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Assessment of mental fatigue during car driving by using high resolution EEG activity and neurophysiologic indices

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Abstract— **Driving tasks are vulnerable to the effects of sleep deprivation and mental fatigue, diminishing driver's ability to respond effectively to unusual or emergent situations. Physiological and brain activity analysis could help to understand how to provide useful feedback and alert signals to the drivers for avoiding car accidents. In this study we analyze the insurgence of mental fatigue or drowsiness during car driving in a simulated environment by using high resolution EEG techniques as well as neurophysiologic variables such as heart rate (HR) and eye blinks rate (EBR). Results suggest that it is possible to introduce a EEG-based cerebral workload index that it is sensitive to the mental efforts of the driver during drive tasks of different levels of difficulty. Workload index was based on the estimation of increase of EEG power spectra in the theta band over prefrontal areas and the simultaneous decrease of EEG power spectra over parietal areas in alpha band during difficult drive conditions. Such index could be used in a future to assess on-line the mental state of the driver during the drive task.**

I. INTRODUCTION

It is largely know that driving a car requires a substantial cognitive effort and attention from driver's brain. According to the World Health Organization (WHO) the primary cause of death in adults from 18 to 29 years old, and the ninth cause of human death globally, is represented by car accidents (Preventing Road Traffic Injury: A Public Health Perspective For Europe, 2009). In fact, we all make mistakes, even when performing common everyday tasks we are used to. Depending on the contingent conditions in which the driver acts, errors can have a significant impact on the success of the performance or even on the safety of people. A situation like long distance driving of cars, busses or trucks in the highway requires attentive and cognitive resources that could be not at full disposal of the driver at the end of a working day. Hence, mental workload, fatigue and drowsiness assessments are really important for improving the road safety and, consequently, reducing car accidents. In fact, it is largely known that one of the major sources of road accidents is due to the drivers' drowsiness, with the relative cohort of lapses of attention during the driving. The analysis of EEG waveforms, and their decomposition in different frequency bands, have been often employed in the assessment of the variation of the internal state of the subjects during the execution of simple cognitive or sensory-motor task and it has been demonstrated by several studies that EEG is sensitive to fluctuations in vigilance and has been shown to predict performance degradation due to sustained mental work. The most prominent event is the increase of the EEG power spectrum in the theta frequency band over the prefrontal, frontal and parietal cortex, often located in a midline scalp position [1][2]. EEG spectral power in alpha band has been also reported to decrease during complex and cognitive demanding tasks. Such decrement occurs over different scalp areas such as the fronto - central and the parietal ones [3]. These results suggested to define a workload index by using the variation of theta and alpha synchronization and, therefore, of their Power Spectral Density (PSD). In addition, we used also other neurophysiologic signs of mental activity and engagement during drive, such as the measurement of the heart rate (HR) and the eye blink rate (EBR). Both of these variables have been demonstrated to be correlated with the mental engage of the driver during the performance. In particular, it has been suggested that increased HR could be related with an increased mental workload while eye blinks (namely duration and frequency) are inversely correlated with the increase of the mental workload of the drivers [4].

II. MATERIALS AND METHODS

A. *Subjects*

The subjects were selected by their ages, driving experiences (i.e. possession of their driving license), cars that normally they used to drive (i.e. manual gear and not automatic one) and physical conditions. All the subjects were prohibited to drink alcohol and to have heavy meals for one day prior to the measurements, and they were asked to avoid caffeine, tea or chocolate consumption 5 hours before the experiment. They were volunteers and experimental instructions were provided at the beginning of the experiment.

B. Experimental protocol

The experiments were performed between 2 PM and 5 PM because day time sleepiness tends to increase during those hours [5]. The experimental protocol is developed along 2 days. The selected track was the Spa – Francorchamps (Belgium) and the car by which performing the driving tasks was the Alfa Romeo – Giulietta QV (1750 TBi, 4 cylinders, 235 HP). The first day was for training the subject with the driving simulator and for familiarize with the task of alert and vigilance (TAV). The alert stimuli, a white "X", were presented on a monitor placed 70 (cm) from the subject just a little below the frontal direction, avoiding

