Cognitive load measurement while driving

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Abstract

Driving is a complex activity requiring good management of attentional resources, efficient cognitive control and decision-making. Numerous studies have sought to understand dual task interference, and in particular whether drivers have enough spare capacity to take on an additional task or whether the mental effort that demands results in driving task alteration. This study aims to analyse the relationship between mental effort and driving performance and to identify mental effort indicators from three different measurements recorded on a car simulator: cardiac activity, driving performance, and subjective data (DALI, Driving Activity Load Index). Three conditions have been designed to vary the driver's mental effort: driving as the sole task (control situation), driving while solving two different cognitive tasks, resolution of verbal or visuo-spatial enigmas. Preliminary results show that although heart rate variability does not seem sensitive enough to reflect the mental effort in car simulator studies the HF/LF ratio could be used as an indicator of the participant's investment in the task. In addition, the DALI seems useful for identifying the mental effort variation between the verbal and the visuo-spatial added tasks. Finally, the detection of mental effort from lane position variability seems encouraging.

Introduction

Driving is a complex activity carried out under time constraints and requiring dynamic adjustment of cognitive control to the driving context. Given that human behavior is active and adaptive, drivers seek to keep an acceptable level of performance at a comfortable level of effort (or energetical state) and achieve such an adaptation by means of a cognitive compromise to maintain an acceptable task load level (Hoc & Amalberti, 2007). As they drive, the task demand fluctuates according to the situations they encounter (e.g. monotonous driving vs. merging into a flow of traffic). Basically, the task load level is low when processes are automatic and high when processes are controlled and/or when several controlled tasks interfere. As pointed out by De Rivecourt et al. (2008), the mental workload concept is often used to indicate to what extent task demand affects a driver's information processing capacity. It is important to avoid confusing three notions – mental or cognitive resources, cognitive capacity and cognitive workload. According to

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Barrouillet (1996), cognitive resources correspond to the maximum energy available, cognitive capacities to the maximum resources available at a given time and cognitive workload to the resources required. Unlike the other two notions, cognitive workload is not an individual property, depending instead on the characteristics of the task to be performed. The consequence of this for the driver is that his/her mental effort varies according to the difference between the information processing system resources available and required for performing a given task.

Both overload and underload can have an impact on drivers' performance. When the resources required exceed those available, human error can occur, but performance may also go down when the resources available exceed those required (e.g. even in complex situations drivers can act in an unconscious mode of activity, investing minimal resources in the present, by virtue of past and future actions, or, more frequently, in private objects that have nothing to do with the driving activity, see Hoc & Amalberti 2007 for a review). To guarantee optimum performance, the resources required should match the resources available to the driver. For example, it was demonstrated recently that mind wandering while driving may jeopardize the driver's ability to take account of information from the environment, thereby threatening road safety (Galéra et al, 2012). Intense mind wandering was associated in the study with being responsible for a crash: 17% [responsible] vs. 9% [not responsible], adjusted OR [95% CI]=2.12 [1.37-3.28]. As well as on-board safety monitoring systems dedicated to avoiding driver distraction caused by multi-tasking at the wheel, research to develop systems that can detect periods of driving vulnerability as a result of inattention due to mind-wandering or mental effort should be supported owing to the potential it offers for further improving safety.

Experimental research can be really helpful in this context. Different types of data (subjective, driving performance, and physiological data) can be collected to evaluate drivers' mental effort. The difficulty with subjective measures is that it is hard to distinguish the task demands from the invested effort, and so the use of complementary physiological measures is a good alternative. Several physiological measures (like heart rate and heart rate variability in two frequency bands) have been shown to be sensitive to mental effort (Boutcher & Boutcher 2006; Causse et al. 2011; Jorna, 1992; Wilson & Eggemeier, 1991). Low frequency bands (LF) are most consistently related to mental effort (Mulder, 1985), but high frequency bands (HF) have also proved to be sensitive to mental effort (Wilson, 1993). In general, Heart Rate (HR) increases and overall Heart Rate Variability (HRV) decreases when mental effort increases. This could be the result of orthosympathetic dominance over parasympathetic (Backs, 1995; Bernston et al. 2007; Task Force, 1996). Even though spectral measures appear to be sensitive to task-rest differences but less so to difficulty levels within the same type of task, the use of physiological measures is promising for capturing mental workload and especially for simulator driving studies (Brookhuis & de Waard, 2010). For laboratory studies involving short tasks (between 30 s to 300 s) requiring demanding mental operations in working memory, the general cardiac response pattern in mental effort studies is similar. With these variables, it now seems possible to explore some important questions with the help of spectral analysis of heart rate measures collected while driving a simulator. Is it possible to measure mental effort variation while driving? What are the methodological problems to be solved? Does the *measure* of mental effort vary according to the type of cognitive tasks performed by drivers? What are the best indicators of cognitive load variation?

