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Electrophysiological and performance variations following driving events involving an increase in mental workload

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Abstract

This study aimed at investigating how driver's mental workload could be assessed during driving, using driving performance as well as electrophysiological and subjective data. Participants had to follow a lead vehicle at a safe and constant distance and to deal with two particular driving events (overtaking and pedestrian occurrence) within two sessions (baseline and experimental) on a driving simulator. Traffic density and time pressure (overtaking event) and time pressure (pedestrian event) were increased in the experimental session in order to induce a higher workload. Participants filled NASA TLX questionnaire after each driving session. Electrophysiological parameters (SCL, ECG), driving performance (SDLP and response to speed change of the lead vehicle: coherence, delay and gain) were analysed after each event in two temporal windows (30 s and 5 min). Results showed that both performance and physiological variables differed as a function of traffic conditions and time pressure. Moreover, while performance variations were systematically observed over a long period (5 min after the events), effects on mean SCL data obtained from experimental session notably differed from baseline values within 30 s after the events. Results are discussed in term of mental workload and suggestions are made about the safety systems that could monitor driver's mental state.

Keywords: Transportation safety, Driving performance, Mental workload; electrocardiography, Electrodermal activity, ADAS

1 Introduction

Driving is a complex dynamic process control activity that requires accurate evaluation of the situation and relevant decision-making. According to Verwey [51] the driving situation is a major determinant of the driver's mental workload. Mental workload can be defined as the ratio between the capacities of the information processing system needed to perform correctly the task and the amount of available attentional resources at any given time [16, 39]. From the driver's point of view, every driving event provokes a specific level of workload depending both on its complexity and on the road environment, such as road design, road layout and traffic flow [21, 41]. In particular, road events with high traffic and/or many pedestrians crossing the street can contain a lot of information to process and can be defined as complex and producing high mental workload [52]. It has also been demonstrated that an increase of the event complexity can lead to impaired performance due to an increase of mental workload [15] and could cause unsuitable manoeuvre and even road accidents [17, 51].

Mental workload is thus a multifaceted concept that could not be quantified by a single measure [38]. In the present paper, we chose to measure workload by using three types of measures: subjective, electrophysiological and behavioural measures (i.e., drivers' performance) [44, 54].

Subjective measures such as self-report questionnaires are widely used as they provide an estimation of the current mental workload felt by the person [16]. One of the most common self-report questionnaire is the NASA-Task Load Index (NASA-TLX) [23]. Nevertheless, one major issue with such a questionnaire is that it can only assess mental workload before or after the task

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and cannot provide any information about its variations in real-time [41].

Electrophysiological measures reflect the peripheral and central nervous system (CNS) activities [13, 28, 54]. They give an online and continuous assessment and, according to the measures taken into account, could give a relatively quick indication of phasic shifts in mental workload [44]. Among them, heart rate (HR) and heart rate variability (HRV) obtained from electrocardiographic (ECG) measurements constitute an accurate indicator of the overall mental workload [16, 45, 46, 53]. Usually, when mental effort increases, HR increases and HRV decreases, as a result of an orthosympathetic dominance over the parasympathetic one [3, 4, 34]. The skin conductance level (SCL) also seems to be sensitive to variations of mental workload. It corresponds to sweat gland innervation and increases significantly with the level of cognitive demand [35]. Collet et al. [11, 12] showed the link between SCL and mental workload in investigating the influence of factors such as the driving task or the environmental context. However, temporal window used to process information related to one driving event taken into account by Collet et al. [12] was limited to the 30 s that followed this specific driving event. This temporal window could be very short to investigate the post effects of traffic conditions producing high mental workload [17, 51]. Moreover, in Collet et al. [10], the predictability of the experimental braking events used is high, increasing the participants' expectancy. Consequently, although research has already provided evidence that skin conductance level could be a good indicator of mental workload when driving, additional experimental data are necessary to question the duration of longer electrophysiological variations after events involving complex traffic conditions.

