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Correlation between driving errors and vigilance level: influence of the driver's age

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Abstract

During long and monotonous driving at night, most drivers progressively show signs of visual fatigue and loss of vigilance. Their capacity to maintain adequate driving performance usually is affected and varies with the age of the driver. The main question is to know, on one hand, if occurrence of fatigue and drowsiness is accompanied by a modification in the driving performance of the driver and, on the other hand, if this relationship partially depends on the driver's age. Forty-six male drivers, divided into three age categories: 20–30, 40–50, and 60–70 years, performed a 350-km motorway driving session at night on a driving simulator. Driving errors were measured in terms of number of running-off-the-road incidents (RORI) and large speed deviations. The evolution of physiological vigilance level was evaluated using electroencephalography (EEG) recording. In older drivers, in comparison with young and middle-aged drivers, the degradation of driving performance was correlated to the evolution of lower frequency waking EEG (i.e., theta). Contrary to young and middle-aged drivers, the deterioration of the vigilance level attested by EEG correlated with the increase in gravity of all studied driving errors in older drivers. Thus, depending on the age category considered, only part of the driving errors would constitute a relevant indication as for the occurrence of a state of low arousal.

Keywords: Age; Driving performance; Driving errors; Driving simulation; Fatigue; Vigilance; Drowsiness; EEG

1. Introduction

Troubles in vigilance and their direct consequences on safety are increasingly considered as major public health problems, especially in the field of transportation. Indeed, if drowsiness is not the only possible failure of the driver, it is nevertheless one of the major causes of death, especially on motorways [10]. According to a survey carried out by the "Association des Sociétés Françaises d'Autoroutes" over the years 1988–1992 on a total number of 1508 accidents, the main causes were fatigue, inattention, and dozing off (29% of the cases), this figure varying little from 1 year to the next [6]. In the United States, out of 50,000 cases of fatal accidents, 15% would be caused by the driver falling asleep [39]. More recently, in a study carried out on 1931 fatal accidents in Finland, Summala and Mikkola [51] concluded that 10% of the cases were due to drowsiness. Thus, many studies show the significant implication of drowsiness in road accidents, involving casual as well as professional drivers.

The fluctuation in the level of vigilance is a natural physiological phenomenon. Such a fluctuation could be due to a more or less important activation or arousal of cortical areas, leading the brain going from deep sleep to highly activated brain. Drowsiness represents one of the intermediate states in the transition from waking to sleeping and its further development can lead to sleepiness and then actual sleep to occur. Several factors contribute to the occurrence of symptoms of fatigue and loss of physiological vigilance in drivers [41]. One of these factors is the time of day. Our biological functions fluctuate over time and they depend on internal clocks (endogenous factors) as well as on external influences (exogenous factors) such as daylight/darkness alternation [14,16,38,40]. Several biological rhythms, such as sleep/wake cycle, body temperature, cardiovascular function, or some hormones, exhibit a circadian component [2,4,5,16,25,44]. The study of these rhythms shows that the organism does not have neither the same level

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of activity nor the same efficiency during the 24-h period. Then, many experiments have shown that, even after a normal night's sleep, vigilance tends to decrease periodically, and at least twice during the 24 h, between 13:00 and 16:00 h and particularly between 01:00 and 06:00 h [10,24,32,34]. This decrease in the level of vigilance would be the cause of both peaks in car accidents that were observed at those periods [36,43,51]. Other studies show the negative impact of uninterrupted hours at the wheel on the vigilance level [27,29]. The effect of this factor appears to be much more significant when the task is very monotonous [51]. Moreover, this is particularly the case on motorways. As far as the impact of these different factors is concerned, all individuals were not offered the same chances. According to gender, motivation, and previous experience, differences in vigilance variations occur. Thus, young people seem to be more sensitive than older people [37]. Several studies showed the implication of young drivers in the majority of accidents related to low vigilance, mainly in those occurring at night [43,49]. Male drivers would also be more often implicated in this type of accident [43]. Other factors, such as sleep deprivation, consumption of substances, such as alcohol, caffeine, or drugs [8,9,33,47], and environmental conditions [53], would facilitate or, on the contrary, limit the occurrence of drowsiness, and perhaps even of unexpected falling asleep.

The car driver is the central element upon whom driving rests. The success or failure of the performance of the task depends upon his/her physiological, psychological, and physical state. The task requires the maintenance of an adequate performance that is sometimes difficult to obtain, especially during long monotonous or night driving, when microsleep and drowsiness episodes are most present [15,28,31,35,48]. Many studies highlight a deterioration of the vigilance level accompanied by a modification of the driver's performance. Among these modifications, a deterioration of the abilities to maintain the required speed is noted, particularly as and when vigilance decreases [43]. Many drivers tend to slow down when their vigilance decreases, whereas others accelerate. However, the increase in the variability of speed around the instructed value seems common to all subjects [23,45]. Besides, the latter appears higher during night driving when the vigilance level is most diminished [35]. Moreover, drowsiness is accompanied by a deterioration of the driver's ability to maintain his/her vehicle's trajectory. Indeed, several studies have shown an increase in the variability of the vehicle's lateral position with duration of the task [9,42]. Besides, most of the trajectory deviations seem to be carried out on the right-hand side of the road [21,43,48,50]. In a survey on near-miss accidents caused by unexpected falling asleep, 42% of the drivers declared to have crossed over the right-edge line of the road. Only 4.6% of them declared to have crossed over the left-edge line of the road. Inverse results have been observed in studies carried out in countries where people drive on the left side of the road [35]. A few studies showed such that differences are due to the age of the driver. In the literature, the only difference concerns the type of accident. Aged drivers would mainly be implicated in accidents at road crossings [26,49]. Young drivers would have proportionately more single-vehicle crashes and drivers 30–59 years would have more crashes with vehicles moving in the same direction [49].