Using empirical research, this study seeks to understand how drivers manage their mental effort while driving a simulator. Drivers' mental effort measurement is investigated by manipulating road type and the performance of two extra tasks (using a dual-task paradigm, i.e. where drivers have to solve verbal and visuo-spatial enigmas). Mental effort in this case is used as an indirect measure of operator capacity. As pointed out by Veltman (2002), it is possible that participants' motivation when performing the added task differs, with some participants willing to make an effort when performing the task and others not). To gain a better understanding of how drivers regulate their mental effort, an in-depth activity analysis will be conducted for each driving scenario.

It is expected that an increase in mental effort as a result of participants performing an additional task will be reflected by both subjective and objective measures. HRV is an objective index of mental effort that should be sensitive even if used during driving. A lower HRV is expected when mental effort is higher. In addition, the cognitive load should be higher for the visuo-spatial task because similar visuo-spatial abilities are required so it shares the same cognitive resources as driving. In our experiment, indicators of drivers' mental effort will also be investigated with a specific driving index (lane position).

Materials and method

Participants

Twenty-one individuals were included in this experiment. All of them had their driving licence for at least 5 years, had normal or corrected-to-normal vision and were naive to the purpose of the experiment. They were recruited via a newspaper advertisement. Participants were asked to avoid energy drinks for 3 days prior to the experiment (and drink less than 2 coffees per day); smokers of more than 5 cigarettes a day were excluded. The CPP Sud-Est Lyon II Ethics Committee approved the experiment, and all procedures were carried out in accordance with the relevant laws and ethical guidelines. All participants were required to read and sign an informed consent form. In return for taking part in the experiment, participants received 45 euros. 4 participants yielded data that could not be used (due to bad cardiac signal, failure of sensors or experimental errors). The mean age of the remaining 17 participants (12 men, 5 women) was 33 years (± 3,5).

Material

The study was carried out in an instrumented full-cab fixed-base simulator developed at IFSTTAR. The simulator is also equipped with virtual reality-based visual and audio systems, a computer program for vehicle motion simulation, and a host computer system for simulating the driving environment. Driving performance data were captured at 60 Hz from the original equipment manufacturer brake, accelerator and steering wheel. A front projection screen provided an approximate 180° horizontal and 40° vertical view of the virtual environment. Force feedback was provided through the steering wheel, and auditory feedback was delivered in the form of engine noise. Audio tasks and instructions were also communicated via the vehicle sound system. A microphone located inside the cab recorded participants' responses to the additional tasks.

Cardiac activity was recorded on lead II according to Einthoven's triangle, with three disposable electrodes (Ag-Cl). This signal was sent to a MP150 unit via a Bionomadix wireless device. AcqKnowledge 4.1 (running on a PC computer) was used for 1000 Hz acquisition with a 0.05 – 35 Hz band pass filter.

Procedure

After a training session with the driving simulator, participants had to respect the Highway Code. They drove on both motorways and secondary roads (with the same driving tasks in each scenario: direction following, speed regulation, overtaking). The experimental plan required them to drive with and without two types of additional cognitive task (verbal or visuo-spatial). Heart rate data were recorded during each experimental session.

- In the verbal task condition (VT), three words were communicated, and the driver had to find a 4th word associated with the other three (e.g.: "Sugar"; "Bees"; "Moon" plus "Honey" as a possible 4^{th} word). After 30 s, if a participant did not find a solution, the three words were repeated once. After a further 30 s, a new enigma was communicated.

- In the visuo-spatial task condition (VST), before driving participants had to learn a 3x3 object grid containing nine different objects. Then, while driving, they were told to listen to a displacement instruction (up, down, left or right) and given 30 s to find and remember the name of the object in the target case. Every four instructions, they had to name the object aloud.