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the interference with the main screen. The vigilance stimuli were presented by two speakers placed on the left and on the right side of the driver (Fig. 1). On the second day the subject had to perform the selected track under different conditions with the priority of the vehicle control; any condition was a race of 2 laps. In the first condition (TASK_0 – day time) the subjects did not receive any requirements and they were told to do the laps normally, as the prior day. From these laps, a baseline time was acquired and in the second condition (TASK_1 – day time) the driver had to perform the race reducing of the 2% the baseline total time. The TASK_2's requirements were like those of the TASK_1 but performing at the same time the TAV. The subject could reply to the TAV stimuli by pressing the button placed on the sides of the steering wheel; the button number 1 (left side) for the vigilance stimuli and the button number 2 (right side) for the alert stimuli. This condition was for enhancing the workload; the alternating tone sequence of the vigilance task simulated the car's radio and the target tone sequence was a phone calling that the driver had to answer as quickly as he felt it is safe to do so. The alert's stimuli simulated the traffic jam, for example, the traffic lights, the pedestrians, other cars or other uncontrollable and unpredictable traffic agents [6]. The fourth and fifth conditions, TASK_3 and TASK_4, were equal to the TASK_1 and TASK_2, respectively, but in the night time. The last condition was a monotonous night driving, in which the subject had to drive, on the same track, very carefully without exceeding the speed of 70 (Km/h).

Figure 1. The experimental protocol consisted in driving the Alfa Romeo Giulietta QV on the Spa – Francorchamp (Belgium) trak under different conditions. The different experimental conditions have been set up for ehnancing the workload, by performing the TAV, and for promoting drowsiness, by asking the subject to drive slowly with a speed limit.

This monotonous task was for making the driver drowsy. Since the previous task, the drivers used to drive almost fast and for this reason the requirement of the speed limit was monotonous enough to promote drowsiness or hypovigilance. At the end of each condition the subject had to fill the NASA-TLX questionnaire for the subjective workload assessment. The TAV performance and the telemetry were evaluated by analyzing the log files in which reaction times, correctness of answers and driving parameters were recorded automatically.

C. *EEG and physiological recording*

Electroencephalogram (EEG) and physiological signals, eye blinks and electrocardiogram (EKG), were recorded by a digital ambulatory monitoring system (Brain Products GmbH, Germany). Sixty-one channels EEG and one EKG channel were collected simultaneously during the experiment with a sampling frequency of 200 (Hz). All the electrodes were referenced to both the earlobes and the impedances were maintained around 10 (kΩ). Electrode for the heart activity was positioned on the Erb's point. A 50-Hz notch filter was applied to all measurements for removing power interference. The EEG recordings was also band-pass filtered (low-pass filter cut-off frequency: 40 (Hz), high-pass filter cut-off frequency: 1 (Hz)) and then the Independent Component Analysis (ICA) was used in order to remove the artifacts from the data. By the separation of the independent sources, the eye blinks component was analyzed for the estimation of the eye blinks rate (EBR), while the EKG raw signal was used for estimate the heart rate (HR).

D. *High resolution EEG cortical estimation*

Cortical activity from EEG scalp recordings was estimated by employing the high-resolution EEG technologies, including the use of quasi-realistic head model, estimation of cortical sources by solving the EEG linear inverse problem with distributed sources, and statistical parametric mapping of significant increase or decrease of EEG spectral activity over the cortex [7-12].

E. *Neurophysiologic indexes for characterizing drowsiness and mental fatigue.*

In the following, we used two major cerebral indices to characterize drowsiness and the occurrence of mental fatigue in drivers during the driving tasks. For all concerns drowsiness recently, the detection of EEG alpha spindles, defined as short burst in the alpha band was suggested as an objective measure for assessing the driver's fatigue during real driving conditions when compared to the normal EEG spectral analysis [13]. The occurrence of these bursts is also consistent with driving error events. Before such events neurophysiologist posed few criteria, according to their observations, which can characterize the potential driving errors as follows "at least 10 (sec) before the driving error event, alpha synchronization bursts from the lower limit of alpha waves gradually to theta waves" [14]. Alpha bursts have frequency between the higher portion of the theta band and the lower portion of alpha bands, 7 – 9 (Hz), with a gradual increase of amplitude. As to topographical distribution, these bursts are more dominant in the central and parietal areas. We then checked the occurrence of such EEG events before the drowsiness-induced drive errors (Fig. 2). It has been previously noted as EEG power spectra increase in the theta band could be correlated with the insurgence of mental fatigue. In this work it has been defined a workload index (IWL) as the ratio between the theta psd in the frontal EEG channels (F3, Fz and F4) and the alpha psd in the parietal channels (P3, Pz and P4) for the left side (F3/P3), central line (Fz/Pz) and the right side (F4/P4) of the brain. The EEG bands were defined by the Individual Alpha Frequency (IAF) [15].