Finally, mental workload can also be estimated through drivers' performance and very complex traffic conditions can potentially lead to an inadequate behaviour at the moment and after their occurrence [17, 51]. Consequently, the investigation of an external factor's influence such as traffic conditions on the driver's workload must also consider performance parameters. Generally, the evaluation of driving performance focuses on lateral and longitudinal control of the vehicle [16, 49]. According to De Waard [14], the deviation of lateral position is one of the most important indicators of degraded driving performances and can be interpreted as the risk to leave the road and to be involved in an accident. The standard deviation of lateral position (SDLP) increases when mental workload is high [16]. Longitudinal driving performance (speed and variations of speed) also plays a substantial role in the traffic flow operations [24]. In particular, the car-following situation, often encountered in high traffic density, involves a specific and accurate longitudinal control. This situation requires to match the speed of the lead car and to maintain a constant distance from it. It has been considered [6] and is now a standard in the field of transportation research. It provides information about the driving performance related to mental workload variations within very controlled conditions. For example, Brookhuis et al. [7] showed that the use of a phone when driving, known to increase workload, could induce slower reaction times (increase of delay) to the speed changes of the lead car. Moreover, it could reduce the accuracy of the driver's speed adaptations to the speed of the lead car (i.e., coherence). However, it is important to note that longitudinal and lateral performance parameters maintain or even improve according to the task [20]. Nevertheless, performing an additional task while driving, like phoning [19, 42], texting [9, 40] or detecting signals in the visual periphery (Peripheral Detection task; [2, 26]) leads to deterioration in performance. It must also be emphasized that an additional effort allows to maintain performance until a certain threshold [27, 41]. More specifically, the performance relying on cognitive control is consistently impaired by cognitive load whereas the performance on automatized tasks is unaffected and sometimes improved (for a review see [20]).

Currently, it is still difficult to determine how electrophysiological and behavioural measures should be combined for a real time estimation of mental workload during driving. One of the main difficulties concerns the identification of the temporal dynamics of each of these measures. Most of research studies investigating the relationship between mental workload and electrophysiological variations use 5 min time periods for the data analysis. It could be explained by the fact that HRV variations are visible within 5 min if we refer to the recommendation of the Kubios HRV User's Guide [48]. Nevertheless, short lasting increase in heart rate and decrease in heart rate variability were found from 10 to 30 s after the disturbance of a planning task by incoming emergency calls [45] and in case of additional task demand during driving [46]. The duration of driving impairment after a complex event still remains unclear. Previous findings suggested that some electrophysiological measures such as high frequency HRV or SCL would be more reactive to mental workload variations than behavioural measures and could precede clear lowering of driving performance [33, 35]. It seems however difficult to draw conclusions for potential real time applications when driving since these studies added a secondary task (working memory) to the main driving task in order to increase mental workload. The use of such a secondary task potentially interferes with driving performance and depends on several contextual parameters (sensory modality of the secondary task, complexity of the driving task …) and individual parameters (vigilance, motivation regarding the main task, etc.).

In the perspective of a real-time estimation of mental workload combining electrophysiological and performance measurement, it is thus necessary to deepen how these data vary over time as a function of the driving events and their complexity. This could contribute to determine the respective optimal temporal window calculation of each of these measures.

The purpose of the present study was thus to provide a better understanding of long-lasting electrophysiological and performance measures' variations following driving events involving an increase of mental workload. Two events were included in a task of car following: the sudden occurrence of a pedestrian, unexpected event which required an manoeuvre in order to avoid crash, and the presence of a truck adopting a slow speed which required to make an overtaking manoeuvre and to accept a certain risk notably in case of opposite traffic. These two events were selected as they could make use of different information processing level. In reference to Michon's three levels hierarchical model [37], overtaking event could make use of the tactical level (second level), with a slow, serial, conscious and flexible controlled processing and pedestrian event to the operational level (third level), with a fast, unconscious and rigid automatic processing [43]. The level of mental workload was induced by manipulating spatiotemporal constraints through notably the density of the opposite traffic (overtaking event) and the time pressure (Time to collision with the pedestrian). In order to further how electrophysiological and performance measure vary over time, we explored two temporal windows (30 s and 5 min following the driving events) for which previous studies [22, 45, 46] reported data variations related to mental workload.

