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ORIGINAL ARTICLE

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On-road experiment for collecting driving behavioural data of sleepy drivers

Fahrversuch zum Erfassen von Verhaltensdaten bei schläfrigen Fahrzeugführern

Zusammenfassung Standardisierte Daten zum ungewollten Einschlafen bei gesunden Probanden wurden mit einem speziell ausgestatteten Fahrzeug unter realen Verkehrsbedingungen erhoben. Die Probanden fuhren unter normalen Bedingungen und mit ausgeprägtem Schlafentzug mit dem Versuchsfahrzeug. Der Versuch wurde durchgeführt, um neue Sensoren und Algorithmen zu testen, die in Zukunft kritische Situationen der Hypovigilanz beim Fahrer erkennen sollen. Die erhobenen Daten werden in einer strukturierten Datenbank aufgenommen und werden Interessierten zur Verfügung gestellt.

Die Datenaufzeichnung umfasste physiologische Signale (acht EEG, vier EOG, zwei EKG und zwei EMG-Kanäle) und Fahrzeugdaten (Fahrzeuggeschwindigkeit, Abstand vom Fahrbahnrand, Bremsdruck, seitliche Beschleunigung, Steuerwinkel, seitliche Geschwindigkeit).

Die visuelle Auswertung der physiologischen Daten ergab mehrere Fälle von schwerer Hypovigilanz. Die Analyse der Fahrverhaltensparameter zeigte signifikante Unterschiede zwischen Schläfrig- und Wachsein für die Standardabweichung des Abstandes zum Fahrbahnrand, die Standardabweichung der seitlichen Geschwindigkeit, der mittleren Fahrzeuggeschwindigkeit und der Standardabweichung der seitlichen Beschleunigung. Die seitlichen Positionsparameter konnten sensitiv die Hypovigilanz in realen Fahrsituationen erkennen. Die Fahrer tendierten dazu langsamer zu fahren, wenn sie schläfrig wurden. Dies ist möglicherweise eine Kompensation für die reduzierte Aufmerksamkeit.

Schlüsselwörter Fahrzeugführer, Hypovigilanz, Monitoring, EEG, Fahrzeuguntersuchungen

Summary An experiment was conducted with the aim of collecting standardised data on the involuntary transition from wakefulness to sleep from a number of healthy subjects while driving an experimental vehicle in real traffic conditions. Subjects drove the car, while being severely sleep deprived and under normal awake conditions. The main objective of this work was to collect data to verify future performance of innovative sensors and algorithms for the detection of critical incidents of a driver's hypovigilance. The collected data have been structured into a database, which can be assessed by those interested.

Recorded data included physiological measurements (8 EEG, 4 EOG, 2 ECG and 2 EMG channels) and vehicle data (vehicle speed, lane distance, brake cylinder pressure, lateral acceleration, steering angle, lateral speed).

Optical analysis of physiological measurements identified several cases of severe hypovigilance in the sleepy condition. Analysis of the driving behavioural parameters revealed a significant difference between the SLEEPY and AWAKE conditions for the standard deviation of the distance to lane, for the standard deviation of the lateral speed, for the vehicle mean speed and for the standard deviation of the lateral acceleration. Lateral position parameters are sensitive to detect hypovigilance in real traffic conditions. Subjects tended to drive at reduced speeds when sleepy, possibly as a compensation for their reduced alertness.

Key words driver's hypovigilance · monitoring system · EEG · vehicle measurements

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Introduction

Driver's sleepiness has been identified as a cause of fatal crashes and accidents on highways caused by car or truck drivers (Philip, 2005; Hakkanen and Summala, 2000). Driver sleepiness countermeasure devices should be developed so as to prevent errors which could lead to accidents (Lal and Craig, 2001). A number of measures have been reported in the literature and have been found to be sensitive and reliable indicators of drowsiness. These include brain wave activity (Lal and Craig, 2002; De Waard and Brookhuis, 1991; Akertstedt et al. 1991), eyelid closure and blinking (Wierwille et al. 1994) and heart rate and heart rate variability (Ako et al. 2003). Furthermore, results in the literature indicate that driving performance measures can also be used for monitoring alertness state (Brookhuis, 1993; Arnedt et al. 2000; Fairclough and Graham, 1999).

