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Real driving at night – Predicting lane departures from physiological and subjective sleepiness[☆]

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ABSTRACT

Only limited information is available on how driving performance relates to physiological and subjective sleepiness on real roads. This relation was the focus of the present study. 33 volunteers drove for 90 min on a rural road during the afternoon and night in an instrumented car, while electroencephalography and electrooculography and lane departures were recorded continuously and subjective ratings of sleepiness were made every 5 min (Karolinska Sleepiness Scale – KSS). Data was analyzed using Bayesian multilevel modeling. Unintentional LDs increased during night driving, as did KSS and long blink durations(LBD). Lateral position moved to the left. LDs were predicted by self-reported sleepiness and LBDs across time and were significantly higher in individuals with high sleepiness. Removal of intentional LDs, enhanced the KSS/LD relation. It was concluded that LDs, KSS, and LBDs are strongly increased during night driving and that KSS predicts LDs.

1. Introduction

Driver sleepiness is a contributing factor to road crashes (Philip & Akerstedt, 2006). Most of the evidence, however, is based on retrospective self-reports of falling asleep events, or on the timing of the drive, or on prior sleep loss, that is, through inference. Very little is known about the details of physiological, behavioral and subjective changes in sleepiness leading up to a crash during real driving.

Simulator studies of night or early morning driving (after a night awake) show alpha/theta activity, slow eye movements or lateral variability to be increased before driving off the road (Anund, Kecklund, Peters, et al., 2008; Horne & Reyner, 1996; Lal & Graig, 2002; Otmani, Roge, & Muzet, 2005). However, there are no studies of real driving and sleepiness indicators that might predict crashes or other serious adverse events. The established knowledge about real driving and sleepiness indicators is that night driving leads to self-reported sleepiness (Åkerstedt et al., 2013; Sagaspe et al., 2008; Sandberg et al., 2011), and to inadvertent lane departures (Åkerstedt et al., 2013; Philip et al., 2005; Sagaspe et al., 2008). In addition, EEG alpha and theta activity, as well as blink duration are increased (Åkerstedt et al., 2013; Sandberg et al., 2011).

Studying physiological and subjective sleepiness indicators leading up to a real crash is obviously not feasible in a well-controlled study. However, studies of drivers in instrumented vehicles could link crashes to inattention/fatigue using video recordings of driver and road (Hanowski, Wierwille, & Dingus, 2003; Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). In a recent field experiment on 90 min of motorway driving it was shown that 40% of drivers during late night were taken off the road by the in-car driving inspector because of dangerous levels of sleepiness (Åkerstedt et al., 2013). This group of drivers also showed increased self-reported sleepiness and increased sleep intrusions in the EEG, compared to the control group.

An alternative approach is to study changes in sleepiness indicators leading up to lane departures, using the latter as a proxy for crash risk (Åkerstedt et al., 2013; Philip et al., 2005; Sagaspe et al., 2008), even if the validity of such an application is undocumented. Lane departures may be caused by many factors unrelated to sleepiness, however, like overtaking or avoidance maneuvers.

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These factors appear to have been removed in the existing studies (Åkerstedt et al., 2013; Philip et al., 2005; Sagaspe et al., 2008). Still, there might be other factors, for example, objects beside the road, the curvature of the road, or oncoming vehicles that the driver may slightly veer away from even if there is no objective risk of interference. These issues need to be addressed in order to arrive at a cleaner measure of sleep related *unintentional* lane departures. Prediction of lane departures is of interest for understanding the role of sleepiness in driving and perhaps for developing drowsiness monitoring systems. However the self-awareness of sleepiness is of particular interest with respect to the ability to refrain from sleepy driving, which is an issue of both legal and personal responsibility. It appears important to determine whether self-reported sleepiness predicts lane departures. This has not been studied in real driving, but simulator studies suggest such a link (Anund, Kecklund, Vadeby, et al., 2008; Reyner & Horne, 1998).

