ($p<0.0001$) than without sleep deprivation (Fig. 2).

3.3. Driving performance indices

3.3.1. Standard deviation of lateral position

Standard deviation of lateral position did not differ significantly with the driver's age [$F(1,18)=0.69$, n.s.] or with sleep deprivation [$F(1,18)=3.14$, n.s.]. Standard deviation of lateral position varied significantly with driving time [$F(8,144)=9.95$, $p<0.0001$]. The means comparison indicated that standard deviation of lateral position increased significantly between the two first periods and the last five ($p<0.007$)(Fig. 3). Sleep deprivation did not influence effects of driving time on standard deviation of lateral position [$F(8,144)=0.85$, n.s.].

3.3.2. Mean amplitude of small steering wheel movements

Mean amplitude of small steering wheel movements was significantly affected by the driver's age [$F(1,18)=4.39$, $p<0.05$], which was $1.99 \pm 0.33°$ for the young and $2.26 \pm 0.35°$ for the middle-aged. Sleep deprivation had no significant effect on mean amplitude of small steering wheel movements [$F(1,18)=0.02$, n.s.]. Mean amplitude of small steering wheel movements varied significantly with driving time [$F(8,144)=10.08$, $p<0.0001$]. The mean

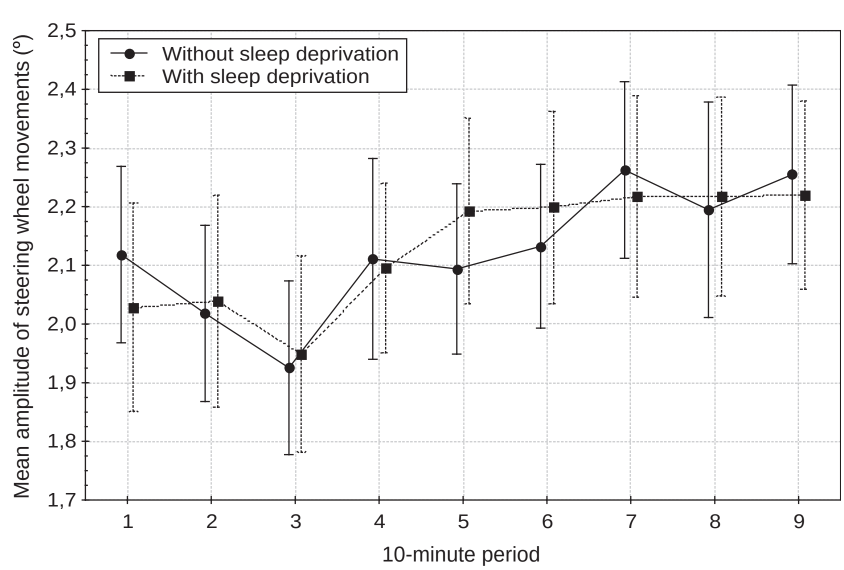

Fig. 4. Mean amplitude of steering wheel movements as a function of sleep deprivation (with and without sleep deprivation) and of driving time (period 1–9) (means ± standard errors).

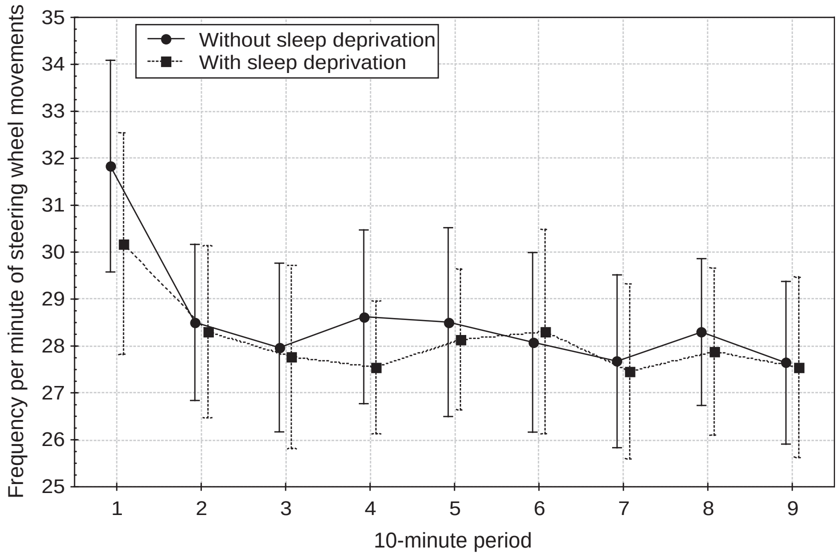

Fig. 5. Frequency per minute of small steering wheel movements as a function of sleep deprivation (with and without sleep deprivation) and of driving time (period 1–9) (means ± standard errors).