The increase in mental workload was expected to be observed first at the electrophysiological level (higher skin conductance level and HR, lower HRV) and then at the performance level (higher lateral position variability and decrease in longitudinal speed reactivity). Furthermore, it was assumed that the influence of traffic conditions on these variables could depend on the nature of the driving event (i.e., the information processing level).

2 Method

2.1 Participants

Thirty-two drivers took part in this experiment (15 women; $M_{\text{age}} = 41.33$ years, $SD = 5.23$ and 17 men; $M_{\text{age}} = 42$ years, $SD = 4.73$). They were required to have a valid full French driving licence for more than 3 years and to be right-handed. They also completed an online short questionnaire designed to find out how susceptible to motion sickness they were. Six questions concerned the frequency of feeling sick or nauseated over the last 10 years for different types of transport (cars, buses, train, aircraft, small boat, ships). For each item, the participants had to describe their experience of motion sickness on a 4-point likert-type scale (0 = never felt sick, 1 = rarely felt sick, 2 = sometimes felt sick, and 3 = frequently felt sick). Only the participants who obtained a mean score between 0 and 1 were selected for the experiment. They all declared to be in good health, without neurological issues, with normal hearing ability and normal/corrected-to-normal vision. They provided written consent prior to the study, which was conducted according to IFSTTAR ethical regulations and the Declaration of Helsinki.

2.2 Materials

The experiment was conducted on a fixed-base simulator. The driving performance parameters (longitudinal position and longitudinal speed of the participant's vehicle) were recorded at 25 Hz. ECG and SCL signals were recorded at 2000 Hz with a BIOPAC MP36 system using 30 mm2 unpolarizable, Ag/AgCl electrodes (Clark Electromedical Instruments). For recording the SCL signal, the electrodes were placed below the distal phalanx of the index and the middle finger of the left hand (dermatom C7) in order to limit the artefacts related to the steering wheel's prehension.

2.3 Experimental design

The participants had to follow a lead vehicle (LV) while driving on an open and suburban simulated single-carriageway two-lane roads. They were instructed to maintain a safe but constant distance behind this vehicle. The investigator gave a verbal feedback when this distance was too long (more than 70 m). Each participant performed this task within two driving sessions (baseline and experimental), each driving session contained two particular driving events (overtaking and pedestrian events). Baseline and experimental driving sessions only differed through the traffic conditions and the time pressure when the driving events occurred. The mental workload induced by the events was thus higher in the experimental than in the baseline session. The first and second events of each session occurred after approximatively one and 6 min of driving, respectively (the durations depended on the participant speed).

After each driving event, the speed of the lead car changed between 70 and 90 km/h, accelerating and decelerating within a randomly varying frequency: 8 speed variations were separated by phases of constant speed of different durations, for a total of 5 min. The order of the two sessions (baseline and experimental) and the order of the events within each session were counterbalanced across participants.

2.3.1 Overtaking events

The lead car overtook a truck that the participants also had to overtake in order to keep following the lead car.

- In the baseline session, no vehicle came in the opposite direction and the participant could easily follow the lead car.
- In the experimental session, the traffic density was higher and in order to overtake the truck, the participant had to choose a gap between vehicles coming in the opposite direction. Eight gaps were proposed: the first one corresponded to a distance of 250 m from the opposite vehicle, each following gap was 50 m more than the preceding one. Furthermore, to put pressure on the participants and to push them to overtake, a vehicle behind them was honking.

2.3.2 Pedestrian events

A pedestrian suddenly appeared on the right side of the road and crossed the street in front of the participants. In both baseline and experimental sessions, the pedestrian was hidden by a truck or a bus shelter (50% of occurrence). To avoid any learning effect and maximise the surprise effect, bus shelters were randomly placed along the circuit.

- In the baseline session, the pedestrian started to cross the road when the participant's vehicle was 4 s from him (Time to collision, TTC = 4 s).
- In the experimental pedestrian session, a TTC of 2 s was used.

Participants came twice at the lab to perform the two driving sessions (1 week delay between each session). They were equipped with the ECG and SCL sensors, trained to the commands of the driving simulator, and then performed one of the two sessions.

In short, each driving session included two driving events (overtaking or pedestrian), each event was followed by a 5 min of simple following task, then by the filling of the NASA TLX questionnaire and a 5 min break.

