Driving performance impairments due to hypovigilance on monotonous roads

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Abstract

Drivers' ability to react to unpredictable events deteriorates when exposed to highly predictable and uneventful driving tasks. Highway design reduces the driving task mainly to a lane-keeping manoeuvre. Such a task is monotonous, providing little stimulation and this contributes to crashes due to inattention. Research has shown that driver's hypovigilance can be assessed with EEG measurements and that driving performance is impaired during prolonged monotonous driving tasks. This paper aims to show that two dimensions of monotony - namely road design and road side variability - decrease vigilance and impair driving performance. This is the first study correlating hypovigilance and driver performance in varied monotonous conditions, particularly on a short time scale (a few seconds). We induced vigilance decrement as assessed with an EEG during a monotonous driving simulator experiment. Road monotony was varied through both road design and road side variability. The driver's decrease in vigilance occurred due to both road design and road scenery monotony and almost independently of the driver's sensation seeking level. Such impairment was also correlated to observable measurements from the driver, the car and the environment. During periods of hypovigilance, the driving performance impairment affected lane positioning, time to lane crossing, blink frequency, heart rate variability and non-specific electrodermal response rates. This work lays the foundation for the development of an in-vehicle device preventing hypovigilance crashes on monotonous roads.

Key words: Monotony, Vigilance, Driving

1. Introduction

Driving a car is one of the most common, though fairly dangerous, tasks in industrial countries. Road crashes are the main cause of premature death of people younger than 45. The burden of crashes is counted not only in lives, life handicaps but also as a cost to the society. The road toll in Australia in 2005 was 1 627 fatalities for an estimated social cost of AUS $ 15 billion [2]. These figures are still of concern, though road safety interventions have improved the situation. Human errors contribute to around 90% of all crashes, and inattention to the forward roadway is often a contributing factor to crashes [1]. This suggests that the major effort to improve road safety should target countermeasures for driver inattention. However current measures focus mainly on safety devices, improvement of the road infrastructure, laws and regulations, but very little on human factors [11]. In Queensland inattention and fatigue (revealed in driver's lapses in vigilance) contribute to 6% and 5% of fatal road crashes respectively. Furthermore, inattention is the second contributing factor to all crash occurrences (12%) [24].

The driving task is complex and demanding and as a consequence, infrastructure authorities have attempted to simplify the driving task, for example through modifications to highways, while vehicle manufacturers have enhanced car design and equipment to improve comfort and safety (e.g. ABS, cruise control, power steering).

A consequence is that the driving task has been almost reduced to a lane-keeping task on highways and new types of crashes have emerged from these contemporary road safety interventions [6]. Drivers, particularly professional drivers, may suffer from the monotony of the driving task resulting in an increase in crash risk due to lapses of vigilance. It has been shown that if the driving task is highly predictable and uneventful then their ability to react to unpredictable events deteriorates [32]. Most fatigue crashes are recorded on roads of good quality, with few curvatures and which were supposedly designed to improve road safety [15, 32]. This raises the question of the role of monotony of the driving task in explaining vigilance related crashes.

The concept of monotony is typically entangled in the research with fatigue and hypovigilance. Nevertheless Thiffault and Bergeron [32]'s experiment demonstrated that driver vigilance decrement as indexed by subjective and physiological measures is more frequent in a monotonous environment, such as highways and rural roads. It is also estimated that 27% of city drivers having reported fatigue related to a road crash or incident did not feel tired prior to the incident and 35% felt slightly tired. Most of these drivers were driving on well known, repetitive routes. This phenomenon appears even more on rural roads where 45% of drivers involved in crashes reported that they were not tired at all prior to the incident and where road geometry are highly monotonous [14].

The aim of this study is to assess the effects of road monotony on driver vigilance and correlate it to impaired driving performance. This study focuses on two factors that decrease vigilance: (*i*) the road design (in terms of predictability) and (*ii*) the roadside environment (in terms of variability). An electroencephalograph (EEG) is used to monitor driver vigilance throughout a simulator experi-

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ment. The effects on vigilance decrement are then correlated to driving performance measurements.

In this experiment a simulated understimulating driving task was designed to isolate the effects of road monotony on driver vigilance. A driver simulator is used in order to ensure the safety of participants as well as control that participants are driving in the same conditions. This is done by creating four different road scenarios which enable all different combinations of high/low road design (geometry) and roadside variability. Road geometry is varied through the curvature of the road as well as its altitude. Roadside environment is varied through road signs, buildings and traffic frequency. Driving more than 30 minutes on monotonous roads has been shown to induce impairments similar to the one observed when fatigued. On the other hand fatigue due to time-on-task is observed after longer (more than one hour) driving tasks [32, 34, 11]. In this study each driving scenario is a short driving task of approximately 40 minutes. This disentangles monotony effects and fatigue due to time-on-task. Such a design enables us first to isolate and quantify effects of road monotony on driver vigilance. Then vigilance levels are correlated with measurements from the driver, the car and the environment. Such knowledge can then be combined with appropriate mathematical models in order to provide accurate real-time estimates of driver vigilance on monotonous roads. Various mathematical models can be used and a range of promising approaches can be found in Larue et al. [21]'s study modelling vigilance evolution during a short vigilance task.

2. Background

2.1. Effects of monotonous driving on vigilance

Driving requires sustained vigilance, i.e. the ability to maintain sustained attention within the road environment [32]. A lack of visual, motor or cognitive stimuli can alter the ability to sustain vigilance. Drivers experience vigilance decrement more frequently in monotonous environments, especially when driving on highways at night. Monotony has a mainly psychological effect on the driver [26] through its effects on alertness and results in a vigilance decrement. In fact the driver experiences boredom, drowsiness or loss of interest quite rapidly when performing an uneventful driving task. Monotony on its own can lead to vigilance lapses and to poor driving performance, independent of other factors [32].