However, the feasibility of identifying any specific type of physiological and/or behavioural change, during the involuntary transition from wakefulness to sleep as a function of time of day and time on task, which could be used as a reference guide for monitoring the current level of subject's alertness, is rather questionable, mainly for two reasons. Firstly, because there is no such clear-cut between level of vigilance and type of behavioural outcome (Sanders & McCormick, 1992), and secondly, because there are large individual differences in the way fatigue and drowsiness are expressed (Fairclough & Graham, 1999; Brown, 1994). Another important constraint that also needs to be taken into consideration is that the pattern of performance decrement is highly dependent on the type of task requirements (e. g. detection vs. responding) and the context in which each task occurs (Gillberg & Akerstedt, 1998).

Thus, taking together the above constraints, it becomes rather self-evident that instead of trying to identify any simple behavioural unit as an individual index of the current level of vigilance, it is more fruitful to try to determine the main outline of the vigilance decrement process, as it is determined by the interaction of the measurable parameters of physiological and behavioural activity, considering the type of task and the contextual factors (Brookhuis, De Waard, & Fairclough, 2003; Johns, 2000).

The main objective of this experiment was to collect physiological and driving behavioural data from severely sleep-deprived drivers falling asleep at the steering wheel of an experimental car. A further objective was to create a databank of such data, so as to allow the verification of future sensors and algorithms for the detection of critical incidents of hypovigilance.

Currently there are some systems on the market or under research claiming to detect or predict sleepiness from one or several variables; however it is generally believed that no system is generally proven as accurate and reliable (Ackerstedt and Kecklund 2000). A non-obstructive system based on vehicle measures only would be more preferable by the driver. Sensors like cameras used to monitor the driver's eyes are also not fully reliable and they are expensive. Previous experiments conducted mainly in driving simulators have identified several vehicle-related measures which seem related to a driver's sleepiness. These include mainly measures of lateral position (Peters et al. 1999, Arnedt et al. 2000) and steering control (Fairclough and Graham 1999), while the sensitivity of speed control measures has not been consistently proven to be related to drowsiness (Haworth et al. 1988). The majority of previous studies have been performed in driving simulators, in which subjects were aware that their behaviour and possible errors would not have an impact on their safety. Indeed in a comparison survey made with sleepy drivers in real conditions and in simulator drivers in a simulator made more frequent line crossings and had longer reaction times (Philip et al. 2005).

Thus, another objective of this experiment was to examine whether vehicle-related measures previously found to be related to drowsiness in driving simulator studies are also sensitive when the drivers are driving in a real highway environment.

Method

Equipment used

The experiment was performed using the CERTH experimental car, in Thessaloniki, Greece, from June 6 to October 12, 2005. The experimental car is based on a Lancia Thesis 2.4 equipped as follows:

- Front obstacle detection radar, providing information about front obstacles (distance, relative speed).
- Lane recognition camera, providing information about vehicle position relevant to the lane.
- Eyelid sensor and software, providing information regarding eyelid movements which are useful to estimate level of a driver's hypovigilance.
- Electronic unit which collects information from the vehicle electronic system and exports them to the central PC for processing. Such information includes acceleration pedal position, brake cylinder pressure, vehicle longitudinal speed and acceleration, yaw rate, steering wheel angle, lights status, wipers status, external temperature, etc.
- Main PC to record and store all information as well as process it on-line.

For EEG recordings an ambulatory EEG monitoring system was used (Brain Vision Recorder, Version 1. 2. 0001) with an independent battery power supply time of approximately 3 hours. The system used for preliminary data browsing was the Brain Vision Analyser, Version 1.05.