2.4 Measures

Synchronization's trigger signals between performance data (i.e., vehicle handling) and electrophysiological data (ECG and SCL signals) were used to identify the end of each driving event (overtaking/pedestrian), from which the car following task was analysed. The end of the pedestrian event was identified 10 s after the crossing of the trajectories of the participant's vehicle and of the pedestrian. The end of the overtaking events was identified 10 s after the complete overtaking manoeuver. Performance and electrophysiological variables were processed over the first 30 s following the end of driving events and over the total duration of the car following task (5 min following the end of driving events).

2.4.1 Performance measures

Responses to the speed changes of the lead car were measured after each driving event by assessing the coherence, the gain and the delay (for the computation method, see [6, 32]). "Coherence" measures how well the subject vehicle matches LV velocity changes. "Gain" is an amplification factor measuring the amount by which the subject overshoots or undershoots the LV velocity changes. When there is an overshoot, the gain is larger than one, while in case of undershoot, the gain is smaller than one. Delay indicates the time it takes for a driver to react to LV velocity changes. The standard deviation of lateral position (SDLP) of the participant's vehicle was also computed.

2.4.2 Electrophysiological measures

The skin conductance level (SCL) was low-pass filtered at 1 Hz using a zero time-lag second-order Butterworth filter (Matlab, Mathworks) to remove high frequency noise. In order to make data comparable among participants, the filtered SCL signals were normalized [12]. To this aim, SCL was first recorded at rest before the drive during 5 min, while participants sat in the simulator without any stimulation, and then averaged to be considered as the reference. SCL recorded during driving was then divided at each sampling point by the reference to obtain the normalized SCL signal (see Fig. 1). At last, the mean value of the normalized SCL signal (noted MSCL in the following sections) was computed.

ECG data were band pass filtered from one to 35 Hz with a IIR digital filter using the AcqKnowledge software (BIOPAC System). The filter could effectively remove the baseline drift and the interference signal such as respiration-related low frequency noise and 50 Hz power-line interference [30]. Then, the ECG signal was cleaned with template correlation and/or manual corrections until a clean tachogram was obtained. At this step, inspection of the ECG can be done in order to correct mistakes in the detection of the R-R intervals process, and also to identify ectopic beats. Heart rate (HR) and the standard deviation of the R-R intervals (HRV) were computed from the cleaned ECG signal.

2.4.3 Subjective measures

A mental workload score from 0 to 20 was obtained from the NASA TLX questionnaire filled in after each driving scenario.