2.2. Consequences of monotonous driving

Monotony related crashes occur mainly on highways (predictable, straight lanes) at night [32]. This can be explained by the fact that a hypovigilant driver is unable to react on time (or react at all) to critical events [18] such as going off the road. This occurs rapidly and thirty minutes of monotonous driving has been shown to be enough to induce vigilance impairment [16].

Both performing a monotonous task and driving in a monotonous environment have consequences on the driver's ability to drive. Indeed under such conditions the driver may quickly lose the motivation to perform the task and then become less vigilant [31]. Particularly the monotony of the road can result in passive fatigue, i.e. fatigue due to the demands of the driving task itself. The experiment by Oron-Gilad [22] shows that underload situations such as monotonous situations lead to fatigue symptoms and impaired driving performance although the drivers were neither tired nor sleep deprived prior to the driving task.

Driving performance is most seriously affected by short episodes of sleep occurring when the individual tried to stay awake, episodes called microsleeps [10]. However, decrement in performance occurs during reduced level of vigilance without microsleeps [10].

2.3. Individual differences in coping with monotonous driving

There is some variability between individuals' capacity to sustain vigilance. The profile of drivers more likely to be involved in vigilance-related crashes have been determined in a simulator experiment [31]. Extravert drivers need more stimulation changes, and as a consequence, they have less capability to perform a monotonous task. This disadvantage disappears with time [12]. Sensation seeking drivers need varied, complex stimuli and experiences. They take physical and social risks to reach such experiences. This sensation seeking level can be more or less developed but leads to risk taking driving, and negative reactions to monotonous driving [36]. Sensation seeking seems to be a good indicator of the driver's ability to focus on a monotonous task [31, 32].

2.4. Measuring effects of monotony on driving

2.4.1. Physiological measures

Effects of monotony are largely an impairment of cognitive functions of the driver and they can be detected through various physiological measures. Different types of technologies are used to detect such variations. Most of them are based on physiological measurements, such as the EEG [17]. They are presented in the following paragraphs.

Brain activity. The most reliable and reproducible way to observe psychological effects of monotonous driving is to use an EEG [18, 23, 33]. EEG signals are analysed in the frequency domain, and four different bands contain the information: α, β, θ and δ. It has been observed that EEG θ and α frequencies rhythms increase during monotonous tasks [18, 30]. The most reliable method to measure this variation is to use the following algorithm: $\frac{\theta+\alpha}{\beta}$. When increasing, this ratio between slow and fast wave activities indicate a decrement of alertness [20, 3]. Bursts are also of interest to detect increments in bands occurring relatively sparsely. It can particularly be used to detect microsleep following alpha and theta activities [11].

An EEG device cannot be used in a vehicle for at least three reasons: (*i*) the inconvenience for the driver, (*ii*) the prohibitive cost, and (*iii*) the noise introduced due to electromagnetic field interferences. Nevertheless, such a device can be used in a laboratory-based experiment so that correlation with driving performance (observed variables from the driver the car and the environment) can be isolated and investigated.

Eye activity. Driving is, to a very large extent, a visual vigilance task [8] so that various eye activity measures are correlated to the observed changes in EEG signals during monotonous driving. Research has shown that disappearance of blinks, mini-blinks and relative quiescence in eye movement are the earliest reliable signs of drowsiness, preceding slow eye movement and EEG alpha frequency and amplitude changes [25]. Blink duration and frequency increase during fatigue [4]. The PERcentage of eye CLOSure (*PERCLOS*) measures the percentage of time during which a driver has his eyes closed over a window of several minutes (usually 1 to 3 minutes). An eye closure is usually characterised by an 80% (sometimes 70%) closure of the eye compared to its nominal size. Fast blinks are removed ($time < 0.25s$) from the computation of the PERCLOS. Driver hypovigilance is then detected using a maximal eye closure threshold [9].

Eye activity can be followed using systems based on cameras. These systems are easily implemented in cars as they are unobtrusive (as compared to EOGs).

Heart activity. Heart rate, measured by electrocardiography (ECG), can be monitored to assess the individual physiological level of workload. Most studies show that the metric heart rate, if it changes at all, increases and the metric heart rate variability decreases during effortful mental processing [22]. It has also been shown that heart rate decreases significantly during a monotonous driving task [17].

Electrodermal activity. Electrodermal activity (EDA) is frequently used as an indirect measure of attention, cognitive effort, or emotional arousal [7]. EDA can be distinguished into tonic and phasic parts. The skin conductance level (SCL) is the tonic value and shows the continuity of activity over time. The skin conductance response (SCR) is the phasic part and reveals changes in skin conductance within a short time period [28]. SCR can be due to stimulus or non-specific causes. An increase in tonic EDA indicates readiness for action and an increase of phasic EDA indicates that one's attention is directed toward a stimulus [27, 29]. Skin conductance, in both tonic and phasic parts, is therefore expected to decrease during monotonous tasks.

2.4.2. *Driving performance*

Impairments of driver's cognitive abilities result in impairment of driving performance. This can be detected through various metrics related to the vehicle and the environment. Driving experiments have highlighted the driving measures that are the most impaired during monotonous driving.