The Eyelid Sensor (ELS), developed by Siemens, was also used during the experiment (Fig. 1). This is a standalone, real time (50 Hz) image processing system for detecting the driver's vigilance state, by measuring blink duration and blink frequency, composed of four main parts: a CCIR standard B/W camera turned 90° left, placed in the bottom of the dashboard which observes the driver's face through the steering wheel, two near infrared lightning (noninvasive light) devices, placed on the top of the dashboard at each side of the steering wheel that illuminate the driver's face, a PC-based ECU, placed in the trunk of the car that processes the images in real time for detecting the eyes and measuring the eyes opening. The opening signal of each eye is then analysed to identify simultaneous blinks and their duration.

Data from this sensor were also collected synchronously to the rest of the data, for cross-checking with the physiological data analysis.

Subjects

Subjects were recruited through advertisements in local newspapers. In total, 28 appointments were made. In one case, the medical doctor (M. D.) did not allow the subject to continue to the next experimental stage of driving the car due to arterial hypertension. In four other cases, the subjects did not come to CERTH and the experiment was cancelled. In another three cases, the subjects did not show enough signs of sleepiness during driving according to the EEG; thus they were excluded from the database.

Fig. 1 The ELS (EyeLid Sensor) system attached to the experimental car's panel

Procedure

Two pilot experiments were performed before the official experiment was started in order to detect and solve technical problems.

The experiment included two rides: First there was a ride under heavy sleepiness condition. If this was successful, namely there were indeed signs of sleepiness, then the subject was called after about two weeks for a second ride under normal alertness conditions. The two rides were scheduled for approximately the same time of day, so as to keep traffic conditions similar as far as possible. Subjects had to give their consent in writing before they could participate in the experiment.

Drive while sleepy

It was asked that the subjects stay awake the night before the experiment, and then to arrive at the CERTH premises at around 20:00. Initially, the subject signed a consent form of agreement to participate in the experiment and a standard medical examination followed by the medical doctor, who supervised the experiment.

Upon arrival and after passing the standard medical examination test, the subjects' level of sleepiness was estimated by using the Karolinska Sleepiness Scale (KSS) test, and their sleepiness behaviour was scaled by the M. D. using the Epworth Sleepiness test. The participants also filled in an entry questionnaire regarding personal data, previous involvement in sleepiness related incidents, period of not having slept, type and timing of last meal, drinks.

According to the Karolinska Sleepiness Scale test, an EEG measurement test was performed for 20 min in a quiet, dark environment. Eight EEG (Table 1), four EOG, two ECG, and two EMG channels were attached to the subject (Fig. 2) and afterwards an impedance checking procedure of the electrodes was followed. EOG recordings were based on two different leads (horizontal eye movements and vertical eye movements), in order to be able to separate eye blinks from vertical movements. The medical doctor did a brief estimation of subject's sleepiness according to the KSS and if the subject was judged to be sleepy enough, the actual experiment began.

Table 1 Recording channels for the EEG measurements. Notations included indicate electrodes' position, according to the 10–20 system. Placements A1 and A2, the mastoids (behind the ear), are used as reference. Subjects' ground was connected to the forehead

Recording channels					
1:	Fp1–A2	(EEG)	5:	Fp2–A1	(EEG)
2:	C3–A2	(EEG)	6:	C4–A1	(EEG)
3:	P3–A2	(EEG)	7:	P4–A1	(EEG)
4:	01–A2	(EEG)	8:	02–A1	(EEG)

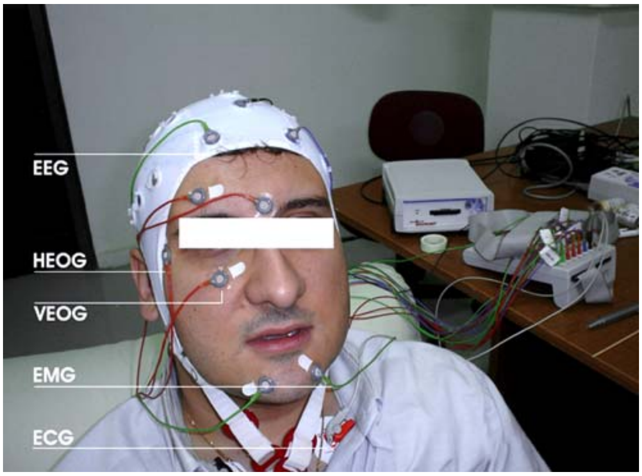


Fig. 2 The electrodes that were attached to the subject: 8 EEG, 4 EOG (2 bipolar), 2 EMG, and 2 ECG electrodes