amplitude of small steering wheel movements increased significantly between the three first periods and the last three ($p<0.04$) (Fig. 4). Sleep deprivation did not influence effects of driving time on mean amplitude of small steering wheel movements [$F(8,144)=1.12$, n.s.].

3.3.3. Frequency per minute of small steering wheel movements

Frequency per minute of small steering wheel movements did not vary as a function of the driver's age [$F(1,18)=2.53$, n.s.] and sleep deprivation [$F(1,18)=0.35$, n.s.]. Frequency per minute of small steering wheel movements varied significantly with driving time [$F(8,144)=6.70$, $p<0.0001$]. Frequency per minute of small steering wheel movements decreased significantly between the first period and all the other periods ($p<0.002$) (Fig. 5); this decline certainly reflecting a learning effect. Sleep deprivation did not impact significantly with driving time on frequency per minute of small steering wheel movements [$F(8,144)=0.67$, n.s.].

3.3.4. Number of right edge-line crossings

Age had no significant effect on number of right edge-line crossings [$F(1,18)=0.18$, n.s.]. At the opposite, sleep deprivation had a significant effect on number of right edge-line crossings [$F(1,18)=5.13$, $p<0.04$]. This number was higher in the test after sleep deprivation (2.73 ± 3.81) than in the test without sleep deprivation (1.37 ± 1.85). Number of right edge-line crossing varied significantly with

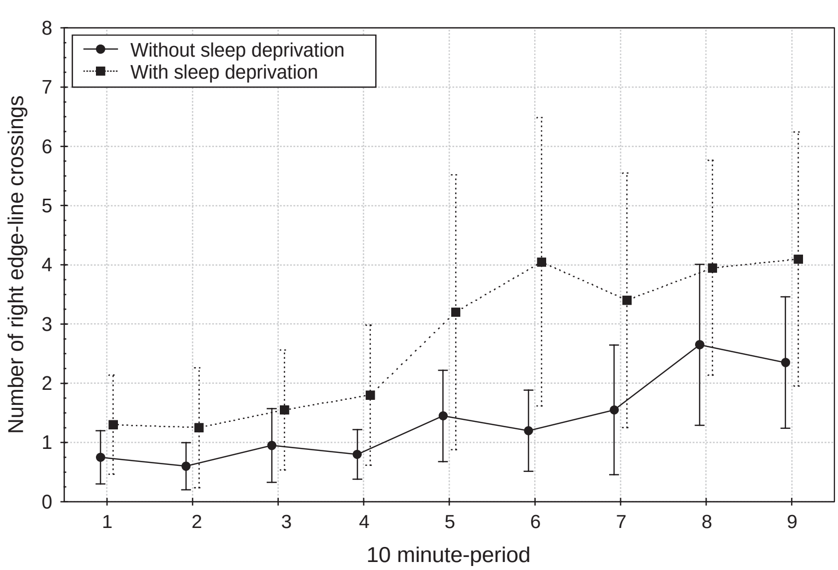

Fig. 6. Number of right edge-line crossing as a function of sleep deprivation (with and without sleep deprivation) and of driving time (period 1–9) (means ± standard errors).

Table 1
Correlation between spectral power in (alpha+theta) band and the four performance indices for the whole driving test and for the two sessions (with and without sleep deprivation)

	Spectral power of (alpha+theta) frequency band			
	Without sleep deprivation		With sleep deprivation	
	r	*p*	*r*	*p*
Standard deviation of lateral position	−.12	.65	−.21	.44
Mean amplitude of small steering wheel movements	.08	.74	.15	.58
Frequency per minute of small steering wheel movements	−.48	.06	−.37	.16
Number of right edge-line crossings	−.07	.79	−.27	.30

driving time [$F(8,144)=8.42$, $p<0.0001$]. Number of right edge-line crossing increased significantly between the two first periods and the last five ($p<0.05$) (Fig. 6). Sleep deprivation did not influence the effect of driving time on the number of right edge-line crossings [$F(8,144)=1.27$, n.s.].