In our study, we were particularly interested in the crossing over, called here "running-off-the-road" incidents and in large speed deviations (insufficient or excessive speed). We wanted to know if there was a general relationship between the deterioration of the vigilance level and the increase in the gravity of driving errors and particularly during the nocturnal period where circadian and homeostasis processes interact most [13]. Thus, driving errors could be a significant index of the occurrence of drowsiness. According to some earlier [7] and many recent studies [17,30,46], in healthy adults without evidence of brain disease, alpha and theta activities in the waking electroencephalography (EEG) are closely related to the evolution of vigilance level [32,42,52] independently of age; only delta activity actually decreases over the life span [18,19,22]. On the contrary, driving ability and driving strategies change with age. So, the relationship between the increase in the gravity of driving errors and the deterioration of the vigilance level could depend on the age of the drivers and on the type of driving errors considered.

2. Methods

2.1. Subjects

Forty-six diurnally active male subjects, divided into two groups of 25 (n_1) and 21 (n_2) subjects of three age categories: 20–30 years ($n_1 = 11$; $n_2 = 10$), 40–50 years ($n_1 = 7$; $n_2 = 6$), and 60–70 years ($n_1 = 8$; $n_2 = 8$) were selected to take part in the experiment. The age range of the three groups was voluntarily chosen with a 10-year difference to accentuate the possible physiological and behavioral differences between them. Each subject had previously undergone a preselection procedure consisting of a medical examination (state of health, examination of the main physiological functions, including vision), a neuropsychological examination, and a driving test to get familiarized with the simulator. They had a driver's license for at least 2 years, they were all using their vehicle regularly at day and night, and they traveled at least 5000 km/year. They were all in good physical condition and their state of health was good. Their vision was normal or corrected to normal.

In addition, the protocol of the study was accepted by the ethics committee. The subjects were informed about the general conditions of the experiment and they signed an informed consent in conformity with the law on biomedical research on human volunteers.

During the experiment, all subjects were dressed similarly with a tee-shirt, a tracksuit, and tennis shoes to homogenize the thermal conditions to which they were exposed. The activity level and the sleep duration of each subject were estimated using a wrist actimeter during the 48-h period preceding the drive. The subjects were to have had a "normal" activity during the 48 h preceding control and to have slept a normal amount of hours during the night before the experiment (this amount was found to be 8 h 11 min on the average). No difference in activity level was observed among the three age groups. During the night preceding the experiment, the average sleep period length was 8 h 45 min (± 1 h 23 min), 7 h 46 min (± 1 h 08 min), and 8 h 02 min (± 0 h 57 min) for the young, middle-aged, and old groups, respectively. No nap was authorized. In the experimental day, the waking time was 08:47 h (± 1 h 43 min) in young, 07:30 h (± 0 h 55 min) in middle-aged, and 06:52 h (± 1 h 07 min) in old drivers. Therefore, the length of waking period was 16 h 09 min (± 1 h 43 min), 17 h 27 min (± 0 h 53 min), and 18 h 03 min (± 1 h 07 min) in the young, middle-aged, and old groups, respectively. However, these average values are not statistically different.

2.2. Driving simulation techniques

The driving task was performed on the moving simulator PAVCAS (Poste d'Analyse de la Vigilance en Conduite Automobile Simulée). It consists of the front part of a passenger car cabin (Peugeot 605) including all the usual controls and commands. This cabin is placed on mobile platforms that permit the generation of longitudinal, vertical, pitching, and rolling movements. The cabin is associated with an interactive display unit (functioning at 60 Hz, the system has a delay in the generation of pictures of 40 ms). In this study, the display unit reproduced on a panoramic screen located in front of the vehicle, a motorway scenery with computer-generated pictures simulating night-driving conditions with or without road lighting. Road lighting was simulated by high light poles placed on the side of the road every 50 m, giving a distance visibility of about 500 m. The visualized 50-km circuit (one circuit lap) includes bends, straight segments of road, and uphill and downhill slopes. In addition, the simulator is situated in a climatic chamber where the thermal, acoustic, and lighting conditions are regulated. In our study, the ambient temperature was maintained at 22 ± 1 °C to avoid any possible influence of ambient temperature on physiological state of the driver.