The purpose of the present study was to investigate the effect of night driving on unintentional lane departures and sleepiness indicators (EEG, EOG, self-reports), as well as to predict unintentional lane departures from such indicators. This also necessitated work to identify and remove different types of intentional lane departures.

2. Methods

2.1. Participants

43 subjects (21 females), aged 44 ± 8 years (mean ± sd) participated in the study. The participants were recruited by random selection of private vehicle owners (between 30 and 60 years) from the Swedish national vehicle register. The inclusion criteria included good self-reported health, absence of sleep disturbances, a minimum mileage of 5000 km/year, driving experience of more than five years, ability to abstain from caffeine and nicotine during the experiment, no medication, no glasses needed for driving, and a body mass index in the range of 18–27. No professional drivers or shift workers participated in the study. The subjects were compensated SEK3000 for their participation.

Before the experiment started, the subjects received written and verbal information about the study and signed an informed consent form. The study was approved by the Regional Ethical Committee in Linköping, Sweden (EPN 142-07 T34-09) and the use of public roads for experiments involving sleepy drivers was approved by the Swedish government (N2007/5326/TR).

2.2. Design

There were three time-of-day conditions: day (10.00–16.00), evening (16.30–23.00) and night (23.00–05.00). The order of the driving sessions was the same for all subjects, i.e. they arrived in the morning and completed all three sessions (day, evening and night) during the subsequent 24 h period. Each driving session was approximately 90 min long. Here, only the first and the last driving sessions have been analyzed.

2.3. Procedure

Three days before the experiment, the participants started to fill out a sleep/wake diary. The participants were instructed to sleep at least 7 h on each of the two nights before the experimental day and to go to bed no later than midnight and get up before 09:00. They were also asked not to drink any alcohol for 72 h before the experiment. On the experimental day the participants were asked to rise at 07:00. They were not allowed to drink any caffeine containing beverages after 07:00 until the end of the experiment. Before the drive the participants filled out a background questionnaire, informed consent form and a form acknowledging that they understood that they were responsible for the drive and that the test leader should be seen as a fall back in case of an emergency situation.

Three persons participated in the study each experimental day. They arrived one at a time. The first participant started his/her driving sessions approximately at 10:00, 16:30 and 11:00. The second and the third participant started their driving sessions about 2 and 4 h later, respectively.

When the participants arrived at the laboratory, they were (again) informed about the procedure, they were trained in the use of the KSS and they also had to take a breath alcohol test. The test leader then applied electrodes for EEG, EOG, EMG and ECG, which the participant had to carry during the entire experiment. The first driving session began as soon as the electrodes were applied. After the driving session the participant stayed in the laboratory while waiting for the two following driving sessions. Between the driving sessions they were allowed to read, watch TV, use the internet, take short walks in the building, etc. They were not allowed to sleep. The participants were served lunch, dinner and a light meal late at night. Fruits and caffeine-free beverages were available all the time. They were not allowed to eat sweets or drink soft drinks.

The participants were instructed to drive as they normally would do if they were alone in the car; however, they were also instructed not to exceed the speed limits. Before each driving session they were reminded about safety aspects, such as to use the main beam when appropriate. During the driving sessions, the participants were not allowed to drink, eat, use nicotine, listen to the radio, speak to the test leader or adjust the temperature or seat. They were allowed to stop for a short break if they felt it was necessary for their safety.

Before and after each driving session (and also during the driving sessions, see below), the participants rated their sleepiness on the Karolinska Sleepiness Scale (KSS). When the participants had completed all three driving sessions, they were sent home by taxi.