The subject was seated in the driver's seat and the attached electrodes were connected to the ambulatory EEG monitoring system. Before each experimental session, an electrode-checking procedure was performed in the experimental car environment.

A sampling rate of 200 Hz, for all channels of the recording, with an amplitude range ± 20 µV was used. The hardware filters were adjusted to the band pass filtering option with a frequency range of 0.5 to 70 Hz, with a notch filter at the 50 Hz power supply component.

The ELS sensor measures the opening of the eyes, detects blink and eyelid closure and measures their duration and finally delivers one of three levels of drowsiness based on long blinks and eyelid closure. The algorithm used for diagnosis was specifically developed by the sensor manufacturer. During driving, the outputs of the ELS system were stored in the ELS PC installed in the vehicle, and include:

- Drowsiness level (DROWSY), according to the following:
  0: the driver is fully awake.
  1: the driver is slightly sleepy.
  2: the driver is very sleepy.
- PERCLOS, which is the ratio of the time eyes are more than 80 % closed over a 1-minute period.

During driving, the driving behavioural data were also collected at 10 Hz (see Table 2) through the research vehicle sensors and software and stored in ASCII files in the vehicle PC for further analysis. Each file is named according to the subject number and end time of recording. The reason is that the system time, stored in the file, is time in ms from start recording, thus in order to know the exact time, the end time should be known too.

Before each experimental session, the time synchronisation procedure for the three independent systems (physiological data monitoring system, ELS system, and driving behavioural data system) was performed. An experienced driving instructor was seated in the co-driver's seat (using double pedals if needed). In the back there was a technician monitoring the functioning of the recording equipment and a medical doctor monitoring the EEG. Every subject drove the research vehicle for a maximum of 1.5 hours on a motorway or until s/he stopped the test run by themselves. In several cases, subjects' sleepiness level during driving was very high, and the driver instructor stopped the measurements after three or more consecutive sleepiness events (unintentionally crossing the lane border). The traffic on the motorway was very low, and the task was monotonous enough to stimulate hypovigilance.

During driving, notes were kept in a specific log by the technician, who noted all events related to EEG activity

Table 2 The driving behavioural data which were collected during the experiment. The data acquisition sampling frequency for these data was 10 Hz

Driving parameter	Measurement unit	Comment
System time	ms	Starts from the start of recording of each file
Vehicle speed	km/h	Valid for speeds over 1.75 km/h.
Lane distance left	m	Has negative values. In lane change manoeuvre: It becomes 0 when the vehicle centre is over the left lane marker, then it becomes positive for a while, and then the system changes reference to the new lane marker, so it becomes negative again.
Lane distance right	m	Opposite to those for the left, it has positive values.
rpm	1/min	
Brake cylinder pressure	bar	
Lateral acceleration	m/s^2	
Steering angle	deg	Positive when the vehicle turns to the right.
Lateral speed to the left	m/s	
Lateral speed to the right	m/s	

(as indicated by the medical doctor), events related to ELS (as shown on the screen), events related to road/route deviations, behavioural notes (i. e. eyes closed for longer than normal, slow eye blinks) and driving instructor interventions (the last two types of events as indicated by the driving instructor). The persons accompanying the subject remained as quiet as possible. There was a mirror located in the front panel, so that the driving instructor could monitor the subject's eye blinking activity.

Originally it was planned to have KSS ratings by the subject every 5 minutes while driving. However, in praxis, this has been shown to decrease sleepiness levels, as was evident by the concurrent optical analysis of EEG recordings; thus this was abandoned.