2.3. Experimental procedures

Monotonous and prolonged night-driving situations, with few occurring events, were used in this study to facilitate a state of low vigilance. Subjects were asked to drive at their own pace in full respect of the driving rules. They were not instructed to cover the journey in a minimum of time and no information about clock time was delivered to them. According to the group they were assigned to, each of the subjects drove in only one of the two experimental conditions. One group (group of 25) drove on a "lighted motorway" condition, while the other group (group of 21) drove in a "nonlighted motorway" condition. Each of the subjects performed a motorway drive of seven consecutive laps, i.e., 350 km, between 1 h 58 min (± 10 min on average) and 4 h, for an average duration of 2 h and 49 min (± 11 min). Their average speed was 125 (± 2) km/h. Each lap was covered in an average of 24 (± 1.7) min; lap is used here as the independent time variable.

The subjects were alone in the vehicle and had no information of the time already passed. The instructions given prior to departure were to drive normally in full respect of the driving rules and speed limitations.

2.4. Analysis of the physiological data and driving performance

2.4.1. Electroencephalograms

A digital data acquisition system (Neuroscan) enabled to record several physiological parameters, including EEG activity. This activity was measured through four electrodes located on the left hemisphere: F3 (frontal), C3 (central), P3 (parietal), and O1 (occipital), referenced to A2 (right mastoid). Physiological recordings were performed continuously during the driving test. In addition, after the subject was settled in the simulator and before the driving test, two baseline periods, "eyes open" and "eyes shut," 5 min each, were recorded, with the subject being still at the wheel. The same recording periods were performed at the end of the driving test and before the subject left the simulator.

After subdividing the EEG records corresponding to each circuit lap and exclusion of the artifact areas, spectral analyses were carried out, preferably on C3 lead or on P3 lead when C3 could not be used, for each 2-s period and then averaged for each lap. Thus, absolute spectral power in theta (4–8 Hz), alpha (8–12 Hz), and beta (12–25 Hz) bands were calculated, together with (alpha + theta)/beta ratio. The alpha band power gives a relevant indication about the occurrence of a state of relaxation or of low arousal. An increase in the power of the EEG signal in the theta band concomitant to the decrease in power of the alpha band indicates a more pronounced state of sleepiness, which may result, within a few seconds, in the driver falling asleep unexpectedly [32,36,42,52]. As for the beta band, it reflects a cortical activation that corresponds to a normal state of arousal or to brain reactivation following a temporary episode of sleepiness. Thus, (alpha + theta)/beta ratio can give a good indication on the progressive evolution of the overall level of physiological vigilance [9].

The waking EEG is affected by both the circadian phase and the duration of prior time awake. Frequency-specific circadian and wake duration-dependent changes of EEG activity during wakefulness have previously been reported [1,3,11,13,20]. Thus, alpha activity is predominately regulated by the circadian process. In addition, circadian phase and time awake contributed almost independently to alpha activity. Similarly to slow-wave activity in NREM sleep [19,20], low-frequency components (<7 Hz) in the waking EEG showed a predominant homeostatic regulation (i.e., are primarily responsible to the elapsed time awake), exhibiting only little circadian modulation [1,13]. Then, theta and delta activities increased with elapsed time awake [1,13]. Nevertheless, this increase was dependent on circadian phase. The power density in the 0.75- to 9.0-Hz range increased steeply during the nocturnal hours [1]. Similarly, as shown by Cajochen et al., a marked increase in delta activity with increasing duration of wakefulness was observed mostly when the latter part of a long waking episode coincides with that part of the circadian cycle during which melatonin is secreted. Intrusion of this low-frequency EEG oscillation during wakefulness was a good correlate of performance decrements at adverse circadian phase [12].

In our study, which was performed in driving simulation condition, delta activity cannot be properly studied. This is mainly because numerous body movement artifacts are generated by the active driver. At the same time, eye blinks and eye movements artifacts spoil the anterior EEG leads with patterns occurring in the same frequency range as delta activity.

2.4.2. Driving performance: indices of driving errors

Simultaneously, a continuous record of the driving performance was carried out involving the information related to the vehicle position relative to the road, the vehicle speed, and the various actions on the commands; the first minutes of the drive serving as baseline measures. From these data, two types of driving errors have been defined: running-off-the-road incidents (RORI) and excessive or insufficient speed according to the given speed limit (large speed variations, or LSV). For each driving error, a penalty calculation was carried out, constituting an index of driving error.

Crossing over the emergency lane (EL) or the continuous white line limiting the left-hand hedge of the passing lane (before the safety barrier) defined a RORI. A RORI score was measured for each second by the amplitude of the exit. When the vehicle stayed in the traffic lanes, the score was 0. Otherwise, it equaled the distance between the right front wheel and the EL for a RORI on the right-hand side and the distance between the left front wheel and the left edge line for a RORI in the central reservation (CR) (cf. Fig. 1). The penalty was then calculated for 1 min and corresponded to the square root of the sum of the RORI amplitudes squared and measured for each second.

$$\text{Running-off-the-road index: Penalty/min} = \sqrt{(\Sigma \text{ amplitude}^2)}$$

Thus, the penalty depended on both the amplitude and the duration of the RORIs. For example, if a subject exits the lane by 1 m for 1 min, the penalty would be 60.