Steering Wheel Movement (SWM) can be used to analyse the lateral control of the vehicle. SWM correlates with the effect of the monotony of the environment, particularly its standard deviation [32]. Another interesting indicator is the ability of the driver to position their car on the road in terms of lateral position (through its standard deviation) [22]. Another indicator of reduced vigilance is the difficulty of maintaining constant speed. This can be checked through the following metrics from the vehicle dynamics on the road: the average speed and the standard deviation of speed. It is also possible to assess it by the driver behaviour through the actions on pedals [22]. The limitation of such indicators is that they do not take into account the environment (road geometry) which has an impact on the steering wheel pattern. Thus such systems are limited to simple driving contexts and should be relevant in the case of a monotonous road design where the road is mainly straight. In the case of more complex road geometry, this indicator can be used on the road sections which are straight.

3. Experiment

3.1. *Participants*

Twenty-five subjects, 7 males and 18 females aged between 18 and 49 (mean age = 29.1 years, SD = 8.3), volunteered to participate in this study. Participants were recruited from the Queensland University of Technology (10 students younger than 25 and 15 staff members older than 25). Participants had their licence for a minimum of two years, drove a minimum of three days a week and drove a minimum of 100 kilometres a week. This is similar to previous research [5] so that potential differences due to age cannot be attributed to inexperience. All subjects provided written consent for this study, which was approved by the Queensland University of Technology ethics committee. Participants were paid AUS $80 for completing the four driving sessions; students undertaking the first year psychology subject received course credit for their participation.

The level of sensation seeking of participants was of interest although participants were not specifically recruited based on their level of sensation seeking. Of the 25 participants, 16 were average sensation seekers, 6 were high sensation seekers and 3 were low sensation seekers.

3.2. *Experimental design*

Monotony is multidimensional and mainly arises during a driving task due to task monotony (no need to check mirrors, change gear, brake, etc.) and environment monotony. Environment monotony results from a lack of stimulation which can occur in a driving context due to the road design (straight or presence of curves) and the roadside environment (quantity and variability of traffic signs, variability of the scenery).

In this experiment, four different scenarios were run (see Table I). In each experiment, the participant was asked to drive and respect road rules for approximately 40 minutes. The driving task was reduced to a lane keeping task to induce task monotony:

- driving consisted in following a lane (no itinerary involved) at constant speed (60 kilometres per hour), without having to stop the car (no red traffic lights, stops) or to brake a lot (no T intersections or perpendicular turns)
- no manual gear changes
- no need to change lane or indicate (turn signals)
- low traffic

Table 1: The four experiment scenarios

		roadside variability	
		low	high
road design variability	low	scenario 1	scenario 2
	high	scenario 3	scenario 4

Road geometry was varied through the curvature of the road as well as its altitude (see Figure 1). In the road design with low variability, the road was essentially straight or had few curves and was flat. Such a design was appropriate to model highways and some rural roads. In the road design with high variability the road was a sequence of small straight sections, significant curves and hills. This modelled urban roads and some rural roads.

The roadside design was done using the spots where most fatigue-related crashes occur (see Figure 1). The characteristics of these spots as well as pictures have been obtained from the Department of Main Roads Queensland (DTMR). The roadside environment was varied in terms of road signs frequency and variability and in terms of scenery (desert with bushes along the road, urban highway, rural road with houses, farms, industries etc.).

3.3. Materials

3.3.1. Driving simulator

Experimentation was conducted on the driving simulator Scaner from OKTAL. The road and environment were developed to fit the study requirements in terms of monotony (see section 3.2). The participant sat in front of a screen where the simulator is played using an RGB video projector. The simulator displayed a view of the road with a speedometer. The participant drove the simulator using a modified computer steering wheel which provided force feedback, and a two pedal set (brake and accelerator only). Five speakers reproduced the inside sound of a car environment.

3.3.2. Sensors

Any data related to the car or the environment was collected by the simulator. These data were collected by the use of a library of functions (speed, lane position, etc.) available through a user graphical interface. Data related to the driver required other sensors. Bioradio provided EEG data (seven channels) and ECG data (one channel). Facelab provided data related to the driver's eyes (eye movements, blinks, etc.). Biopac provided data related to skin conductance.

3.3.3. Synchronisation interface

Data collected from the simulator and the different sensors were synchronised using RTmaps. This software recorded and time stamped data from the different devices.

3.3.4. Questionnaires

Different questionnaires were used to determine drivers' profiles. The Eysenck Personality Questionnaire - Revised (EPQR) was used to define the driver's extroversion level [13]. The Sensation Seeking Scale - Form V (SSS) was used to obtain the participant's sensation seeking level (Zuckerman, 1994). Finally a general background questionnaire was used to control driving experience, sleep pattern and caffeine consumption.

3.3.5. Softwares

Data extraction was performed with Matlab version 7.4.0.287. Particularly, the EEGLAB v6.03b and Autonomic Nervous System Laboratory toolboxes have been used to analyse raw EEG, ECG and skin conductance data. Statistical modelling was performed with the software R version 2.5.0.

3.4. Procedure

Participants were tested individually in a quiet room in four sessions lasting approximately one hour each. Each participant drove in one of the four scenarios (randomly assigned) in the simulator once a week at a fixed testing time. Testing times were 9am (7 participants), 11am (5 participants), 1pm (9 participants) and 3pm (4 participants). Each participant chose a testing time for which they felt they would be the most alert. During the first session participants were asked to answer the questionnaires presented before. Then, for each of the four scenarios participants were given instructions about the nature of the experiment (that is to drive following the road rules, at the speed limit, staying in the same lane). A short practice was performed to familiarise the participant with the driving task on the simulator. Then the participant performed their scenario (about forty minutes) at the end of which they answered questions about their alertness at the end of the experiment.