Drive under normal alertness condition

In this case subjects were asked to arrive at CERTH at 19:00, so that the traffic situation was comparable to the previous ride, being at a normal alertness condition. In this case, only driving behavioural and ELS data were recorded, in the same way as for the previous ride.

Results

Subjects

Twenty subjects (19 males, 1 female) were selected for inclusion in the SENSATION database (see Table 3). The subjects were average drivers (mean driving experience: 11.2 years), with a mean age of 30.7 years.

Visual interpretation of the EEG identified microsleep events in 12 of the 20 subjects. In four cases, the driving instructor stopped the experiment after two consecutive unintentional crossings of the lane border. A total of nine severe driving errors occurred during the experiment, all during the last 15 minutes of each ride. There were also other minor events recorded by the driving instructor.

EEG data pre-processing and results

The data collected during all experimental sessions were transformed and stored in the EDF format. The physiological data were filtered according to the following settings:

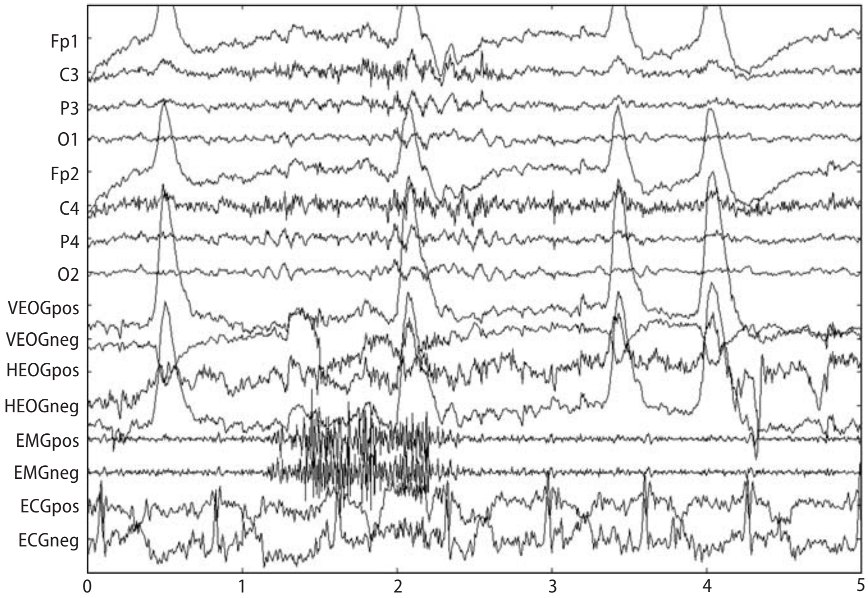
EEG data Band pass filtering (3rd order Butterworth filter), Band pass range: 0.5–45 Hz.
ECG data Band pass filtering (3rd order Butterworth filter), Band pass range: 0.1–15 Hz.
EMG data Band pass filtering (3rd order Butterworth filter), Band pass range: 20–80 Hz.
EOG data Band pass filtering (3rd order Butterworth filter), Band pass range: 0.1–13 Hz.

After physiological data filtering, the experimental data were divided into 5-second duration segments (Fig. 3). On these segments, the Independent Component Analy-

Table 3 Subjects included in the database

Subject	Gender	Age	Driver for (years)	Not slept for (hours)	ESS	KSS	MWST	Notes
1	Male	50	25	36	2	7	12.5	
2	Female	28	9	30	0	5	12.27	
3	Male	34	16	28	0	8	5	
4	Male	23	4	35	0	8	6.39	
5	Male	23	4	30	0	8	2	
6	Male	31	13	34	2	8	2.59	
7	Male	22	3	25	0	8	4	
8	Male	55	30	32	0	8	3.88	
9	Male	29	12	28	2	8	7.50	
10	Male	26	8	16	0	7	4	
11	Male	22	3	31	0	8	11.24	
12	Male	42	25	36	0	7	13	
13	Male	27	7	28	0	7	9.09	
14	Male	27	9	27	0	7	12.42	
15	Male	22	2	31	0	7	6.16	Bad driver, could not control the vehicle laterally
16	Male	23	5	30	0	8	8	
17	Male	49	23	26	0	8	7.2	
18	Male	24	4	25	2	7	2.42	
19	Male	32	10	38	1	7	10.88	
20	Male	25	7	21	1	7	4.88	