As to LSV, they were penalized in the following way: An absolute difference between the vehicle speed and the highest speed authorized in the segment of road considered was calculated for each second. If the absolute difference was more than 20 km/h, the subject would get a penalty (per second) proportional to the number of kilometers per hour above the speed authorized. This difference of 20 km/h was chosen arbitrarily. However, according to previous data obtained in similar types of situation and road, most of the attentive drivers, not showing any sign of low vigilance, would not exceed or reduce their speed by more than 20 km/h around the speed limit indicated for a given segment.

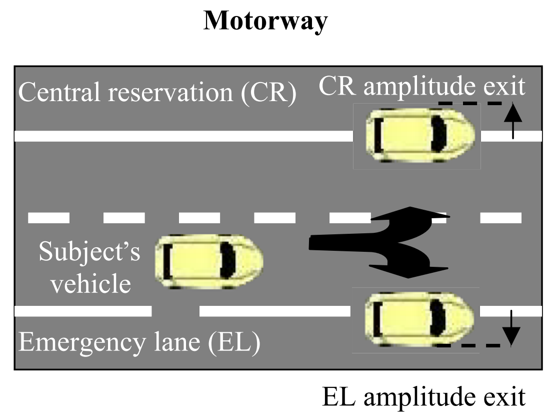

Fig. 1. Types of RORIs.

$$\text{If } |\Delta \text{ speed}| > 20, \text{ then penalty (per second)} = (\Delta \text{ speed}/10) - 1$$

Then, the sum of the penalties was made for each minute on the whole experiment.

For each of the physiological indices and each driving performance index, the data analysis was carried out on each of the seven laps of the driving task. Then, the penalties due to RORI and the penalties due to LSV were averaged for each lap. Moreover, a more detailed analysis was also carried out: a distinction was made between the penalties due to RORIs in the EL and the penalties due to RORIs on the left-hand side of the passing lane (CR). A separation of the penalties due to excessive (high speed) and insufficient speeds (low speed) was also carried out.

The effect of "driving duration," "driver's age," and "lighting condition" variables on the occurrence of a state of drowsiness (alpha, theta, beta) and on the gravity of the driving errors in each category was assessed using a analysis of variance (MANOVA) with repeated measures for duration of driving test combined with a post hoc test, the Newman–Keuls' test, with a probability threshold of error of .05.

2.4.3. Correlation analysis of physiological (EEG) and behavioral (driving errors) data

The statistical correlation analysis between the EEG data and the driving errors could not be made according to the lap because of the dependent variables. Besides, there was a certain degree of interindividual variability in the evolution of the different indices studied as a function of the lap. Some of the subjects presented an increase in the physiological and/or performance indices. For some other subjects, these indices showed irregular increases or remained stable whatever the lighting condition and the age group considered. To make a global comparison between these indices, a comparison between the beginning and the end of the driving test was carried out. Thus, the ratio between laps 6 and 7 (48 last minutes of the drive after 2 h of driving) and laps 1 and 2 (48 first minutes of driving) was calculated for each of the physiological and performance indices to correlate their global evolutions. No difference in alpha, theta, and beta spectral powers has been found between the first two laps. Also, no difference in driving error penalties has been found for RORIs and "excessive speed" errors between laps 1 and 2. However, the adaptation period seen in lap 1 was associated with "too low speed" errors and penalties due to "low speed" and LSV were higher in lap 1 than in lap 2. Therefore, to take into account the time needed to adapt to the simulator, which occurred in the first part of lap 1 for some subjects, lap 1 was not included in the calculation of the ratio for the low and overall speed errors.

The driving error indices were correlated with physiological indices. A correlation analysis was also performed between RORIs and speed errors. These correlation analyses have been made globally for the whole group of subjects and the two ambient conditions, then for each ambient condition, and finally for each of the three age groups and two ambient conditions. For data related to interval or ratio level, Pearson's r must be used. Spearman's rho is a meaningful alternative to Pearson's r only for data on an ordinal scale. Then, the correlation analysis was carried out by using Pearson's product–moment correlation test with a probability of error $\leq .05$.

3. Results

In the presentation of the results, the three age groups, 20–30, 40–50, and 60–70 years old, will be named young, middle-aged and old groups, respectively.

3.1. Analysis of physiological data and driving performance errors

No difference between the two lighting conditions and among the three age categories was noted for the physiological EEG indices.

However, the time on task had a statistically significant effect on these indices. Whatever the driver's age, the spectral power in theta and alpha bands progressively increased lap after lap, indicating a progressive deterioration of driver's vigilance level [$F(6,240) = 3.66$, $P = .002$; $F(6,240) = 11.97$, $P = .001$, respectively] (see Fig. 2). The same time on task effect was seen for the (alpha + theta)/beta power ratio [$F(6,240) = 2.76$, $P = .014$].