4. Analysis A: Effects of road monotony and personality traits on vigilance decrement

4.1. Data analysis

Driver vigilance was assessed through analysis of data collected with the EEG. EEG data were collected at 7 different positions on the scalp (O1, O2, T5, T6, P3, P4 and F3) following the *International 10-20 Electrode Placement System* at 80 Hz and are divided into 1 second epochs. Epochs with too high/low values (threshold $\pm 75\,\mu V$), linear trends, improbable data and/or abnormally distributed data were rejected. A 4-term Blackman-Harris window and a 0.5 Hz cut-off high-pass filter were also used to reduce low frequency artefacts. Then Fast Fourier Transform (FFT) was performed. This provided α, β, θ and δ band activities. $\frac{\alpha+\theta}{\beta}$ was used as an energy ratio. When increasing, this ratio underlines an alertness decrease. These values were then averaged over the different locations in 10 second time windows. A mean value over the 5 first minutes was computed:

- the mean and standard deviation of $\frac{\alpha+\theta}{\beta}$. Energy values above 2 standard deviations were then categorised as high and correspond to decreased alertness.

- a threshold (1.5 times the mean) for α and θ bursts. Three consecutive epochs with values above the threshold were categorised as microsleeps.

Figure 1: Screenshots of the four scenarios

The 5 first minutes were used as a reference for comparison with the performance impairment throughout the driving. Finally, high energy values and microsleeps were counted over 120 second windows.

Vigilance was categorised into four levels: (*i*) level 1 similar to the 5 first minutes of driving, (*ii*) level 2 characterised by alertness decrement alone, (*iii*) level 3 defined by microsleep alone and (*iv*) level 4 with microsleep during a period of decreased alertness. Then a regression analysis was performed to link the effects of different parameters to the occurrence of alertness decrements and microsleeps. This analysis required the use of Generalised Linear Mixed Models (GLMMs) to take into account the correlation between repeated measures on the same participant (longitudinal study). GLMMs with multinomial logit regression were fitted to obtain the probabilities of the four different vigilance levels. The different predictors used were:

- road monotony: road design and roadside monotony
- time-on-task
- subjects factors: personality traits (SSSV, EPQR), testing time, driving experience, age, amount of sleep the previous night, usual sleeping times and caffeine consumption before the experiment.

Participants' personality traits were categorised into one of the following classes: low (less than one standard deviation (S.D.) in the available participants sample), normal (within one S.D.) or high (greater than one S.D.) [35]. Driving experience was categorised into inexperienced (driver has held licence for less than 5 years) and experienced (more than 5 years). Age was categorised following age brackets reported in government crash data: young (if less than 25) and middle aged (up to 49). Amount of sleep was categorised into less than 4 hours, between 4 and 6 hours, between 6 and 8 hours and more than 8 hours sleep. Caffeine consumption prior to the experiment was categorised into none, 1 to 2 hours ago, 2 to 4 hours ago and more than 4 hours ago. The participant's ID and the week were considered as mixed effects in the model.

The multinomial logistic regression could not be obtained directly using available statistical software. It was obtained through the combination of binomial regressions (three in this experiment). Therefore the linear combination of predictors could be factorised into three parts η_1, η_2 and η_3 with:

$$\begin{aligned} \eta_i = \alpha + \textstyle\sum_j \beta_j \cdot Monotony_j + \gamma \cdot Time\,, \quad i = 1 \ldots 3 \\ + \textstyle\sum_j \delta_j \cdot Profile_j \end{aligned} \tag{1}$$

where $Monotony_j$ is the level of road design/roadside variability and $Profile_j$ is one of the participant traits used as a predictor. The resulting probabilities for each level were:

$$\begin{cases} P\,[\text{Level } 1] = p_1 = \frac{e^{\eta_1}}{1+e^{\eta_1}} \\ P\,[\text{Level } 2] = p_2 = (1-p_1) \cdot \frac{e^{\eta_1+\eta_2}}{1+e^{\eta_1+\eta_2}} \\ P\,[\text{Level } 3] = p_3 = (1-p_1-p_2) \cdot \frac{e^{\eta_1+\eta_2+\eta_3}}{1+e^{\eta_1+\eta_2+\eta_3}} \\ P\,[\text{Level } 4] = p_4 = (1-p_1-p_2) \cdot \left(1 - \frac{e^{\eta_1+\eta_2+\eta_3}}{1+e^{\eta_1+\eta_2+\eta_3}}\right) \end{cases} \tag{2}$$

4.2. Results

Among the factors studied, the following were shown in this experiment to have no statistically significant impact (p-value $p > 0.05$) on the occurrences of alertness decrements or microsleeps: the EPQR scale, gender, testing time, age , driving experience, amount of sleep (both usual and the night preceding the experiment) and caffeine consumption before the experiment. The other factors influencing performance are given with their log-odds as well as their p-value in Tables II to IV: time-on-task, road design variability, roadside variability and sensation seeking level. All of these factors were statistically significant and had a noticeable impact on vigilance impairment. The main factors were the time-on-task and the level of road design monotony, these values depend on the sensation seeking level of the participant.