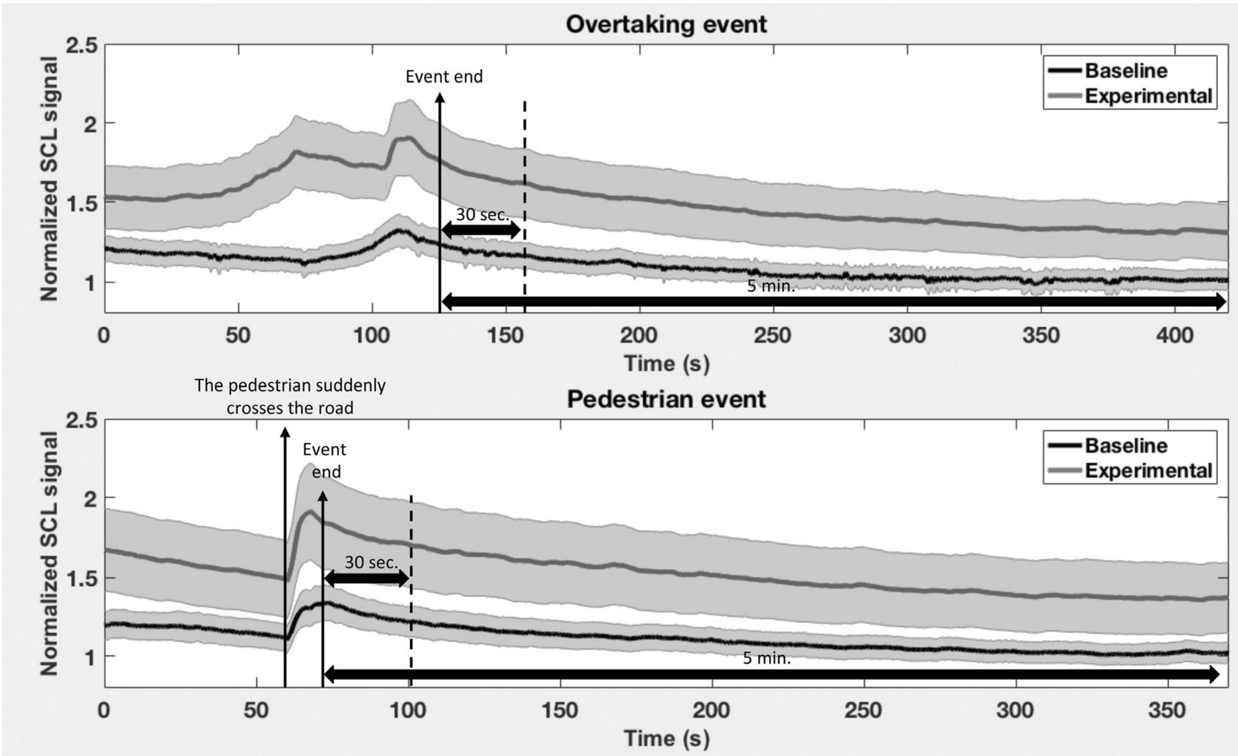

Fig. 1 Mean normalized skin conductance level as a function of time, session and event. For a better visualization, the normalized skin conductance level has been averaged across participant. In grey, the plot standard error envelopes. Note also that the duration of the pedestrian event (i.e., duration between the begining of the crossing and the end of the event) was not exactly the same for each participant, depending of the driver's avoidance maneuver

2.5 Statistical analysis

It has been already demonstrated that crashes involve some form of driver distraction [18, 29] that reduces drivers' awareness of the traffic situation, delays their responses to driving events, increases their perceived mental workload, and the intensity of disruptions in driving performance [8, 25, 31]. Consequently, given our objectives, two participants who crashed the pedestrian were excluded from the analysis.

All the performance and electrophysiological measures were computed during the 30 s and the 5 min following the end of the driving events (i.e. total duration of the car following task). Repeated measures analyses of variance (ANOVAs) were used to test the effects of session (i.e., experimental versus baseline), temporal window (i.e., 30 s versus 5 min following the end of the driving events) and event (overtaking versus pedestrian) on each performance and electrophysiological measure.

Concerning the subjective measures, the effect of temporal window had not been investigated as the NASA TLX questionnaire was only filled in after each driving session. Consequently, ANOVA tested the effects of session and event on mental workload scores.

In case of significant interaction Bonferroni tests were applied. The significance level for analyses was set at $p < .05$.

3 Results

3.1 Performance measurements

3.1.1 SDLP

ANOVA revealed an effect of session on SDLP values ($F(1, 29) = 9.25$, $p < .004$, $\eta^2_p = .24$) with higher SDLPs for the experimental session (170.89 mm ± 63.25) than for the baseline session (148.19 mm ± 57.39). The analysis also indicated a significant effect of temporal window on SDLP values ($F(1, 29) = 29.04$, $p < .001$, $\eta^2_p = .50$). Higher SDLPs were obtained during the 5 min (172.32 mm ± 48.19) than during the 30 s (146.76 mm ± 70.01) following the events. Finally an effect of event was noted ($F(1, 29) = 16.60$, $p < .001$, $\eta^2_p = .36$) with higher SDLPs for the overtaking (173.21 mm ± 59.75) than for the pedestrian event (145.87 mm ± 60.06). No statistically significant interactions were observed.

3.1.2 Coherence

While no significant effect of session ($F(1, 29) = 0.17$, $p = .073$, $\eta^2_p = .004$) and event ($F(1, 29) = 2.47$, $p = .13$,

$\eta^2_p = .08$) on coherence values were reported, the analysis underlined a main effect of temporal window (F (1, 29) = 43.17, p < .001, $\eta^2_p = .60$). Higher coherence values were obtained during the 30 s than during the 5 min following the events (Table 1).