Fig. 3 The physiological data of a 5-s segment derived after the filtering procedure

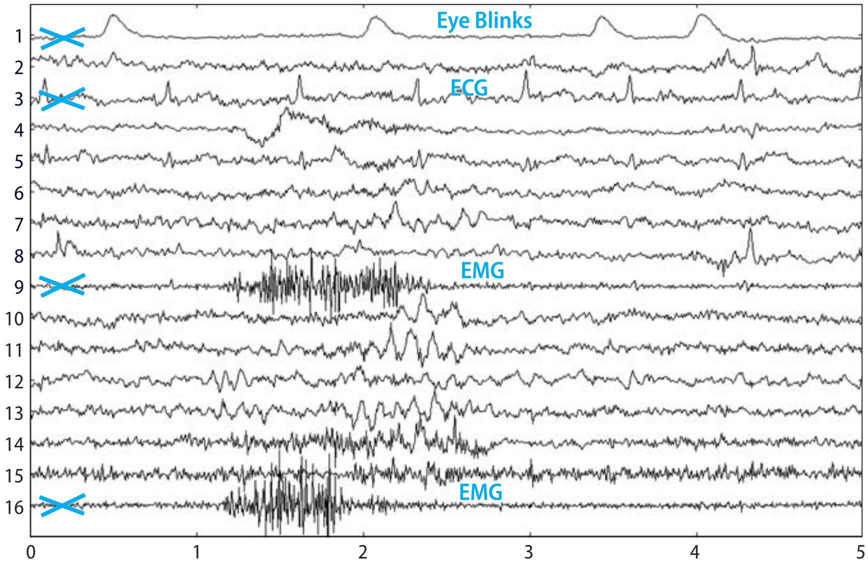


sis (ICA) technique was performed in order to remove the EOG component and muscle artefacts from the EEG measurements. For this procedure, EEGLab software was used and the whole analysis was performed using Matlab v 5.3. The physiological data segments were used as a data set and the Infomax algorithm was applied to this data set, deriving the independent components of the data set (Fig. 4). Afterwards, the components that were contaminated with eye blinks, eye movements or muscle activity were rejected and the remaining independent components were used for the inverse composition of the physiological signals segment (Fig. 5).

The EEG signals were divided into 3-second segments (containing 600 samples each) and for each segment and each channel the percentage of typical brain waves was estimated. More specifically, the percentage of delta waves (1–3.5 Hz), theta waves (3.5–7.5 Hz), alpha waves (7.5–12.5 Hz), beta (12.5–30 Hz) and gamma waves (30–40 Hz) were estimated. The brain waves percentage was estimated for a time window with size 600 samples (3 s) and 0.5 overlapping (the window was shifted 300 samples every time). The data analyses revealed the following observations:

- Significant increase of the theta band waves (in all EEG channels) by the end of the measurement (when the subject was more tired and sleepy).

Fig. 4 The independent components that were derived from the ICA Infomax algorithm applied to a 5-s physiological data segment. In the figure, the Eye Blinks, ECG, and EMG components have been recognised and removed from the decomposition procedure