2.4. Instrumented car and test route

The vehicle used in the study was a Saab 9-3 Aero (model year 2008) which was instrumented with sensors and equipment for data logging. Driving data from the CAN network, such as speed, steering wheel angle, yaw rate, acceleration, etc. was continuously logged with a sampling frequency of 40 Hz. In addition, the vehicle was equipped with a GPS receiver, a camera based driver monitoring system (Smart Eye AntiSleep 3.2, Smart Eye AB, Sweden) and a lane tracker system (MobilEye N.V., The Netherlands) that provided lateral position data. The data acquisition system was monitored by a test leader, sitting in the backseat during the driving sessions. There was also a test leader in the front seat, who was prepared to take control of the vehicle in case the driver started losing control due to sleepiness. The vehicle was equipped with dual control brakes.

Physiological data (EEG, EOG, EMG and ECG) was acquired by a portable digital recording system (Vitaport 2, Temec Instruments BV, The Netherlands) that was synchronized with the vehicle's logging equipment by means of a common signal, logged in both systems.

Every five minutes, a small screen positioned on the dashboard to the right of the driver showed the text “Sleepy?” and the verbal descriptions for each stage of the Karolinska Sleepiness Scale. The driver then rated his/her average sleepiness for the past five minutes by saying the corresponding KSS value. The rating was registered by both test leaders (the test leader in the back seat registered the value directly into the computer data log).

The test route consisted of a two-lane rural road that was 9 m wide. The road was fairly straight and the traffic density varied from low (night) to moderate (afternoon). The posted speed limit was 90 km/h except for a few short road sections where the speed limit was lower (mostly 70 km/h but a few segments of 50 km/h were present, the latter also included passing through suburban areas). Subjects 1–21 drove 53 km before they turned and drove the same stretch of road in the opposite direction back to the starting point, while subjects 22–43 drove 62 km before they turned back. In total, the test routes were 106 and 124 km respectively, and took about 80–100 min to complete. It was always daylight during the day sessions and mainly dark during the night sessions (for some subjects it started getting light at the end of the night session). In the evening session, the lighting conditions varied, which was one of the reasons for excluding this session.

2.5. Measures

The participants rated their sleepiness using the modified version of the Karolinska Sleepiness Scale (KSS) with labels on all nine steps (Åkerstedt & Gillberg, 1990). The KSS scale ranges from 1 = extremely alert to 9 = very sleepy, effort staying awake, fighting sleep. Each rating refers to the preceding five-minute period.

Three EEG channels were recorded: Fz-A1, Cz-A2 and Oz-Pz. The EOG was recorded from both eyes, i.e. two vertical channels, and also one horizontal channel. The EMG electrodes were positioned on the lower cheekbone in order to capture muscle tensions (such as yawns) in the face. The ECG consisted of two electrodes on the trunk, i.e. one channel approximately corresponding to lead II. Silver cup electrodes were used for the EEG and disposable wet gel electrodes were used for all other signals. The sampling frequency was 256 Hz for the EEG, EMG and ECG, and 512 Hz for the EOG.

The EEG and EOG data were visually scored according to the Karolinska Drowsiness Score (KDS) procedure (Åkerstedt & Gillberg, 1990). The data were divided into 20-s epochs, which in turn were divided into 2 s periods. Each 2 s period was scored with regard to the presence of alpha (8–12 Hz) or theta (4–8 Hz) waves, or slow rolling eye movements. The number of 2 s periods containing sleep-related signs per epoch was converted to a percentage, i.e. if three 2 s periods within the same epoch showed sleep-related signs, the corresponding KDS value is 30%. In the analysis, the mean and maximum KDS values were used. EMG and ECG were not further analyzed.

Blink duration was extracted from one of the vertical EOG channels by using an automatic blink detection algorithm (Jammes, Sharabty, & Esteve, 2008). The algorithm low-pass filters the EOG data, calculates the derivative, and searches for sequences where the derived signal exceeds a threshold and falls below another threshold within a short time period. If the amplitude of the original, low-pass filtered EOG signal in such a sequence exceeds a subject specific threshold, the sequence is assumed to be a blink. To reduce problems with concurrence of eye movements and blinks, blink duration was calculated at half the amplitude of the