These tasks require only the utterance of a single word, interfering moderately with the HRV indices. The two additional cognitive tasks both required participants to remain focused on the enigmas throughout the driving scenarios. Each driving scenario lasted 7 to 10 minutes. All the conditions were counterbalanced between participants. After each driving scenario, participants used the Driving Activity Load Index (DALI) to assess their (subjective) mental effort.

Measures and analysis

Cardiac data

Before analysis, the cardiac signal was cleaned with digital filtering and/or template correlation and/or manual corrections until a clean tachogram was obtained. HRV was then calculated from a 5-minute recording in the LF (0.04 to 0.15 Hz) and HF (0.15 to 0.40 Hz) bands via FFT transformation and Power spectral density computation (expressed in $sec^2.Hz^{-1}$). LF and HF HRV as well as the LF/HF ratio in HRV were retained. All these computations were performed with AcqKnowledge 4.1. Five variables were used to describe cardiac activity: mean heart rate (HR), total heart rate variability (HRV), LF HRV, HF HRV and the LF/HF ratio in HRV.

Subjective data

Participants filled out the Driving Activity Load Index (DALI), a revised version of the NASA-TLX questionnaire adapted to the driving task (Pauzié et al. 2008). It assesses various dimensions including effort of attention, temporal demand, situational stress, and interference. Participants have to answer each question using a 6 point scale (0 = low, 5 = high). The total score is the sum of the four dimensions.

Driving data

In the search for a real-time indicator of drivers' low attentional status, we also analysed driving performance by studying lateral control during nominal driving. Lane position (the distance between the middle of the road and the vehicle's center of gravity) was analyzed with wavelet transforms. We extracted the wavelet coefficients at 10 Hz (best frequency defined after data visualisation). An individual baseline was set at the 70th percentile of the wavelet coefficients (arbitrary expertise-based value). Lane position variability was defined as the wavelet percentage below the baseline.

Regulation strategies

To gain a better understanding of how each driver coped with the mental effort, we analysed video data to obtain an in-depth activity analysis for each driving scenario. It was decided to assign penalty points whenever a driver was not able to perform the driving task or cognitive task in a manner deemed efficient. A penalty point was assigned every time a participant asked the experimenter for help, with the same procedure used for both driving errors and secondary task errors. An extra penalty point was given whenever the experimenter observed any signs of stress (breathing, mimics, scratching). It was thereby possible to define a workload regulation score: a low value indicated that the driver used the best regulation strategy (i.e. driving performance remained at a high level), and a high value indicated a worsening of driving performance in the two secondary task conditions. The penalty scores are shown in Figure 1 (min = 0 to max = 16.5). With a score of 0 to 8 points the workload regulation strategy was considered focused (9 participants were in the focused group; they were motivated by the driving task). With a score of 9 to 16.5 it was considered distracted (8 participants were in the distracted group; it was also noticed that they were often stressed by the experimental settings).

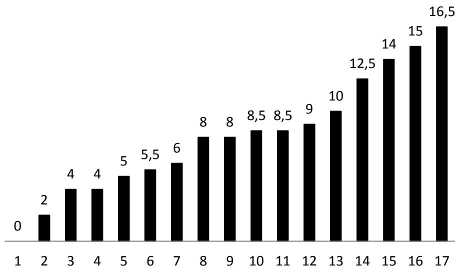

Figure 1: Workload regulation scores for all participants

Statistical analysis

Cardiac and subjective data were tested with a univariate repeated measures analysis of variance. Two independent variables were used: road type (motorway vs secondary road) and task type (driving alone, driving while solving verbal enigmas, driving while solving visuo-spatial enigmas). Standard post-hoc tests were used to compare all driving conditions.

In addition, as two mental load regulation strategies were identified (more focused on the driving task vs distracted by the additional task), a between-subject factor was added (group type). To analyse the effects of participants' workload regulation strategies on the cardiac data, an exploratory analysis was conducted including type of road and type of task as within-subject variable and group type as between-subject variable. This group analysis was performed on the HF power and LF/HF power ratio in order to test for differences in subjects' investment in the tasks. Finally, correlation coefficients were calculated between workload regulation scores and lane position variability.