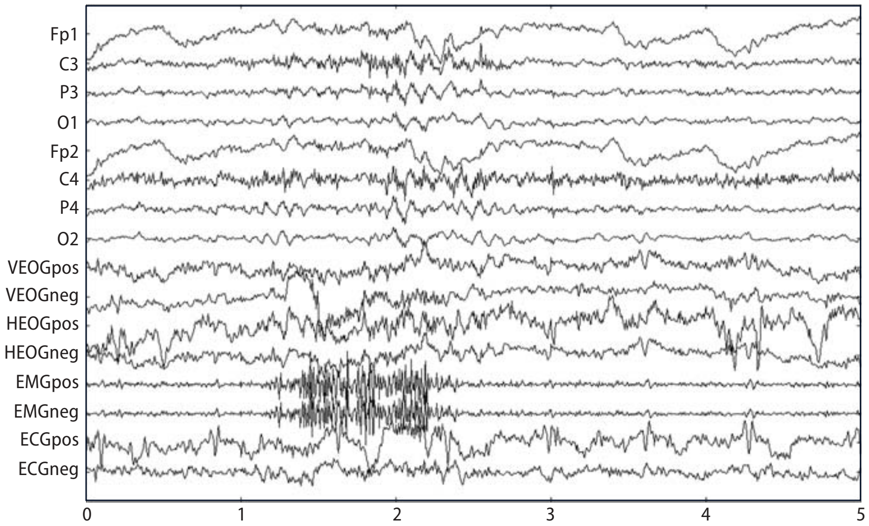


Fig. 5 The physiological data segment that was derived after the ICA artefacts removal procedure

- Significant decrease of the beta and gamma waves, especially in the vision cortex channels (O1 and O2) by the end of the measurement (when the subject was more tired and sleepy).
- Short-time variations of alpha band waves, but no significant change by the end of the measurement.
- No significant alterations for the delta band brain waves.
- Increase of EGG signal synchronisation among different channels before the driving errors.

The detailed analyses of electrophysiological recordings from this experiment have been presented elsewhere (Papadelis et al. 2007).

Driving behavioural data

In the following, we used ANOVA for statistical analysis. There was a difference between the standard deviation of the distance to the right lane among the sleepy awake conditions ($p = 0.067216$ for the distance to the right, Fig. 6).

There was a significant difference between the standard deviation of the lateral speed to left and right among the sleepy awake conditions ($p = 1.27\ 10^{-7}$ for the lateral speed to the left and $p = 1.62\ 10^{-7}$ for the lateral speed to the right, Fig. 7).

There was a significant difference between the mean longitudinal speed among the sleepy awake conditions ($p = 1.2\ 10^{-5}$, Fig. 8).

There was a significant difference between the standard deviation of the lateral acceleration among the sleepy awake conditions ($p = 1.02\ 10^{-8}$, Fig. 9).

Lane exceedances were not analysed. The reason is that the driving instructor was intervening in order to avert a possible lane exceedance due to safety reasons, as the experiment took place on a real highway with real traffic.

Conclusions

This experiment was performed in order to collect data for inclusion in an alertness monitoring database within