Table 2: Linear regression estimates for η_1

	Estimate	Std. Error	*p*-value
Intercept	1.23	$4.55 \cdot 10^{-2}$	< 0.01
Time	$-2.08 \cdot 10^{-2}$	$2.49 \cdot 10^{-3}$	< 0.01
Low SS†	$-3.63 \cdot 10^{-1}$	$8.44 \cdot 10^{-2}$	< 0.01
Low SS/roadside	$3.16 \cdot 10^{-1}$	$1.60 \cdot 10^{-1}$	0.05

† sensation seeker

Table 3: Linear regression estimates for η_2

	Estimate	Std. Error	*p*-value
Intercept	$-9.38 \cdot 10^{-1}$	$3.81 \cdot 10^{-2}$	< 0.01

Table 4: Linear regression estimates for η_3

	Estimate	Std. Error	*p*-value
Time	$6.69 \cdot 10^{-2}$	$6.99 \cdot 10^{-3}$	< 0.01
Low road design/time	$-3.78 \cdot 10^{-2}$	$9.49 \cdot 10^{-3}$	< 0.01
High SS†	$-3.86 \cdot 10^{-1}$	$1.52 \cdot 10^{-1}$	0.01

† sensation seeker

The evolution of the proportion of epochs characterised by the decreased alertness state ($p2 + p4$) is shown in Figure 2 for the four different scenarios designed in this experiment. Different curves are presented for the three different levels of sensation seeking. It can be observed that the proportion of epochs with high energy ratio increases throughout the experiment for scenarios 1 and 2 (from around 17% to 24%), while it remains fairly constant for scenarios 3 and 4 (at 17%). An increment in this proportion reveals decrement in alertness, and this is observed for scenarios characterised by a low road design variability. On the other hand the effect of roadside variability is very small. High and average sensation seekers performed approximately the same in this experiment. Low sensation seekers have a different trend for driving scenarios with high roadside variability. They have an offset of 5% at the start of the experiment. When the road is mainly straight, their alertness does not improve throughout the experiment, while their alertness increases on curvy roads to reach the level of the other groups of sensation seekers at the end of the experiment.

The evolution with time of the proportion of occurrences of microsleeps ($p3 + p4$) is shown in Figure 3 for the different driving scenarios.

Microsleeps doubled throughout the experiment, on average from 10 to 25%. Road design variability had no effect on microsleep occurrences. Roadside variability had an impact only for low sensation seekers, with an offset of 5% in the case of high roadside variability. Average and high sensation seekers had the same pattern for microsleeps. This suggests that during a low demanding driving task, microsleep occurrences tend to increase rapidly and almost independently of the road design or roadside variability.

4.3. Discussion

Monotonous road design is shown to have the most impact compared to monotonous road scenery. Also, during this low demanding driving task, microsleep occurrences tend to increase rapidly and almost independently of the road design or roadside variability. This monotony induced impairment driver should not be mistaken for driver fatigue due to sleep deprivation or circadian rhythms. Vigilance decrement on straight roads emerges quickly and increases as long as the task remains monotonous. Vigilance evolution over time during a driving task has not previously been studied and so these results are therefore novel.

No difference is observed in this experiment between medium and high sensation seekers. This research suggests that monotonous roads are of concern not only for high sensation seekers but also for average ones. This supports the need for a countermeasure efficient for a wide population. Particularly, assessing the level of sensation seeking for professional drivers would not result in a reduction of hypovigilance occurrences while driving. In this study low sensation seekers do not perform better than the other groups and perform even worse when the road design is not varied. Such results are unexpected and might be the result of the small number of low sensation seekers in our sample (3). Further investigation would be required to conclude on the effects of low sensation seeking on monotonous roads.

5. Analysis B: Correlation between vigilance level and driving performance

5.1. Data analysis

Episodes of reduced alertness and microsleeps - as assessed through the states presented in section 4.1 - can be correlated to different measures (surrogate measures) obtained from sensors which can be used in real cars (see details in section 2). All epochs of each participants are categorised into the vigilance levels described in the previous section. Values of surrogate measures are investigated by vigilance level in order to detect any correlation between the driving performance and the vigilance level.

5.1.1. ECG

ECG data were recorded at 80 Hz and were used to automatically extract the heart rate (HR), inter-beat-interval (IBI) and T-wave amplitude. Thresholds to detect peaks were manually adapted for each session of each participant. Unrealistic values obtained for IBIs were filtered using 500 and 1300 ms as lower and upper limits respectively.

5.1.2. Eye activity

Eye activity data were collected at 60 Hz. Blink frequency, blink duration, eye closure and PERCLOS were extracted by Facelab. PERCLOS was computed using a 75% threshold over a 3 minutes time window.

5.1.3. Skin conductance

Skin conductance was collected at 1 Hz. Skin conductance level (SCL) and non-specific fluctuations (NSF) were extracted. A threshold of 0.02 μS was used to find non-specific responses. NSFs were categorised by their rates, amplitudes, rise times and NSF half-recovery time.