Results

Subjective data for the mental effort measurement

For technical reasons, five participants failed to fill in the DALI questionnaire properly and were excluded from the analyses. No main effect of road type was found, but a main effect was observed for the driving task condition ($F(2,22)=5.24$, $p=0.029$, $\eta^2=0.32$). The subjective mental efforts as measured with the DALI differ, with post-hoc comparisons indicating that scores were lower in the control condition than in the other two conditions (verbal task and visuo-spatial task) (Figure 2). No significant interaction was observed between road type and driving task condition. The total score for the Driving Activity Load Index incorporating four dimensions (effort of attention, temporal demand, situational stress and interference) would appear to be sensitive to our experimental manipulation.

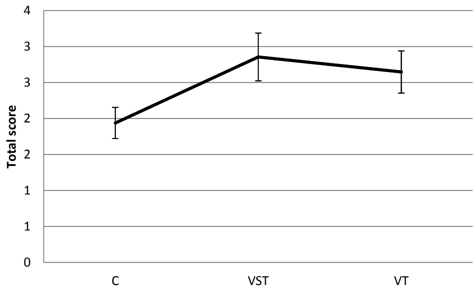

Figure 2: Total DALI scores for the three driving conditions

Objective data for the mental effort measurement

A unique significant effect was observed with the ANOVAS conducted on the five cardiac variables (HR, HRV, LF HRV, HF HRV, LF:HF ratio in HRV). A main effect was observed for the driving task condition for the HRV ($F(2,32)=3.99$, $p=0.033$, $\eta^2=0.20$). As illustrated in Figure 3 and confirmed by post-hoc analysis, HRV is higher in the verbal task condition than in the two other conditions (control and visuo-spatial). No significant interaction was observed between road type and driving task conditions.

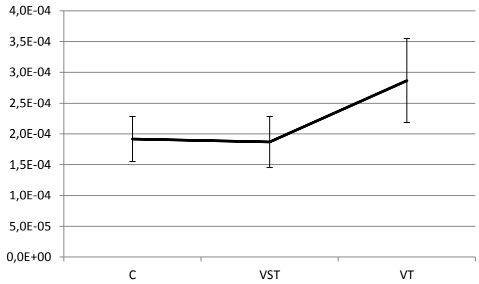

Figure 3: Total heart rate variability for the three driving conditions

The traditional correlation between HR and HRV is observed for the VST condition ($r=-0.702$, $p=0.002$), with HR increasing as HRV decreases.

Exploratory analysis according to the workload regulation strategies

These preliminary results must be interpreted with caution because of the small number of participants in each group. Many more participants will be included in the coming months to improve the statistical power of the results.

To understand the workload regulation strategies of the two participant groups, the LF/HF ratios in HRV (Figures 4 and 6) were analyzed in parallel to the HF HRV values (Figures 5 and 7). Based on these preliminary results, a significant interaction effect is expected between road type and group type for the LH/HF ratio and the HF HRV values (F(1,15)=3.78, p=0.07, η^2=0.20 and F(1,15)=4.26, p=0.06, η^2=0.22 respectively) as more participants will be included. As the HF HRV values for the distracted group did not change according to road type (Figure 5), it would seem participants still invest in completing the secondary task, even on secondary roads in the case of greater driving task complexity (the cognitive load in this situation also increases slightly as the LF/HF ratio increases, cf. Figure 4. For the focused group the HF HRV value is higher on secondary roads. Participants seem to invest less in the additional tasks on secondary roads; it would appear that they retire from the secondary task more easily.

As shown in Figures 6 & 7, presented by task type, the two groups adopt different workload regulation strategies, especially for the verbal task. An interaction effect between task type and group type reaches significance for the LF/HF ratio and marginal significance for HF variability (respectively, F(2,30)=3.43, p=0.05, η^2=0.19 and F(2,30)=3.02, p=0.07, η^2=0.17). The only significant effect at this stage is a shift in the LF/HF ratio for the focused group in the VT task (see Fig 6)