3.1.3 Gain
The analysis revealed a main effect of temporal window on gain (F (1, 29) = 26.67, $p < .001$, $\eta^2_p = .48$) with higher values obtained during the 30 s (.80 ± .28) than during the 5 min (.67 ± .17) following the events. No significant effect of session (F (1, 29) = 2.84, $p = .10$, $\eta^2_p = .009$) and event (F (1, 29) = 1.006, $p = .32$, $\eta^2_p = .03$) on gain was noted (Table 1).

3.1.4 Delay
The ANOVA on delay revealed significant main effect of session (F (1, 29) = 6.34, $p < .02$, $\eta^2_p = .18$) with higher delays for the experimental than for the baseline session. The analysis also indicated that higher delays were obtained during the 5 min than during the 30 s following the events (F (1, 29) = 81.29, $p < .001$, $\eta^2_p = .74$). There was no significant effect of event on delay (F (1, 29) = .36, $p = .55$, $\eta^2_p = .01$) (Table 1).

A significant "session x temporal window" interaction was also found (F (1, 29) = 9.42, $p < .005$, $\eta^2_p = .24$) and highlighted higher delay values during the 5 min following experimental session (3.02 ± 1.77) than during the 5 min following the baseline session (2.10 ± 1.63) ($p < .002$). No significant difference was found between the experimental (.56 ± 1.58) and baseline delays during the 30 s following the events (0.62 ± 1.06).

3.2 Electrophysiological measurements
3.2.1 MSCL
No significant effect of event was found (F (1, 29) = .06, $p = .81$, $\eta^2_p = .002$) but ANOVA revealed an effect of session on MSCL values (F (1, 29) = 3.96, $p < .05$, $\eta^2_p = .12$) with higher MSCLs for the experimental session than for the baseline session. The analysis also indicated a significant effect of temporal window on MSCL values (F (1, 29) = 47.02, $p < .001$, $\eta^2_p = .62$). Higher MSCLs were noted during the 30 s than during the 5 min temporal window (Table 2).

A significant "session x temporal window" interaction was found (F (1, 29) = 5.7, $p < .02$, $\eta^2_p = .16$) and showed higher differences between experimental and baseline MSCL values during the 30 s than during the 5 min following the events (Fig. 2).

3.2.2 HR and HRV
Only temporal window had an effect on HR (F (1, 29) = 13.44, $p < .001$, $\eta^2_p = 032$) with higher HR values obtained during the 30 s (35.62 ± 96.19) than during the 5 min temporal window (17.32 ± 79.90). The effect of *session* (F (1, 29) = 2.09, $p = .02$, $\eta^2_p = .07$) and event (F (1, 29) = .01, $p = .91$, $\eta^2_p = .000$) were not significant (Table 2).

No significant effect were found for HRV values concerning session (F (1, 29) = .64, $p = .43$, $\eta^2_p = .02$), temporal window (F (1, 29) = 2.62, $p = .12$, $\eta^2_p = .08$) and event (F (1, 29) = .04, $p = .85$, $\eta^2_p = .001$) (Table 2).

3.3 Subjective measurements
ANOVA revealed a significant main effect of *session* on mental workload scores (F (1, 29) = 7.81, $p < .05$, $\eta^2_p = .18$) with higher mental workload scores for the experimental session (8.46 ± 3.70) than for the baseline session (7.13 ± 3.14). No effect of *event* was found on mental workload scores (F (1, 29) = .54, $p = .47$, $\eta^2_p = 0 = .02$), values were (8.46 ± 3.65) for the experimental and (7.13 ± 3.10) for the baseline session.