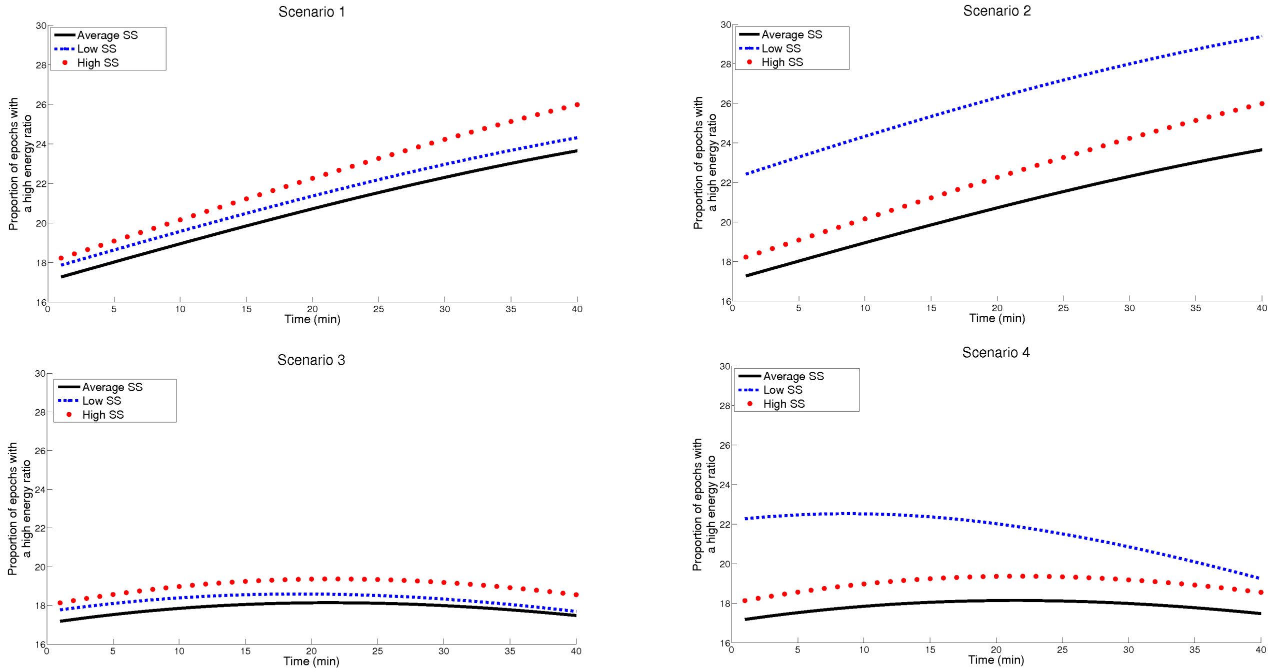

Figure 2: Evolution of the proportion (in percentage) of epochs with high energy ratio for the four different scenarios (taking into account the influence of the sensation seeking level SS of the participant)

5.1.4. Simulator data

Car and environment variables were obtained from the simulator. Simulator data were sampled at 20 Hz. Lane lateral shift, speed, steering wheel movement and Time to Lane Crossing (TLC) were used in this analysis. Only straight parts of the road were used to compute these metrics.

Each variable was normalised for each participant using the 5 first minutes of driving of each of the 4 sessions. This provided a reference for the assessment of impairment for each individual. For instance, the normalised heart rate $HR_{norm}(t)$ at time t was obtained from the heart rate $HR(t)$ at time t as follows:

$$HR_{norm}(t) = \frac{HR(t) - \mu_{HR}}{\sigma_{HR}} \quad (3)$$

where μ_{HR} and σ^2_{HR} are the mean and variance of the heart rate during the five first minutes of the experiment respectively.
To assess whether the driving performance was impaired in the different vigilance states a linear model was fitted on all these different metrics with the two factors *presence of alertness decrement* and *presence of microsleeps*.

5.2. Results

Factors associated with p-value $p > 0.05$ were considered to show no statistically significant correlation between vigilance state and an evolution of such factors. Statistically significant correlations are presented below and summarised in Table V. In this Table, the normalised value of each variable is presented for:

- episodes of good vigilance
- episodes of reduced alertness (hypovigilance)
- episodes of microsleeps.

The standard deviation of such estimate is reported in brackets. Episodes of good vigilance are used as a reference and values for reduced alertness and microsleeps are reported only when statistically different from this reference ($p < 0.05$).

5.2.1. ECG

This experiment showed that heart rate decreased from 0.10[1] to 0.00 in the case of alertness decrement.

No difference with the reference was observed in the case of microsleeps for heart rate and inter-beat-intervals.

Heart rate variability (SDNN) increased only when microsleeps occurred, from 0.07 to 0.16, while no trend was observed for the T-wave amplitude.

5.2.2. Eye activity

The analysis of eye activity data revealed that the blink frequency increased when the driver was in a low alertness state from 0.12 to 0.39. This trend was also observed during microsleeps, though with a smaller amplitude (increment to 0.26).

Eye closure followed the same trend as blink frequency, with similar impairment for reduced alertness and microsleeps with an increase to 0.16 from 0.05. On the other hand blink durations and PERCLOS were not impacted by the vigilance level during this experiment.

[1] This means that the average value observed in the reference level (no lapses in alertness as assessed with an EEG) is 0.10 standard deviations above the reference obtained during the first five minutes of driving.