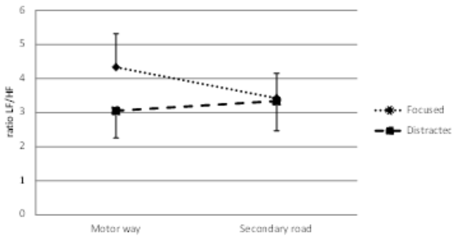

Figure 4: Interaction between road type and group type for the LF: HF ratio

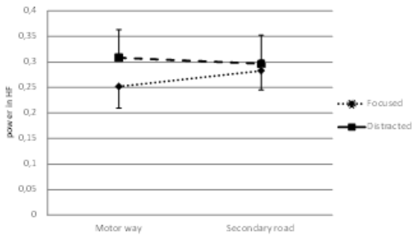

Figure 5: Interaction between road type and group type for HF variability

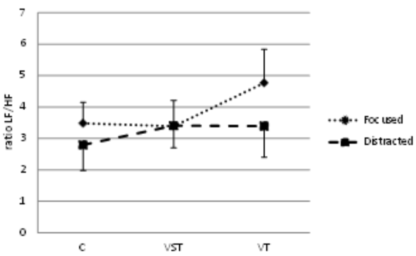

Figure 6: Interaction between task type and group type for the LF/HF ratio

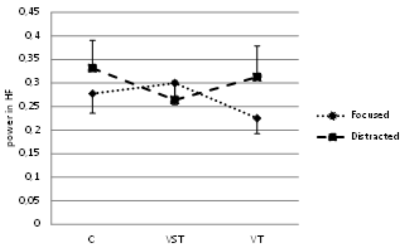

Figure 7: Interaction between task type and group type for HF HRV variability

Correlations between lateral control and workload regulation scores

To explore the influence of an extra task on driving performance, we studied lateral control during nominal driving by analysing lane position in the driving simulator. With reference to an individual baseline performance, we observed that, for both additional tasks, the workload regulation score was correlated with lane position variability at 10 Hz (VST: $r = 0.66$, $p = 0.005$; VT: $r = 0.75$, $p = 0.001$): the higher the penalty score, the higher the lane position variability. When a mental effort is made, lane position at this specific frequency seems amplified.

Discussion

Through an experimental approach using a dual-task paradigm, subjective, cardiovascular, task performance and driving indices were measured in a driving simulator in order to analyse the relationship between mental effort and driving performance and in an attempt to identify mental effort indicators. The subjective and objective data results indicate that the drivers made an extra mental effort to solve a number of enigmas. Consequently, at the subjective level, the mental effort measured in the DALI is higher for the two additional tasks than for the control situation.

Regarding the cardiac data, the results were less clear-cut. As overall HRV was lower for the control and VST conditions, the mental effort measured with the cardiac data seemed higher for these two conditions. What is surprising is that HRV was also low for this control situation, whereas it was supposed to be the lowest in mental workload. It seems that even when the participants were driving without an additional cognitive task the mental effort invested by them was higher when they were only driving the simulator than when they were driving while solving the verbal enigmas. Further analysis will be conducted in an attempt to explain the low HRV obtained in the control condition. Contrary to our expectations, cardiac activity as measured through the overall HRV index is not the right one for discriminating the control condition (only driving) from the other two conditions (driving while performing an additional cognitive task).

For the Verbal condition, it was expected that HRV would be lower than for the control task, but, surprisingly, it was higher. This result can be discussed in terms of the mental effort invested in carrying out the extra task. It is assumed that an increase in task demands is linked to an increase in mental effort (Cnossen et al. 2004; Vicente et al., 1987). Accordingly, we hypothesized that a more demanding task would require greater mental effort in order for it to be adequately completed. We noticed, however, that the complexity of the verbal task was not constant throughout the period studied, insofar as the difficulty to find a solution varied depending the different three-word sets. For some sets, the solution was sometimes obvious (found fairly automatically without any mental effort required). For the more difficult enigmas, it is possible some of the participants failed to spend the entire minute with their attention focused on finding the solution, withdrawing instead from solving the task. Because of their successive failures, the motivation for these participants to complete this task may also have been lower and their mental effort not constant (Veltman, 2002). Further experiments are currently being conducted on this specific issue (Baracat et al., 2012) in order to test this hypothesis.

For the Visuo-Spatial condition, the traditional correlation was observed between HR and HRV (e.g. Mulder, 1992; Jorna, 1992), in other words HR increases as HRV goes down. In this particular condition, the mental effort seemed greater than in the verbal condition. This result can be interpreted as strong investment on the part of the participants for the whole 5-minute period. The difference observed between the two additional tasks is also consistent with our hypothesis that the visuo-spatial task should be more disruptive than the verbal one as it shares some visuo-spatial characteristics in common with the driving activity.