RORIs (EL, CR, and both) and LSV (high, low, and both) did not vary significantly between the two lighting conditions.

RORIs (EL, CR, and both) were significantly more frequent in young drivers [$F(2,40) = 3.23$, $P < .049$; $F(2,40) = 3.35$, $P < .045$; $F(2,40) = 3.29$, $P < .047$, respectively] than the other age groups. On the contrary, LSV were significantly more frequent in the old drivers group [$F(2,40) = 5.135$, $P < .01$] than the other age groups.

We also noted that this prolonged and monotonous seven-lap drive (average duration: 2 h 39 min) induced RORIs that were statistically increasingly frequent and longer with time on task [$F(6,240) = 2.77$, $P < .013$] and this for both types of RORIs considered [EL: $F(6,240) = 2.36$, $P < .032$; CR: $F(6,240) = 2.667$, $P < .016$] (see Fig. 3).

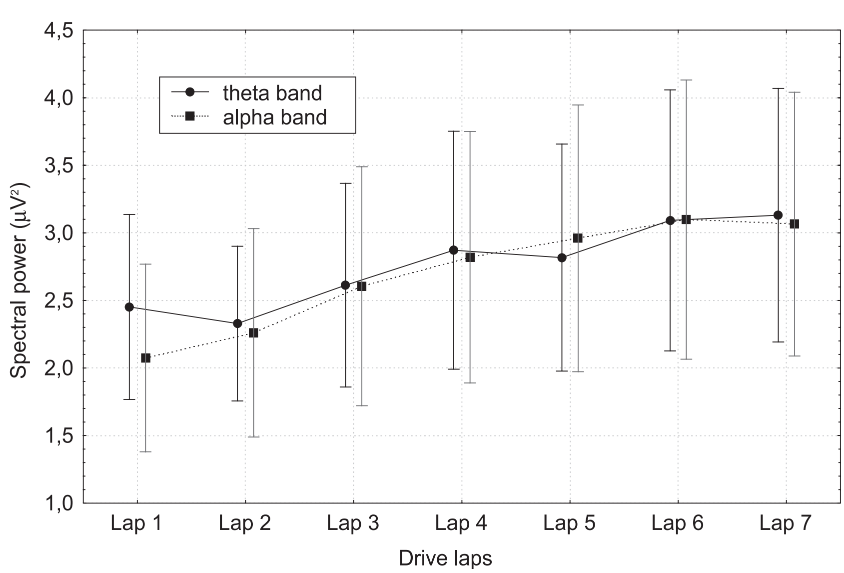

Fig. 2. Evolution of the spectral power in theta and alpha bands.

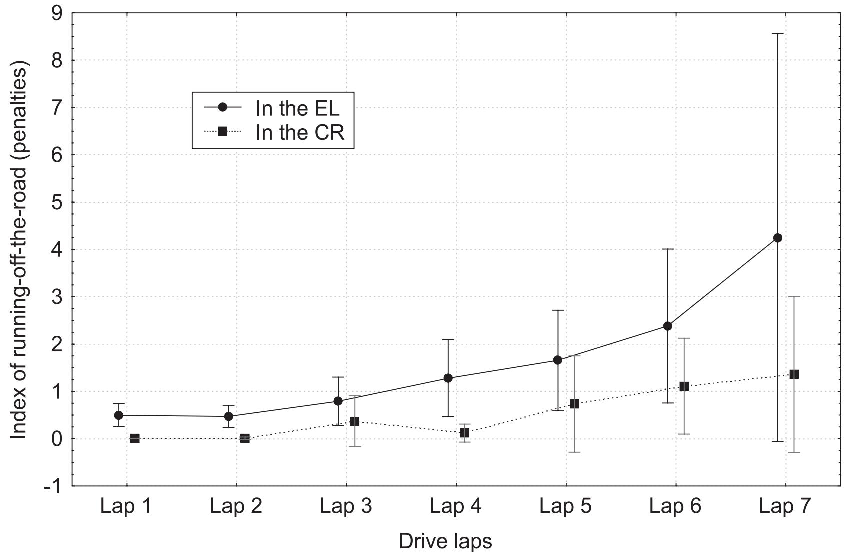

Fig. 3. Evolution of RORIs in the EL and on the left-hand-side of the passing lane incidents from lap to lap.

The amplitude of high-speed LSV was also statistically more significant as and when the number of the laps increased [$F(6,240) = 3.73$, $P < .002$]. The statistic analysis also showed a significant time effect on seriousness of all LSV and low speed [$F(6,240 = 6.97$, $P < .001$; low speed: $F(6,240) = 14.733$, $P < .001$]. The value of LSV increased with laps starting from the fourth lap. However, a high proportion of low speed and overall speed errors was observed during the first lap. Fig. 4 illustrates these results.

3.2. Correlations between driving errors and physiological data (EEG spectral powers)

3.2.1. Running-off-the-road and EEG spectral powers

Considering all groups of subjects, the only significant positive correlation with the level of vigilance, assessed by alpha power, was observed with the RORIs on the left-hand side (CR) ($r = .407$, $P < .005$; see Fig. 5).