3.4. Correlations between EEG data and driving performance indices

No significant correlation was observed between any driving performance indices and EEG data either in control or sleep deprived subjects (Table 1).

4. Discussion

Moderate sleep restriction during the night prior to the driving session interacted with the effect of time on task (driving periods) to amplify the decrease in the level of alertness and the occurrence of sleepiness, evidenced by the progressive increase of the spectral power in the (alpha+theta) frequency band. This interaction was also observed in the subjective assessment. Partial sleep deprivation increased KSS scores of our drivers, as in the study of Fairclough and Graham [30]. Recent papers point out the fact that subjects must be aware of their sleepiness [54,59]. In our study, drivers seemed to be aware of the deterioration of their level of alertness produced by time on task and sleep deprivation. However, we must not forget that subjects knew that they were under sleep deprivation and this fact may have influenced their assessment of sleepiness. Furthermore, by asking them to regularly estimate their degree of sleepiness their perception of sleepiness might be affected.

One night of partial sleep deprivation had just a mild effect on driving performance impairment. We have found no change for the standard deviation of lateral position, for the mean amplitude and for the frequency per minute of steering wheel movements. The only consequence of the sleep restriction on driving performance was a doubling of the mean number of right edge-line crossings. Our results have to be compared with those of Peters et al. [42], which found no change in lateral placement variance in a simulated driving task after a 4 h sleep deprivation but, an increase in the number of lane excursions. Fairclough and Graham [30] found that the effect of a partial sleep loss (4 h) has few consequence for driving performance. He found that the only evidence of impairment in the partial sleep deprived group was an increased frequency of near-lane crossings. They probably found an increased in the frequency of near lane crossings rather than in the frequency of actual lane crossings because the driving task had a moderate duration (40 min) and was composed of six driving scenarios, generating a task that was not really monotonous.

Thus, the schedule chosen in our study seemed too moderate to produce a great decrement in driving performance. What would have been the results if this partial sleep deprivation had been repeated for several successive nights? In fact, Thorne et al. [41] found no change in the crash rate after one night of partial sleep deprivation (3 h) but this rate significantly increased with continued nights of such sleep restriction (from the second night to the fifth night). Moreover, people are more confronted with chronic partial sleep deprivation [60] than just one full night of sleep loss. We could ask what would have been the degree of deterioration if the driving task had taken place during the primary trough (4 and 6 a.m.)?

The most important factor, which produced a great decline in performance, appeared to be the time on task. Sequential 10-min periods of analysis allowed study of the evolution of the performance but this analysis did not take into account the characteristics of the circuit sections covered in each 10 min. However, we think that we have compensated for this possible effect by the application of a threshold for each index. In fact, each circuit section drove in 10 min was not equivalent in term of overtaking number and of road geometry (right and left curved segments, straight segments). This is why, to calculate the standard deviation of lateral position, we used data of the right lane. This was also the reason of the use of a criterion to only study the steering wheel movements needed to adjust lateral position within the lane (comprised between 0.5° and 5°). We found that with time on task, standard deviation of lateral position, mean amplitude of steering wheel reversal, and number of edge line crossings increased. These results are in agreement with those of numerous studies [27–29,45] and clearly suggest that sleepiness negatively impacts on the driver's ability to maintain the car's trajectory.

We must not forget that theses results have been obtained on a driving simulator. Subjects knew that the consequences of their driving errors would not affect their safety. However, we could not, from an ethical standpoint, put our sleep-deprived drivers in a real driving situation. Moreover, simulators offered a number of advantages: a better control of experimental parameters, ability to measure many indices, and the possibility of confronting the drivers with a monotonous and long driving task, thus promoting the occurrence of the sleepiness and more risky driving [61] without dramatic consequence. Even, if there are some differences between results collected in a real driving situation and on simulated driving, we consider that the link between the evolution of driver's alertness and his performance would be equivalent in the two cases.

Our results tend to suggest that the modifications of the level of alertness (expressed by the power spectrum content variations) caused by sleep deprivation did not reflect themselves in a direct manner in the amount of deterioration of performance. This link is actually influenced by many factors [62], and particularly by the interindividual variability. In fact, the way the low-alertness reveals itself in a car driver depends on his driving experience and many other personal factors. Furthermore, according to Van Dongen et al. [63], there is a great interindividual variability in the vulnerability to impairment from sleep loss.