The general cardiac response pattern in mental effort studies is characterized by an increase in heart rate and a decrease in heart rate variability (HRV) when mental effort increases, and vice versa. The same pattern of results is also found in field studies and simulator studies (Brookhuis & De Waard, 2010; Jorna, 1993; Mulder, 1992), such that cardiac activity and especially HRV has long been used to gauge mental effort (i.e. Boutcher & Boutcher 2006; Causse et al. 2011; Jorna, 1992; Wilson & Eggemeier, 1991). However, this pattern of variations could be obtained in different ways at the autonomic level. Generally a rehearsal in sympathetic activity is observed, coupled with a reduction in parasympathetic activity. Nevertheless, this is not systematically the case, and the same kind of variations in HR and HRV could be obtained with a different mode of autonomic regulation (Berntson et al., 1991; Berntson et al., 1993). An interesting issue here is the evaluation of a subject's investment in the tasks as attested by a shift in orthosympathetic activity, independently of parasympathetic variations. The LF/HF ratio can be analysed in this context, but, unfortunately, at the autonomic level there is only one unambiguous measure namely the power in the HF band which is related solely to the parasympathetic activity. For its part, the power in the LF band is a mixture of parasympathetic and orthosympathetic influences. Consequently, an orthosympathetic shift can be asserted only when the LF/HF ratio changes without any change in HF. Thanks to the workload regulation strategies approach, the group comparison to be conducted in future with more participants in each group could provide a possible explanation regarding dual task management or investment in carrying out additional tasks.

It is possible that this study has a methodological limitation relating to the width of one frequency band chosen. As recommended by the Task Force (1996), HRV was calculated in the 0.04 to 0.15 Hz Low Frequency band. As mentioned in De Rivecourt et al. (2008), the HRV in the 0.02 to 0.06 Hz band is mostly to do with the regulation of body temperature and gradual change in task characteristics. As changes in temperature regulation functions often arise with simulator sickness (Casali et al., 1988), this may have had an influence on the mental effort measurement conducted in this experiment. We shall be studying the HRV in the two different bands (0.04 to 0.07 Hz and 0.07 to 0.14 Hz) to clarify this issue.

A major restriction to the use of ECG-based measures is the effect speech has on blood pressure, and therefore on the 0.10 Hz component of heart rate variability (Mulder, 1988; Sirevaag et al., 1993). In our experiment, verbalization was not a predominant aspect of operator performance. The answers to the enigmas were really short and infrequent (about one word per minute). As Porges & Byrne (1992) recommend no corrective action in cases where the verbalization duration is short (less than 10 s) or if speech is relatively infrequent (one to five times per minute), we thought we could use ECG-based measures to evaluate drivers' mental effort with these two cognitive tasks.

Other methodological approaches regarding mental effort assessment could be envisaged. For example, the development of short-erm analysis techniques seems promising. First, the possibility to analyse Evoked Cardiac Response (ECR) associated or not with galvanic skin response (GSR) is being examined (Baracat et al, 2012). Another study also indicated that a short-segment averaging approach is well suited for obtaining spectral power estimates of short data segments even with varying length (de Rivecourt et al. 2008). Finally, realtime detection of workload changes with heart rate variability using sub-Gaussian fitting could be used (Hoover et al, 2012).

Moreover, to take this type of studies furthers, an in-depth analysis of driving behaviour is also necessary. In a road safety perspective, it is important to increase our knowledge about attentional failures during driving. With this kind of experimental procedure associated with a driving activity analysis, a classification of attentional failures could be considered and could allow us to gain a better understanding of how driving performance is impaired (for example, distraction errors leading to a failure of routines could be dissociated from failures in motor control or interruption errors and discrimination errors).

This study aimed to explore the influence of cognitive task completion on driving activity taking into account the cardiac signal. In the near future, the complementarity between this technique and electrophysiological techniques already used in driving simulator studies (Bueno et al, 2012; Fort et al, 2010; Fort et al., 2013) will be investigated. Better understanding of drivers’ cognitive workload regulation should be sought in order to identify avenues worth exploring regarding awareness campaigns and the design of driving assistance. To that end, driver monitoring with the help of computational techniques have the capability to determine optimal sensor fusion and automated data analysis for the recognition of mental effort and stress manifestation. In this regard, the result regarding lateral control of the vehicle, identifying a possible indicator of the impairment of driving performance when the driving activity is monotonous (nominal driving) is encouraging.

The experimental approach developed in this study with physiological, behavioural and subjective data, combined with the methodological development suggested is a promising approach towards better identification of driving performance degradation, a necessary step to improving road safety.

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