III. RESULTS

A. *Visual interpretation of the EEG*

Fig. 2 shows an example of the occurrence of EEG alpha burst (circled in red) occurred during the monotonous driving task (TASK_5) as signal of drowsiness and reduced vigilance. Subjects after the appearance of such particular EEG patterns drove off from the correct trajectory lane with an high statistical occurrence when compared to the drive errors performed during standard driving conditions ($p<0.05$). In agreement with the previous observations, also in our case the major occurrence of such EEG bursts were located in subjects over the centro - parietal scalp areas.

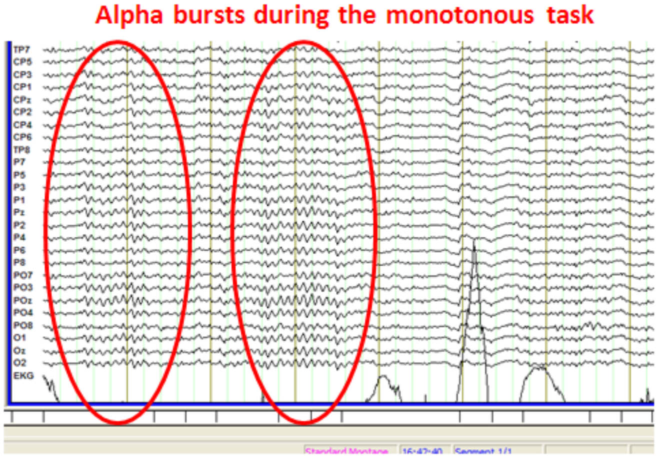

Figure 2. Alpha bursts (circled in red colour) occurred during the monotonous driving task condition (TASK_5) as signal of drowsiness and reduced vigilance. These bursts are more dominant in the central and posterior EEG channels.

B. *Workload index*

Fig.3 shows an example of how the employed workload index changed during the different experimental conditions, respect to the rest condition (TASK_0). For example, in the central brain region and in the alpha2 band, the conditions in which the TAV was performed (TASK_2 and TASK_4) have the highest index's values and the monotonous task (TASK_5) the lowest. This was true for almost all sub-bands, especially in the central and left brain regions.

C. *Heart and eye blinks rate*

A significant decrease of heart rate (HR) and an increase of eye blinks rate (EBR) have been observed in the comparison between all the driving conditions and the monotonous drive condition (TASK_5) in all the subjects studied ($p<0.05$, corrected for multiple comparisons). Fig. 4 shows an example in a particular subject of how the HR increases (blue line) during the occurrence of high workload conditions, passing from a quite driving (TASK_0) to situations in which there are specific requirements, for example improving the driving performance (TASK_2) or doing the TAV in the night time (TASK_4). The lower magenta line shows how the EBR inversely correlates with difficulties of the driving tasks. In fact, the lower the difficulty of the task, the greater is the value of EBR; in fact, the highest EBR's value was obtained during the monotonous driving condition and the lowest during the execution of the TAV in the night time.

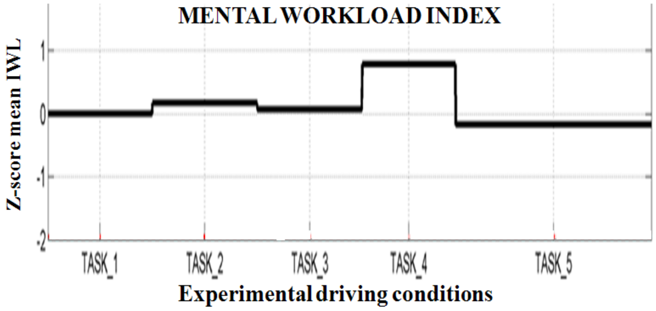

Figure 3. The workload index reflects the mental engagment for the task faced during the different experimental conditions. As the difficulty of the task increase, the higher was the IWL's value. Note that as during the TAV conditions (TASK_2 and TASK_4) the index has highest values and how during the monotonous task (TASK_5) the index has the lowest one.