Confirmation of correlation between alteration of driving performance and physiologic low-alertness is nowadays a scientific challenge [51,52,64,65]. Actually, the idea of possessing a driver survey system capable of detecting or anticipating any deterioration in performance is attractive [44,66]. The difficulty in demonstrating a clear relationship between quality of performance and level of alertness in several subjects (with their many personal differences) was verified in our study. What appears easier to demonstrate is the temporal linear link between these two parameters. In fact, when the level of alertness decreased with time on task, driver's performance tended to diminish, but even this relation depended on the performance index considered, as the degree of deterioration will not be the same for all the indices. We are therefore still far from being able to describe general rules of driving activity in low-alertness state, without taking into account the numerous factors that influence these two elements.

Acknowledgements

This research was supported by the European community (Awake project: IST-2000-28062). The author wishes to thank subjects for their participation in the experiment, and the research technicians for their assistance.

References

[1] Akertstedt T, Folkard S. Validation of the S and C components of the three process-model of alertness regulation. Sleep 1995;18:1–6.

[2] Dijk DJ, Czeisler CA. Contribution of the circadian pacemaker and the sleep homeostasis to sleep propensity, sleep structure, electroencephalographic slow waves, and sleep spindle activity in humans. J Neurosci 1995;15:3526–38.

[3] Benoit O, Foret J. Circadian regulation of the sleep–wake cycle. Neurophysiol Clin 1998;18:403–31.

[4] Jewett ME, Dijk DJ, Kronauer RE, Dinges DF. Dose–response relationship between sleep duration and human psychomotor vigilance and subjective alertness. Sleep 1999;22:171–9.

[5] Lumley M, Roehrs T, Asker D, Zorick F, Roth T. Ethanol and caffeine effects on daytime sleepiness/alertness. Sleep 1987;10:306–12.

[6] Wesensten NJ, Belenky G, Kautz MA, Thorne DR, Reichardt RM, Balkin TJ. Maintaining alertness and performance during sleep deprivation: modafinil versus caffeine. Psychopharmacology 2002; 159:238–47.

[7] Santamaria J, Chiappa KH. The EEG of drowsiness in normal adults. J Clin Neurophysiol 1987;4:327–82.

[8] Makeig S, Inlow M. Lapses in alertness: coherence of fluctuations in performance and EEG spectrum. Electroencephalogr Clin Neurophysiol 1993;86:23–35.

[9] Strijkstra AM, Beersma DG, Drayer B, Halbesma N, Daan S. Subjective sleepiness correlates negatively with global alpha (8–12 Hz) and positively with central frontal theta (4–8 Hz) frequencies in the human resting awake electroencephalogram. Neurosci Lett 2003; 340:17–20.

[10] Akerstedt T, Gillberg M. Subjective and objective sleepiness in the active individual. Int J Neurosci 1990;52:29–37.

[11] Torsvall L, Akerstedt T. Sleepiness on the job: continuously measured EEG changes in train drivers. Electroencephalogr Clin Neurophysiol 1987;66:502–11.

[12] Rechtschaffen A, Kales A. A manual of standardized terminology, techniques, and scoring system for sleep stages of human subjects. Los Angeles: UCLA Brain Information Service; 1968.

[13] Valley V, Broughton R. The physiological (EEG) nature of drowsiness and its relation to performance deficits in narcoleptics. Electroencephalogr Clin Neurophysiol 1983;55:243–51.

[14] Carrier J, Monk TH. Circadian rhythms of performance: new trends. Chronobiol Int 2000;17:719–32.

[15] Mitler MM, Carskadon MA, Czeisler CA, Dement WC, Dinges DF, Graeber RC. Catastrophes, sleep, and public policy: consensus report. Sleep 1988;11:100–9.

[16] Dement WC, Gelb M. Somnolence: its importance in society. Neurophysiol Clin 1993;23:5–14.

[17] Dinges DF. An overview of sleepiness and accidents. J Sleep Res 1995;4(S2):4–14.

[18] Assecar-Sécurité Autoroute (ASA). Quinze ans de sécurité routière sur autoroute-Bilans et Perspective. Paris: Publication Assecar; 1995. p. 1–21.