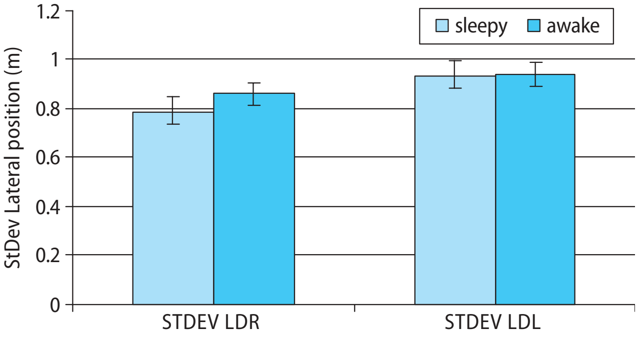


Fig. 6 Standard deviation of distance from the right and left lane

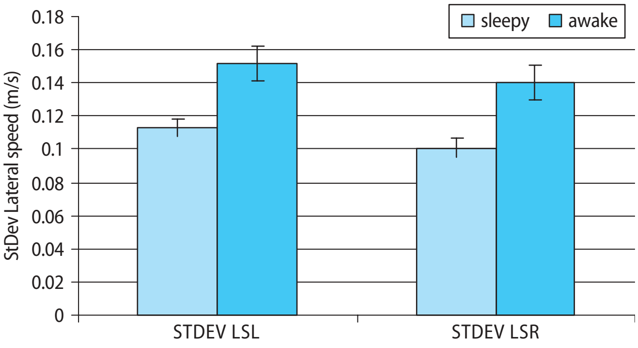


Fig. 7 Standard deviation of lateral speed to the right and left

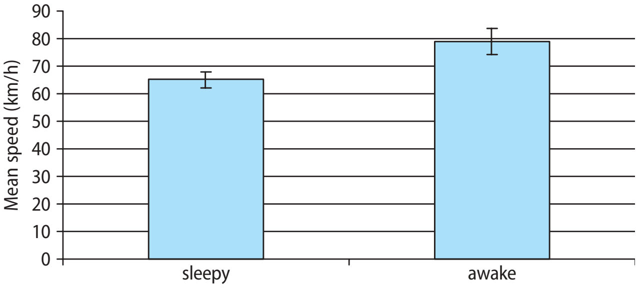


Fig. 8 Mean speed

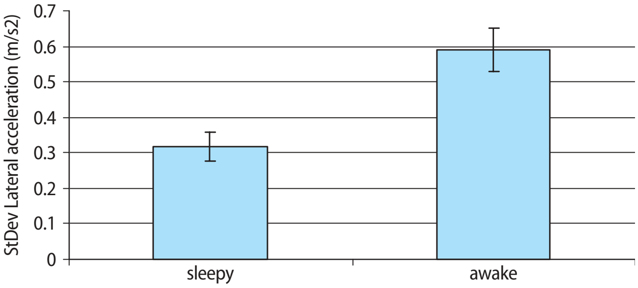


Fig. 9 Standard deviation of lateral acceleration

the SENSATION project. Recordings from 20 sleepy subjects were recorded and included in the database. Recordings include physiological data in the EDF format, ELS sensor output and driving behavioural data in the ASCII format. The subjects were indeed sleepy, as the analysis of physiological data reveals a number of events and micro-sleeps in each subject. Those subjects who were qualified to be included in the database were asked to drive once again at a normal awake condition, so as to obtain baseline recordings of their driving behaviour.

All the recorded data are available to interested sensor and system developers to verify their own algorithms and systems.

The analysis of the driving behaviour data between the two conditions reveals significant differences for standard deviation of distance to lane, which is in line with previous findings in the literature in driving simulator experiments (i. e. Peters et al. 1999). Moreover we found significant differences for the standard deviation of lateral speed and of lateral acceleration. Finally we found significant differences for mean speed, which is in line with the on-road study findings of Fairclough (1997), while contradictory to the findings of the simulator study of Peters et al. (1999). This difference could be because in the driving simulator drivers tend to drive faster at the cost of increased accident risk, knowing that no real harm would happen to them, while under real driving conditions self-adaptation to the reduced vigilance occurred by means of lower mean speed.

Vehicle measures have been reviewed in the past, mainly in simulator studies, and some of them have been found to be sensitive to hypovigilance. The present on-road experiment confirms that the standard deviation of distance to lane is a variable that can be used for developing a hypovigilance detection system that would be unobtrusive to the driver. The standard deviation of lateral speed and of lateral acceleration as well as the mean speed itself are sensitive to a driver's hypovigilance according to our results; thus a future system that would have a baseline profile of such measures from a driver could identify differences and detect hypovigilance. This is in line with the recent developments of various automotive industries, which are developing systems to unobtrusively monitor driver's vigilance based on lane position measures.

According to Dinges & Mallis (1998) the effectiveness, practicality, acceptance and consequence of a system monitoring driver's impairment should be properly evaluated. As with other driving support systems it should be studied whether a hypovigilance warning system may create unwanted changes in driving behaviour. It may happen that drivers tend to use warnings as "alarms" to wake them up when they fall asleep and continue driving even when they would otherwise have stopped for a rest. An issue that should be studied in the future is whether a warning system could create driver's overreliance to it thus having an adverse effect on traffic safety.

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