D. *Estimation of cortical activity*

In (Fig. 5) are shown examples of cortical maps relative to the theta psd differences (statistically significant, $p<0.01$) between the rest task (TASK_0) and the task with the TAV during the day time (TASK_2), on the top of the image and between the rest task and the monotonous condition (TASK_5) in the alpha band, on the bottom of the image. The red colour means that the difference (TASK_2/TASK_5 – TASK_0) is positive, while the blue colour means that the difference is negative. The red colour means that the psd of the considered task are greater than those of the rest condition, thus it is possible to see how with the TAV the theta psd increases and during the monotonous task the alpha synchronization increases respect a normal driving condition.

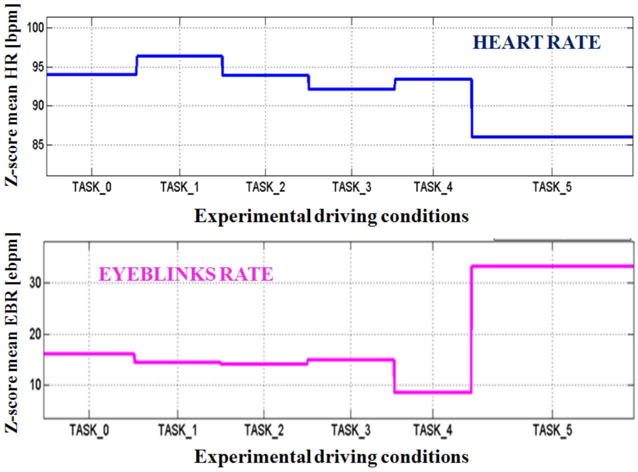

Figure 4. The HR (blue line) and .the EBR (magenta line) have been demonstrated that are correlated with the occurrence of the workload; the HR increases with the workload and it decreases in monotonous and droswy conditions (TASK_5). On the contrary, EBR is inversely correlated with the increase of workload.

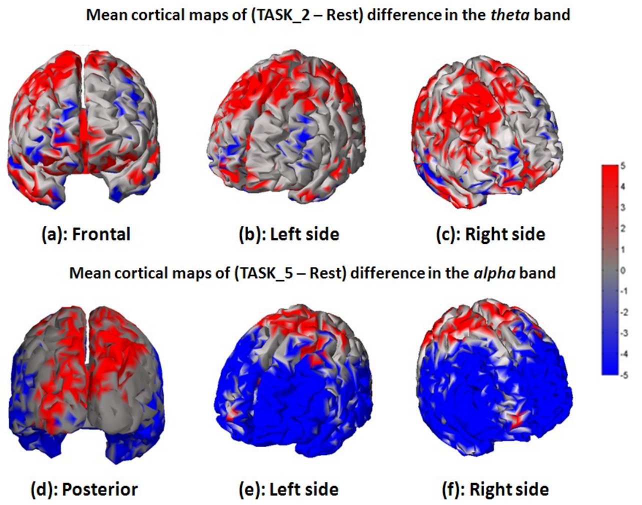

Figure 5. Mean cortical maps reflecting the psd theta differences (statistically significant, $p<0.01$) between the rest task (TASK_0) and the task with the TAV in the day time (TASK_2), on the top (views a, b, c) and between the rest task and the monotonous condition (TASK_5) in the alpha band, on the bottom (views d, e and f). conditions. View (a) is a frontal perspective, while view (d) is a posterior perspective.

IV. DISCUSSION

The results show how these neurophysiological signals could help the assessment of the driver's mental and physical status, as drowsiness and alertness for the various driving conditions and how they are correlated with the driving performance. A common trend has been found; the higher task's difficulty, the higher the IWL and HR values, the NASA-TLX scores, the TAV errors, the mean reaction times (RT) and the driving errors (off road). In addition, the EBR decreased with the increase of difficulty and it decreased during the monotonous condition.

The present study illustrates the development of a cerebral mental workload index based on EEG data, and the integration of its information with those of the autonomic indexes, such as heart rate and the eyeblinks rate. The proposed workload index could be estimated in a near future in "real-time" system and could be eventually integrated inside the car to provide a feedback to the user about its internal cognitive conditions during the drive task.

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