However, considering separately the two lighting conditions, only subjects driving on "lighted motorway" showed this positive correlation between RORIs on the left-hand side and the spectral power in the alpha band ($r = .45$, $P < .024$; see Fig. 6).

In this "lighted motorway" condition, only young drivers showed this positive correlation between RORIs on the left-hand side and the spectral power in the alpha band ($r = .812$, $P = .002$). The middle-aged group tended to show a positive correlation between RORIs into the EL and the alpha power ($r = .743$, $P = .091$). On the contrary, in the "nonlighted motorway" condition, only young drivers showed a positive correlation between the alpha power and both types and overall RORIs (EL alpha: $r = .684$,

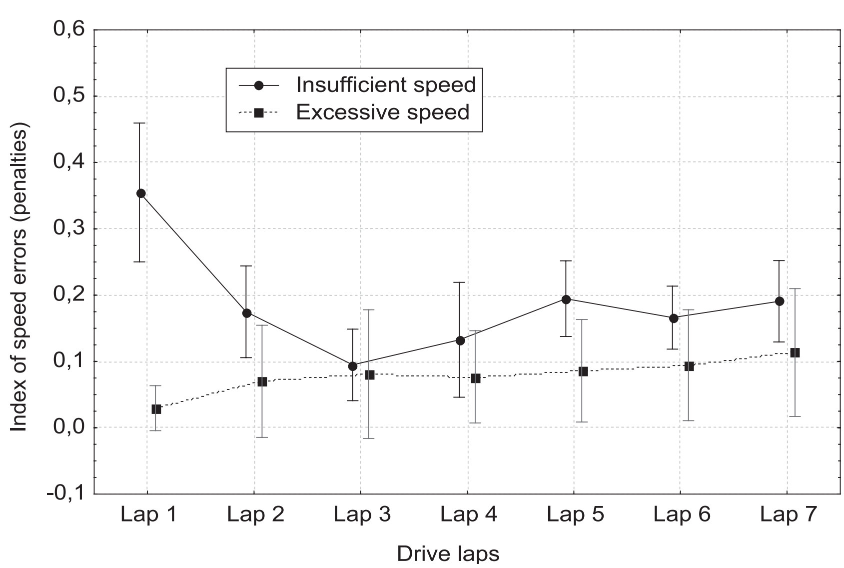

Fig. 4. Evolution of LSV in the excessive speeds and insufficient speeds incidents from lap to lap.

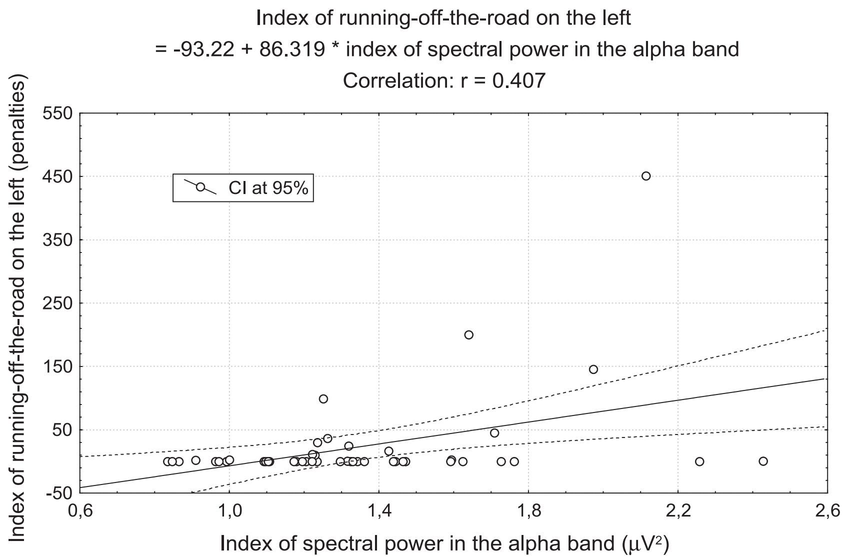

Fig. 5. Evolution of RORIs on the left-hand-side of the passing lane as a function of the spectral power in the alpha band.

P=.043; CR alpha: r=.78, P=.013; overall alpha: r=.685, P=.042). For the old drivers, no correlation was observed between any type of RORI and vigilance level evaluated through the alpha power, whatever the lighting condition considered.

When considering the spectral theta power, only the group of old drivers exhibited a positive correlation between this variable and both types and overall RORIs (EL theta: r=.884, P=.004; CR theta: r=.877, P=.004; overall theta: r=.882, P=.004).

In addition, whatever the age and the type of RORIs considered, no significant correlation was noted with the (alpha + theta)/beta power ratio.

3.2.2. Speed errors and EEG spectral powers

Considering all groups of subjects and each lighting condition, no significant correlation was observed between the physiological indices and the speed errors.