[19] Horne JA, Reyner LA. Sleep related vehicle accidents. BMJ, Br Med J 1995;310:565–7.

[20] Haraldsson PO, Akerstedt T. Drowsiness—greater traffic hazard than alcohol. Causes, risks and treatment. Lakartidningen 2001;98: 3018–23.

[21] Garbarino S, Nobili L, Beelke M, De Carli F, Ferrillo F. The contributing role of sleepiness in highway vehicle accidents. Sleep 2001;24:203–6.

[22] Summala H, Mikkola T. Fatal accidents among car and truck drivers: effects of fatigue, age, and alcohol consumption. Hum Factors 1994; 36:315–26.

[23] Maycock G. Sleepiness and driving: the experience of UK car drivers. Accid Anal Prev 1997;29:453–62.

[24] Langlois PH, Smolensky MH, His BP, Weir FW. Temporal patterns of reported single-vehicle car and truck accidents in Texas U.S.A. during 1980–1983. Chronobiol Int 1985;2:131–40.

[25] Pack AI, Pack AM, Rodgman E, Cucchiara A, Dinges DF, Schwab CW. Characteristics of crashes attributed to the driver having fallen asleep. Accid Anal Prev 1995;27:769–75.

[26] Sagberg F. Road accidents caused by drivers falling asleep. Accid Anal Prev 1999;31:639–49.

[27] Riemersma JBJ, Sanders AF, Wilderwanck C, Gaillard AW. Performance decrement during prolonged night driving. In: Mackie RR, editor. Vigilance: theory, operational performance and physiological correlates. New York: Plenum; 1977. p. 41–58.

[28] Brookhuis KA, de Waard D. The use of psychophysiology to assess driver status. Ergonomics 1993;36:1099–110.

[29] Van der Hulst M, Meijman T, Rothengatter T. Maintaining task set under fatigue: study of time on task effect in simulated driving. Transp Res 2001;4(part F):103–18.

[30] Fairclough SH, Graham R. Impairment of driving performance caused by sleep deprivation or alcohol: a comparative study. Hum Factors 1999;41:118–28.

[31] Lenne MG, Triggs TJ, Redman JR. Time of day variations in driving performance. Accid Anal Prev 1997;29:431–7.

[32] Philip P, Ghorayeb I, Leger D, Menny JC, Bioulac B, Dabadie P, et al. Objective measurement of sleepiness in summer vacation long-distance drivers. Electroencephalogr Clin Neurophysiol 1997;102: 383–9.

[33] Devoto A, Lucidi F, Violani C, Bertini M. Effects of different sleep reductions on daytime sleepiness. Sleep 1999;22:336–43.

[34] Rosenthal L, Roehrs TA, Rosen A, Roth T. Level of sleepiness and total sleep time following various time in bed conditions. Sleep 1993;16:226–32.

[35] Gillberg M, Akerstedt T. Sleep restriction and SWS-suppression: effects on daytime alertness and night-time recovery. J Sleep Res 1994;3:144–51.

[36] Jewett ME, Dijk DJ, Kronauer RE, Dinges DF. Dose–response relationship between sleep duration and human psychomotor vigilance and subjective alertness. Sleep 1999;22:171–9.

[37] De Valck E, Cluydts R. Slow-release caffeine as a countermeasure to driver sleepiness induced by partial sleep deprivation. J Sleep Res 2001;10:203–9.

[38] Lenne MG, Triggs TJ, Redman JR. Interactive effects of sleep deprivation, time of day, and driving experience on a driving task. Sleep 1998;21:38–44.

[39] Brunner DP, Dijk DJ, Borbely AA. Repeated partial sleep deprivation progressively changes in EEG during sleep and wakefulness. Sleep 1993;16:100–13.

[40] Dijk DJ, Brunner DP, Borbely AA. EEG power density during recovery sleep in the morning. Electroencephalogr Clin Neurophysiol 1991;78:203–14.

[41] Thorne DR, Thomas ML, Sing HC, Balkin TJ, Wesensten NJ, Hall SW, et al. Driving-simulator accident rates before, during and after one week of restricted nightly sleep. Sleep 1999;21:S135.

[42] Peters RD, Wagner EK, Zlicandri E, Fox JE, Thomas ML, Thorne D, et al. Effects of partial and total sleep deprivation on driving performance. Public Roads 1999;62:2–8.