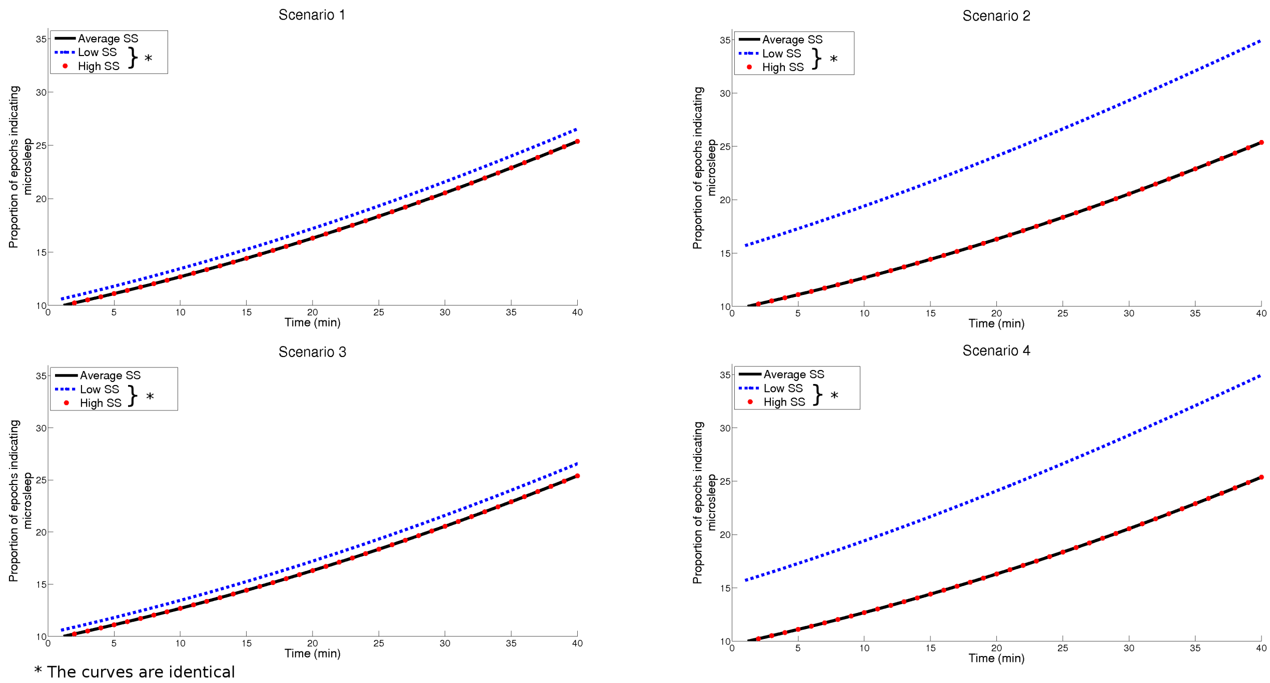

Figure 3: Evolution of the proportion (in percentage) of epochs indicating microsleep for the four different scenarios (taking into account the influence of the sensation seeking level SS of the participant)

5.2.3. *Skin conductance*

Most skin conductance metrics were shown to be correlated to the vigilance state in this experiment. Only the NSF amplitude did not change with the vigilance level. SCL diminished in the case of alertness decrement from 0.30 to 0.10.

The NSF rate seemed to be smaller during alertness decrement - −0.26 compared with −0.09 - whereas a small increase was observed during microsleeps.

NSF rise time and NSF half-recovery were impacted only during alertness decrement. The NSF rise time increased from 0.35 to 0.45, while the NSF half-recovery time increased from 0.33 to 0.40.

5.2.4. *Driving simulator data*

As for the data obtained from the car and the environment, it can be observed that the standard deviation of the lane lateral shift decreased from −0.04 to −0.20 in case of alertness decrement. The same trend was observed during microsleep with −0.09.

For the speed, an increase from 0.22 to 0.27 was obtained during microsleep. The standard deviation of the speed tended to decrease during alertness decrement: −0.28 compared to −0.22. But it led to a small increase in the case of microsleeps to −0.19.

In terms of the standard deviation of the steering wheel movement, only the alertness decrement had an effect, with a decrease from −0.11 to −0.28.

Finally the Time to Lane Crossing tends to decrease both during alertness decrement and microsleep with 0.12 and 0.18 compared with 0.29.

5.3. *Discussion*

This experiment shows that the vigilance classification presented in section 4 is correlated to the driving performance. Indeed the driving performance and some physiological markers of alertness are impaired when the alertness level as assessed by EEG is below the reference level or during microsleeps.
During an alertness decrement, the heart rate tended to decrease and as a consequence IBIs tended to increase. This suggests a reduced workload with no effortful mental processing. This was expected during monotonous driving since there is a low level of important information to process.

Eye activity was also importantly impaired. Blink frequency and eye closure were increasing while blink duration and PERCLOS remained the same. Eye closure increases only due to the higher rate of blinks since the PERCLOS remains constant (blinks are removed for the PERCLOS computation). These results are consistent with a hypovigilant driver as opposed to a drowsy or falling asleep driver using Lal and Craig [19]'s categorisations. Indeed drowsy and falling asleep drivers would also have longer blink durations and eye closure would also increase between eye blinks. Furthermore the effects of monotony on PERCLOS appear to be different from ones observed with fatigue. The use of PERCLOS to identify and warn drivers of the potential for a crash should be limited to fatigue and this study suggests that PERCLOS would not be efficient in the event of boredom.

Non specific electrodermal activity was reduced. This shows a reduced readiness for action. This suggests that driver's attention is no longer focused toward the task to perform (here a lane keeping task).

In terms of driving performance, the standard deviation of the lateral position of the car decreased. In the literature, this is expected to increase as the driver becomes less vigilant [32]. Indeed, the car tends to go closer to the edge of the road, and the driver takes more time to realise it and