According to the lighting condition and age considered, correlations appeared between the speed errors and the evolution of vigilance level. Indeed, in "lighted motorway" condition, the old drivers presented a significant correlation between LSV (low, high, or overall) and the vigilance level assessed by theta power (low speed theta: r=.785, P < .021; high speed theta: r=.88, P < .004; overall speed theta: r=.756, P < .03). In the two lighting conditions, no correlation was found between LSV and neither alpha spectral

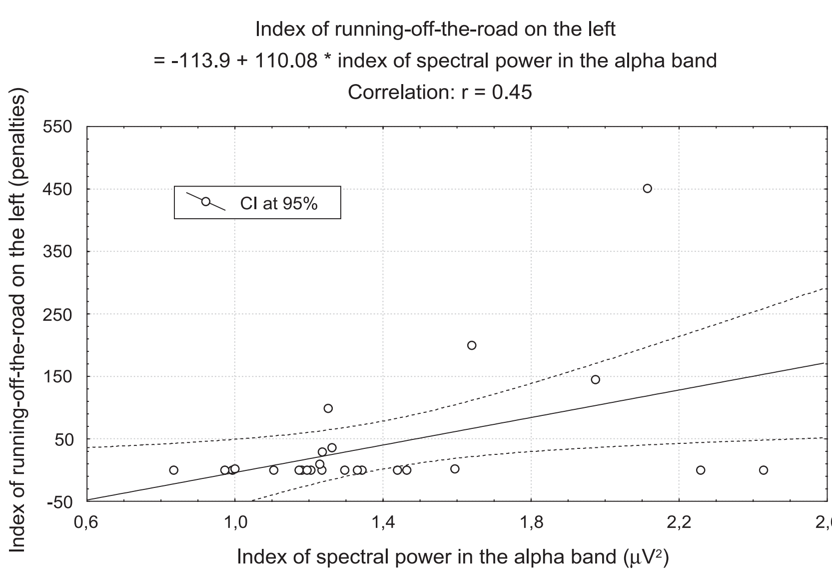

Fig. 6. Evolution of RORIs on the left-hand-side of the passing lane as a function of the spectral power in the alpha band in the "lighted motorway" condition.

power nor alpha + theta/beta ratio in this old group. Young and middle-aged groups showed no significant correlation between LSV and any of the physiological indices, whatever the lighting condition considered.

3.3. Correlations between the performance indices: running-off-the-road and speed errors

In the whole group studied, no significant correlation was observed between the performance indices, i.e., RORIs and LSV.

On the contrary, considering the lighting condition, only the lighted motorway condition showed correlations between the performance indices and particularly among the three age groups. Indeed, in the "lighted motorway" condition, the total number of RORIs, particularly those in the EL, was positively correlated with excessive speed values (r=.689, $P<.001$; r=.696, $P<.001$, respectively). In the "lighted motorway" condition, the same results were observed in the young group (r=.805, $P<.002$; r=.811, $P<.001$, respectively), while in the old group, excessive, low, and overall speed values were correlated with total number of RORIs (r=.902, $P<.002$; r=.683, $P<.062$; r=.697, $P<.055$, respectively), RORIs into the EL (r=.883, $P<.004$; r=.697, $P<.055$; r=.712, $P<0.048$, respectively) and RORIs into the CR (r=.879, $P<.004$; r=.694, $P<.057$; r=.712, $P<.048$, respectively). The middle-aged group showed a positive and significant correlation between excessive speed values and RORIs into the CR only (r=.991, $P<.001$). In the "nonlighted motorway" condition, the excessive speed and overall speed values correlated with each RORIs type (EL, CR, overall) in the middle-aged drivers only (EL high speed: r=.999, $P<.001$; EL overall speed: r=.971, $P<.001$; CR high speed: r=.848, $P<.033$; CR overall speed: r=.775, $P<.071$; overall RORIs high speed: r=.999, $P<.001$; overall RORIs overall speed: r=.971, $P<.001$).

4. Discussion

The use of a driving simulator allowed us to study long, monotonous, and uninterrupted driving task, which, in real traffic situation, could have led to severe driving errors and even accidents. The car cabin environment, including commands, instruments, and ambient noise, is quite identical to any operative car. In addition, the cabin movements induced from the driver's actions are quite close to movements experienced in real driving situation. All these factors combined are able to recreate real-alike sensations for the drivers as this is confirmed by both their subjective reports made afterward and their spontaneous reactions (such as fear or angriness) when they are facing difficult driving situations or are involved in an accident. We are, however, fully aware that driving simulation is not real driving (especially in term of risk), but we also consider that this experimental situation is the only one to be used when possible danger might occur in the experiment. In addition, we make the hypothesis that the relationship between physiological state (and its modifications) and driving performance (and its degradation) would be quite similar in simulated and real driving situations.