Table 1 Mean values of gain, coherence and delay as a function of temporal window, session and event (SD in brackets)

Experimental factors	Performance measurements		
	Gain	Coherence	Delay
Temporal window			
30 s. following the event	0.65 (0.21)	0.80 (0.28)	0.59 (1.34)
5 min. Following the event	0.53 (0.14)	0.67 (0.17)	2.56 (1.76)
Session			
Baseline	0.59 (0.17)	0.77 (0.20)	2.08 (1.79)
Experimental	0.58 (0.20)	0.71 (0.27)	1.56 (1.36)
Event			
Overtaking	0.60 (0.18)	0.72 (0.24)	1.51 (1.54)
Pedestrian	0.57 (0.19)	0.75 (0.24)	1.65 (2.12)

Table 2 Mean values of MSCL, HR and HRV as a function of temporal window, session and event (SD in brackets)

Experimental factors	Electrophysiological measurements		
	MSCL	HR	HRV
Temporal window			
30 s. following the event	1.27 (0.55)	96.19 (35.62)	0.17 (0.09)
5 min. Following the event	1.08 (0.41)	79.91 (17.40)	0.15 (0.10)
Session			
Baseline	1.27 (0.60)	84.61 (23.53)	0.16 (0.09)
Experimental	1.08 (0.35)	91.52 (33.60)	0.16 (0.10)
Event			
Overtaking	1.19 (0.51)	88.16 (28.25)	0.16 (0.09)
Pedestrian	1.17 (0.48)	88.01 (30.20)	0.16 (0.10)

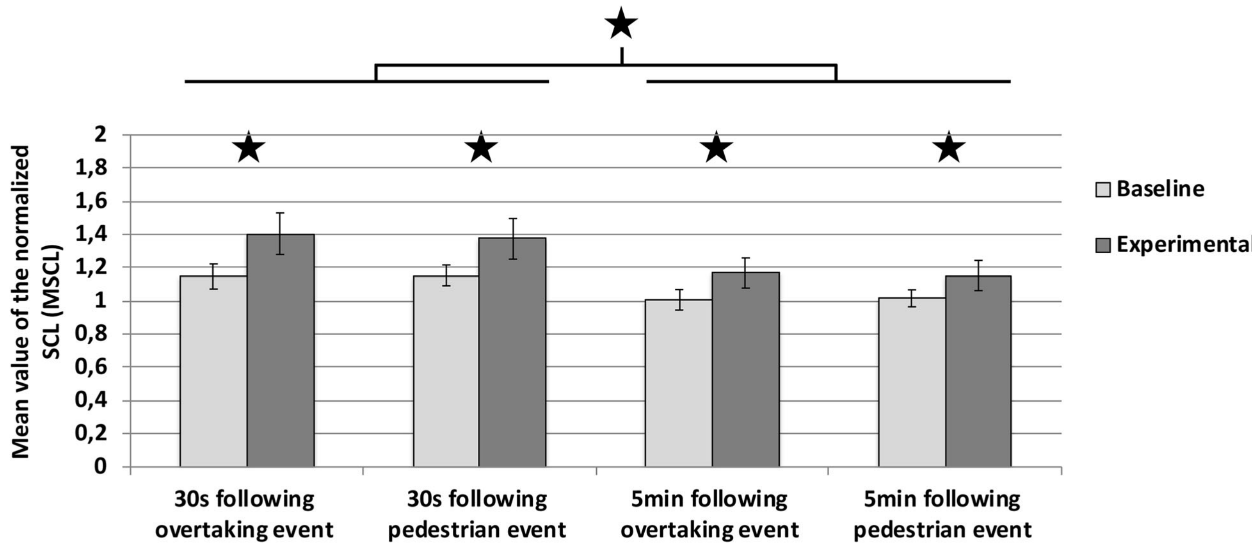

Fig. 2 Mean value of the normalized SCL (noted MSCL) obtained after the events as a function of the temporal window and the condition. The vertical bars indicate the standard error and the asterisks indicate a significant difference

4 Discussion and perspectives

The objective of the present study was to provide a better understanding of long-lasting electrophysiological and performance variations induced by driving events involving an increase in mental workload. To this aim, traffic density and time pressure were varied during two driving sessions in which a standardised car following task was performed after some specific driving events. Electrophysiological and performance data were cut into temporal windows (short: 30 s and long: 5 min after the events) to analyse the impact of an increased mental workload experienced by the participants.