Table 5: Effects of vigilance level on normalised surrogate measurements

	Vigilance level (from EEG)	Vigilant[†]	Hypovigilant	Microsleep
ECG	Heart rate	0.10 (0.01)	0.00 (0.03) ⇊	-
	IBI	−0.06 (0.01)	0.05 (0.03) ⇈	-
	Heart rate variability	0.07 (0.01)	-	0.16 (0.03) ↑
	T-wave amplitude	−0.09 (0.01)	-	-
Eye activity	Blink frequency	0.12 (0.02)	0.39 (0.07) ⇈	0.26 (0.04) ⇈
	Blink duration	−0.27 (0.02)	-	-
	Eye closure	0.05 (0.01)	0.16 (0.03) ⇈	0.16 (0.02) ⇈
	PERCLOS	−0.62 (0.01)	-	-
Skin conductance	SCL	0.30 (0.02)	0.10 (0.06) ⇊	-
	NSF rate	−0.09 (0.01)	−0.26 (0.03) ⇊	−0.01 (0.03) ↑
	NSF amplitude	0.32 (0.01)	-	-
	NSF rise time	0.35 (0.01)	0.45 (0.03) ⇈	-
	NSF half-recovery time	0.33 (0.01)	0.40 (0.03) ↑	-
Simulator	SD lane lateral shift	−0.04 (0.01)	−0.20 (0.03) ⇊	−0.09 (0.02) ↓
	Speed	0.22 (0.01)	-	0.27 (0.02) ↑
	SD speed	−0.22 (< 0.01)	−0.28 (0.02) ↓	−0.19 (0.01) ↑
	SD steering wheel	−0.11 (0.01)	−0.28 (0.03) ⇊	-
	TLC	0.29 (0.02)	0.12 (0.06) ⇊	0.18 (0.04) ⇊

Values in the Table are: **Normalised value (Standard Deviation)**

[†] reference

[-] no statistical difference with reference

↑ increment < 0.1 ⇈ increment > 0.1 ↓ decrement < 0.1 ⇊ decrement > 0.1

correct the car trajectory. On monotonous roads (in terms of road design), this standard deviation increases with time as it does for driver hypovigilance. An explanation of our result is that during the alertness decrement, the car moved toward the edge slowly, therefore leading to a small standard deviation. This is consistent with the observation that the standard deviation of the steering wheel movement decreased during that period and that the time to lane crossing diminished. These other measures suggest that the driver was inattentive. When the driver realised that the trajectory had to be corrected, they moved rapidly toward the centre of the road, which increased the standard deviation. The latter part is in fact included in the vigilant level (since it would be captured by the EEG). This explanation is supported by the fact that independently of the vigilance level, the standard deviations tended to increase with time, as was observed for the alertness decrement probability. Another possible explanation of these results is the fact that the standard deviation of the lane positioning increases in the literature when random lane deviations are generated by the driving simulator [32], which was not the case in this experiment.

During this alertness decrement, it was also observed that the speed was maintained more closely, which was the only result not consistent with a hypovigilant driver.

The state characterised by microsleeps was also consistent with driving impairment. During microsleeps, the heart rate variability increased. Heart rate variability is expected to decrease during effortful mental processing. This shows that mental processing is reduced during short lapses in vigilance, which is of great concern while driving.

These results were consistent with the reduced eye activity, similar to the one observed during decreased alertness. In terms of non-specific electrodermal responses, the only difference was a small decrease in NSF rate as compared with the decrease observed during alertness decrement.

The same trend was observed for the standard deviation of the lane position and for the time to lane crossing, but no trend was observed in terms of steering wheel variability. Speed tended to increase and to be more variable during microsleeps.

The vigilance states obtained from the analysis of EEG data were shown to be highly correlated to many measures suggesting a driver in a low vigilance state, with reduced ability to analyse the road surrounding them and with impaired driving performance. Therefore driver's inattention results in driving performance impairment which can be detected through measurements from the driver, the car and the environment.

6. Limitations

The research reported in this article features a number of limitations which should be acknowledged.

A relatively small number of participants is used in this experiment. However the sample size is statistically sufficient to study effects of monotony on a range of surrogate measures. Females and university students are over-represented in the samples used in this study. While the likely impact of such bias is unclear, it still represents a potential limitation. Nevertheless no statistical difference was observed between genders.

University student received course credit while other participants received money. Such methodology might have enhanced the boredom/monotony/lack of enthusiasm of students. Nevertheless participants were not told that the aim of the experiment what to monitor their alertness level during monotonous driving. It is unlikely that paying student would have increased their performance, since (*i*) the experiment was very repetitive and they had to do it four times (coming four times), (*ii*) the amount of money paid was not dependant on the performance and (*iii*) participants did not know what was investigated. Furthermore no statistical difference was observed for the group of participants paid and the group of participants receiving course credit.

Another limitation of this study is that participants were not asked to avoid drinking caffeine beverages before the study. Nevertheless, only four participants had a coffee less than two hours before the study (and more than one hour before the study). All other participants did not have any caffeinated drinks or more than two hours before the experiment. Moreover no statistical difference has been observed related to caffeine, which should insure the independence of the result to effects of caffeine.

The findings in this study supports that monotony contributes to changes in alertness in driving. Circadian rhythmicity and sleep restriction might be confounding variables since participants were not driving at the same time and their sleep before the experiment was not monitored (continuous or broken). Nevertheless no statistical difference associated with time-of-day or self-reported amount of sleep the previous night (all participants reported at least 6 hours of sleep) was observed.

7. Conclusion

The impact of monotony on driver vigilance has not been thoroughly studied, although it is an important factor contributing to crashes. This experiment shows that during a monotonous driving task two dimensions of monotony, namely the road design monotony and the roadside variability, can lead to a rapid decrement of the alertness of the driver. Such impairment is assessed with EEG analysis and is associated with increasing probabilities of alertness decrement and microsleeps as time increases. This is emphasised when the road design is mainly straight (as in the case of highways). Such inattention results in driving performance impairment which can be detected through measurements from the driver, the car and the environment. Such measurements include blinks, non-specific electrodermal responses rates, heart rate variability, variability of the lateral lane positioning of the car and the time to lane crossing. These measurements are consistent with symptoms of a hypovigilant driver with decreased driving performance. This experiment supports the vision to predict driver vigilance in monotonous driving conditions through surrogate measurements related to the driver, the car and the environment. Further research is required to model the occurrences of hypovigilance to allow their prediction in real time.

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