In this study, the analysis of the time evolution of the spectral powers in the alpha and theta bands, closely related to the fluctuations of vigilance level [32,42,52], revealed a significant increase in both indices during the prolonged driving task at night. The results were very similar to those obtained for train and truck drivers [32,52]. This entails a progressive deterioration of the driver's level of vigilance, and the concomitant increase in the (theta + alpha)/beta ratio confirms the gradual occurrence of drowsiness. Moreover, a deterioration of the driving performance was also observed. The drivers presented growing difficulty in maintaining their vehicle within the traffic lanes (increase in the number of RORIs). Crossing over the EL and of the full white line limiting the left edge of the passing lane (CR) became increasingly frequent and longer as the number of laps increased. In addition, the drivers had growing difficulty in maintaining the speed of their vehicle close to the speed limit or suited to the situations met, fluctuating between excessive and insufficient speed values. Thus, a progressive increase in penalties due to too low speed (20 km/h margin below the speed limits) and/or too high speed (20 km/h margin above the speed limits) was observed. The whole of the results corroborate the different studies previously carried out [23,45,48,50].

It seems obvious that the progressive occurrence of a state of low arousal or drowsiness could be the main cause of the deterioration in the driving performance. Several studies have shown similar evolutions between decreased vigilance and degraded performance. However, to our knowledge, few of them have tempted to correlate actual driving errors and physiological indices of brain state [8,23,31,35,45] and particularly taking into account the age of the driver.

The use of indices such as those related to RORIs and LSVs has allowed us to link these driving errors to occurring drowsiness. However, this link appears for more or less pronounced drowsiness state depending on the age of the driver. Thus, in young drivers, a significant correlation existed between driving penalties and the vigilance level as measured by alpha band spectral power, a relevant sign of the occurrence of a state of relaxation or of low vigilance. In middle-aged drivers, driving penalties also tended to be correlated with increasing power in the alpha band. In the old group of drivers, however, the link between progressive loss in vigilance and driving errors appeared for more severe low-vigilance state, including risk of unexpected falling asleep within a short delay. Thus, in this group, the correlation observed with driving errors was limited to the worst degradation of the waking state reflected by the increase in theta spectral power. This result could be explained by a slower impact of low vigilance level on driving performance with age. It could also reflect the differences in alpha production among the three age groups. Some studies have shown that alpha 1 density tends to decrease with age [37]. However, similar to other studies [18,19], our own study does not confirm this hypothesis, as it did not show any change in the alpha and theta activities with age. Only a faster increase and a larger final value in the ratio alpha 1 (8–10 Hz)/alpha 2 (10–12 Hz) were observed in the young drivers when compared to the old drivers and, to a lesser extent, to the middle-aged drivers.

Besides the correlations that do exist between vigilance level and driving performance, the relationships seem to depend on the type of driving error considered. Considering the ‘‘lighted motorway’’ condition in young drivers, only some RORIs appeared to be correlated with drowsiness, i.e., those into the CR. In middle-aged drivers, increased alpha power tended to be associated with RORIs into the EL. In old drivers, each of the three types of RORIs, as well as LSVs tended to or were correlated to theta power.

Therefore, depending on the age of the driver, the link between loss in vigilance and increase of errors could be limited to specific types of errors (young and middle-aged drivers) or seen globally for all kinds of errors (old drivers). A possible difference among the three age categories could be related to differences in driving behavior depending on age. An inadequate speed could be partly the cause of the difficulty met by the driver in maintaining his/her vehicle within the traffic lanes. The RORIs would include position and trajectory errors and would be at the origin of observed noncorrelations. The analysis of driving errors and their correlations tended to confirm this hypothesis. Thus, young and middle-aged drivers drove faster than old drivers and their excessive speed errors were positively correlated with exiting the road on the left and right sides, respectively. A reduced visibility condition, such as the unlighted one, could contribute to position and trajectory errors and this could explain the absence of correlation in this ambient condition for middle-aged and old drivers. Indeed, in middle-aged drivers, the excessive speed errors were positively correlated with the RORIs. On the contrary, in young drivers, this reduced visibility could change their driving behavior. Indeed, in contrary to the ‘‘lighted motorway’’ condition, each of the three types of RORIs was correlated with alpha power in the ‘‘nonlighted motorway’’ condition. This change in behavior could limit position and trajectory errors. Thus, the specific errors done by the young and middle-aged drivers would be more related to these particular attitudes and not the vigilance level per se.

However, these data were obtained in a limited number of subjects and the discrepancies in the results could be due to statistical limitations. Therefore, a replication on a larger population would be necessary before any definite statement.

The consequences of prolonged driving at night on the driver’s ability and on his/her motor behavior are multiple. In this study, this was shown through examples, such as increased number in RORIs on the left or on the right side of the road and increase in insufficient or excessive speed. This type of phenomenon constitutes an essential preoccupation in our society, where night driving are multiple (long-distance driving, leisure, or occupational travels). Based on the correlations found in this study, any incursion of the vehicle in nonauthorized lanes or large variations in vehicle speed could be seen as a sign of inadequate driving reflecting changes in vigilance level. This kind of index, associated with other physiological measures could be used to prevent the driver falling asleep at the wheel. However, the detection of low-vigilance state in the driver by the analysis of his/her driving errors, such as those used here, remains limited in the absence of generalized results, which appeared among the three age categories and the two lighting conditions. It is of course possible that waking EEG and performance errors are both manifestations of a common underlying process, where factors varying with age remained to be identified.

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