As expected, a higher mental workload subjective estimation (NASA TLX questionnaire) was obtained for the experimental session compared to the baseline session regardless of the event (occurrence of a pedestrian or overtaking manoeuver). Thus, different levels of task demand lead to corresponding self-estimated workload in line with previous studies [36, 42]. Moreover, the experimental session induced higher mean normalized skin conductance level and heart rate, but also higher SDLP than the baseline session. Taken together, these first results clearly indicate that the demand caused by the task induce different level of workload [52]. In past studies, estimated workload [44], SCL [11] and SDLP [20] were already found to be higher when mental demand and/or perceived difficulty increase but our work allows to go one step further by considering the duration of the changes. Splitting data into temporal windows indicates that the subsequent effects of SCL were significantly higher during the 30 s than during the 5 min following each event. Such a result suggests that MSCL could be a short-term marker of the driver's mental workload variations according to traffic conditions and time pressure.

Focusing on driving performance, SDLP increased and speed adaptation degraded (increase of delay) with workload [14–16, 49]. These results are consistent with higher workload estimation and higher MSCL. Performance changes were observed within the 5 min following the driving events, while SCL returned more rapidly to its baseline level. This means that mental workload's increase due to external factors may cause long-term effects on performance and shorter effects on electrophysiological measures [33, 35]. Safety systems based on drivers' mental state monitoring must thus include both behavioural and physiological parameters to provide a comprehensive diagnostic. Further studies are needed to determine if other electrophysiological measures available while driving may also reflect longer or shorter impact of mental workload change than behaviour ones.

We did not find any significant effect of the session on gain and coherence. However, all the measures of performance highlighted a degradation during the 5 min temporal window when compared to the 30 s temporal window (higher SDLP and delay, lower coherence and gain). This overall effect of our driving events reinforce the idea that performance is impacted over a long time period.

Moreover, behavioural results slightly differ as a function of the nature of the driving event. Overtaking event produced higher vehicle handling impairments (degraded SDLP) than the pedestrian event. As expected and in line with Michon's hierarchical model [37], this result could be explained by the different processing modes involved by the two driving events. When manipulating traffic conditions, the automatic processing involved in an avoiding manoeuvre (pedestrian event) could be less affected than the controlled processing involved in the overtaking event [20].

We did not find any effect of traffic conditions and time pressure on heart rate (HR) and heart rate variability (HRV) electrophysiological measures nevertheless known to indicate workload [45, 46]. However, these authors' task differed from ours (workload manipulated in disturbance of a planning task by incoming emergency calls or disturbance by an additional task while driving). Moreover, in their studies, HR and HRV were calculated during relatively short periods of high demand, and then compared to reference values calculated during the direct preceding periods. Here, HR and HRV values were compared after two driving events involving different levels of workload but only an effect of temporal window was reported with higher HR values in the shorter temporal window. This result highlights the effect of our events on heart rate independently of the level of mental workload induced. Thus, in line with previous works [1, 50] which investigated the sensitivity of the cardiac activity for different task load's levels, mental workload would be quite high in our two sessions during the 30 s following the events, resulting in a ceiling effect for HRV and HR. Thus, we assume that SCL consequently demonstrates a high degree of sensitivity when compared to HRV and HR for catching some subtle relatively short-term electrophysiological modifications after an increase in mental workload.

In conclusion, this work assumes that combining electrophysiological and behavioural measures improves the quality of driver's mental workload estimation by considering its variations through different time scales. This combination allows a real enhancement of safety systems (ADAS) so as to overcome the limitations associated with any single measure that can be underreactive for a given driver [53]. It must also be noted that the effect of traffic conditions on mental workload could be highly different according to driving experience and other intrinsic specific factors [47, 54]. Consequently, research in the transportation safety area should probably move towards more accurate drivers' characteristics and the monitoring of the driver's mental workload could help to enhance future advanced driver's assistance systems. For example, an individual MSCL threshold from which mental workload would be estimated as too high could be computed for each driver by considering his/her baseline electrophysiological activity during a driving calibration period. In this perspective, some already existing systems could enable to interpret/recognize the current driving event by using a combination of sensors, radars, GPS, and cameras [5].

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Authors' contributions

All authors made substantial contributions to the design of the work, helped to the interpretation of data and substantively revised the work. Moreover, LH acquired the data and carried out the treatments. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests. A communication was made in 2017 but results have not been published because some confidential agreements. Now, the data are no more confidential and can be published.

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