[43] Roehrs T, Beare D, Zorick F, Roth T. Sleepiness and ethanol effects on simulated driving. Alcohol, Clin Exp Res 1994;18:154–8.

[44] Verwey WB, Zaidel DM. Preventing drowsiness accidents by an alertness maintenance device. Accid Anal Prev 1999;31:199–211.

[45] Thiffault P, Bergeron J. Monotony of road environment and driver fatigue: a simulator study. Accid Anal Prev 2003;35:381–91.

[46] Harris W. Fatigue, circadian rhythm, and truck accidents. In: Mackie RR, editor. Vigilance: theory, operational performance and physiological correlates. New York: Plenum Press; 1977. p. 133–46.

[47] Kecklund G, Akerstedt T. Sleepiness in long distance truck driving: an ambulatory EEG study of night driving. Ergonomics 1993;36: 1007–17.

[48] Ranney TA, Simmons LA, Masalonis AJ. Prolonged exposure to glare and driving time: effects on performance in a driving simulator. Accid Anal Prev 1999;31:601–10.

[49] Philip P, Taillard J, Quera-Salva MA, Bioulac B, Akerstedt T. Simple reaction time, duration of driving and sleep deprivation in young versus old automobile drivers. J Sleep Res 1999;8:9–14.

[50] Hack MA, Choi SJ, Vijayapalan P, Davies RJ, Stradling JR. Comparison of the effects of sleep deprivation, alcohol and obstructive sleep apnoea (OSA) on simulated steering performance. Respir Med 2001;95:594–601.

[51] Risser MR, Ware JC, Freeman FG. Driving simulation with EEG monitoring in normal and obstructive sleep apnea patients. Sleep 2000;23:393–8.

[52] Campagne A, Pebayle T, Muzet A. Correlation between driving errors and vigilance level: influence of the driver's age. Physiol Behav 2004; 80:515–24.

[53] Khardi S, Vallet M. Drivers vigilance. Analysis of differences in vigilance states assessments by physiological and mechanical indicators. Conference proceedings of the first world congress on applications of transport telematics and intelligent vehicle-highway systems. 30 November–3 December, Paris, France; 1994.

[54] Horne JA, Baulk SD. Awareness of sleepiness when driving. Psychophysiology 2004;41:161–5.

[55] Horne JA, Östberg O. A self-assessment questionnaire to determine morningness–eveningness in human circadian rhythms. Int J Chronobiology 1976;4:97–110.

[56] Akerstedt T, Gillberg M. Subjective and objective sleepiness in the active individual. Int J Neurosci 1990;52:29–37.

[57] Jasper HH. The ten twenty electrode system of the International Federation. Electroencephalogr Clin Neurophysiol 1958:371–5.

[58] Gasser T, Bacher P, Mocks J. Transformations towards the normal distribution of broad band spectral parameters of the EEG. Electroencephalogr Clin Neurophysiol 1982 (Jan);53:119–24.

[59] Reyner LA, Horne JA. Falling asleep whilst driving: are drivers aware of prior sleepiness? Int J Leg Med 1998;111:120–3.

[60] Bonnet MH, Arand DL. We are chronically sleep deprived. Sleep 1995;18:908–11.

[61] George CFP. Driving simulators in clinical practice. Sleep Med Rev 2003;7:311–20.

[62] Vaugeois P. Effet de la vigilance sur la performance en conduite automobile. In: Bideau A, editor. Vigilance et transports: aspect fondamentaux, dégradation et prévention. Lyon: Press Universitaire de lyon; 1995. p. 350–4.

[63] Van Dongen HP, Baynard MD, Maislin G, Dinges DF. Systematic interindividual differences in neurobehavioral impairment from sleep loss: evidence of trait-like differential vulnerability. Sleep 2004;27: 423–33.

[64] Gillberg M, Kecklund G, Akerstedt T. Sleepiness and performance of professional drivers in a truck simulator—comparisons between day and night driving. J Sleep Res 1996;5:12–5.

[65] Lemke M. Correlation between EEG and driver's action during prolonged driving under monotonous conditions. Accid Anal Prev 1982;14:7–17.

[66] Brown ID. Driver fatigue. Hum Factors 1994;36:298–314.