Mental Strain while Driving on a Driving-Simulator: Potential Effect on Central and Autonomic Responses

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Abstract

We recorded magnetoencephalographic (MEG), autonomic nervous system (ANS) activities and behavioral data during normal driving conditions (ND) and during driving under time constraint (TCD) while drivers had to respect traffic lights in a simulated driving task. Electrodermal activity and heart rate were the dependent variables from the ANS. Cerebral regions of interest, reaction time (RT) and rate of traffic light violations were those from MEG and behavior, respectively. Under TCD conditions, scenarios were likely to elicit high strain. In these conditions, response selection was more complex when drivers should respect traffic law, thus eliciting longer RT with increased activation in the left dorso-lateral prefrontal cortex. Heart rate decrease preceding light change perception was larger under TCD suggesting that drivers focused their attention toward potential light changes before decision-making (i.e. respecting the traffic law or the requested scenario). We finally observed a negative correlation between ANS and left-brain activities. Consequences upon safety are then discussed.

Keywords: Mental Strain, Time Constraint, Cerebral, Electrodermal and Cardiac Activities, Driving Simulator, Safety, Traffic Behavior.

1. INTRODUCTION

Driving requires more or less complex information processing, and thus a series of decisions. Much information should be hierarchically processed resulting in a mental load depending on both task features (eliciting various constraints) and the perception of these constraints (the cognitive cost the individual underwent during task performance). The objective perception of task difficulty, i.e. task complexity, time pressure, or dual-task situations refers to stress, while its subjective perception, related to both the level of experience and anxiety state, refers to strain [1] and [2]. Luczak and Göbel [2] described the strain-stress concept as the specific reactions of the individuals (strain) resulting from task demands and task conditions (stress). Accordingly, the stress induced by the task may interact with intrinsic factors of the individuals, which may cause overload conditions. Thus, the individual's information processing capacity may be too low for adequate task completion [3] and [4]. Overload may thus have detrimental effects on task performance, particularly on reaction time (RT), response accuracy or both [5]. Where holding a conversation with a passenger while driving may elicit distraction, conversation content, however, constitutes an aggravating factor especially when it is emotionally loaded [6] and [7]. Indeed, complex conversations eliciting emotional load may have a detrimental effect on road safety [8] and [9]. Emotion and cognition may thus interact with deleterious effect of emotion upon cognition. The role of emotion in decision-making has been studied in the field of neuroscience [10], [11], [12], [13], [14], [15] and [16]. Negative emotions may reduce information-processing efficiency, information being missed or processed less favorably due to excessive strain [17].

Physiological variables of both central and autonomic nervous system (ANS) provide reliable correlates about changes in mental and affective states. It may vary as a function of strain the participants undergo. Electrodermal activity (EDA) and cardiac measures are reliable indices of physiological arousal changes. While Zhang et al. [18] reported that sympathetic activity obviously increased during task performance, EDA is also known to be sensitive to emotion-related information [19]. As there is no parasympathetic innervation of sweat glands, changes in EDA can only be attributable to changes in sympathetic ends in effectors. Skin Conductance (or resistance) Responses (SCRs) are recorded almost simultaneously with stimulus onset. Electrodermal response is larger and longer when the task demands, the perceived difficulty or both increase [20]. Strain may also be assessed by processing heart rate (HR – [3] and [4]). HR increases during tasks requiring high cognitive demands [21], [22] and [23] and during negative, stressful or adverse events. HR is regulated by both ortho- and parasympathetic systems and might be more sensitive to vigilance, alertness, and probably less sensitive to physiological arousal due to its metabolic function [24]. HR decreased drastically few seconds prior to imperative stimulus, during the preparation phase, when attention is focused on task cues of high interest [25], [26], [27], [28] and [29]. Thus, there is a link between HR decrease and preparation for action or stimulus processing. However, decrement in HR varies as a function of task requirement, difficult trials being associated with larger fore period of HR deceleration [30], [31], [32] and [33]. These results are consistent with Lacey's intake-rejection hypothesis [21] and [22]: a decrease in HR is reported when attention is focused on the environment (individuals are thus more sensitive to new information) while, HR increase might favor the processing of internal cues with simultaneous rejection of external stimuli. ANS activity could be easily recorded through ambulatory and non-intrusive device [34] and [35].

Neuroimaging methods which examine the different stages of information processing also aim at better highlighting the impact of attentional deficit on driving performance [36]. For this purpose, electroencephalography (EEG) and magnetoencephalography (MEG) may be suitable and reliable methods. Event related potentials (ERP) or evoked magnetic fields might be measured in order to assess the dynamics as well as the spatial distribution of cortical activities elicited by both perception and processing of a specific event with good temporal resolution [37]. Regarding cortical activities, many studies reported that the prefrontal cortex (PFC) is a key-cerebral structure in decision-making processes, in particular the ventro-median (VM) and the dorso-lateral parts (DLPFC). Broche-Pérez et al. [38] reported that cortical structures involved in decision-making include the orbitofrontal cortex (OFC), anterior cingulate cortex (ACC), and dorsolateral prefrontal cortex (DLPFC). This process is assisted by subcortical structures including the amygdala, thalamus, and cerebellum. These cortical areas are also involved in secondary emotional processing [10]. As shown by Bechara [14], decision-making depends on neural substrates that regulate emotion and feeling. Many papers reported that a lesion of the VM cortex interfered with the normal processing of somatic or emotional signals and impaired the quality of decisions in daily life [10], [12], [13], [14] and [15]. The amygdala, the somatosensory insular and the anterior cingulate cortices (ACC – [10] and [12]) are also involved in neural networks integrating emotion and have crucial functions in decision-making processes. The neurofunctional correlates of emotional significance of various stimuli could be assessed by isolating the γ-band on different brain areas [39], e.g. in the amygdala, the visual, prefrontal, parietal and cingulate cortices [40]. Emotional stimuli elicit greater increase of the γ-band event related synchronization as compared with neutral stimuli [40]. Balconi and Lucchiari [39] also showed that the γ-band activity provided more reliable insight during high (i.e. anger, fear) than during low arousal (i.e. happiness, sadness) emotions.

This preliminary experiment aims at studying the influence of emotional strain on both the neural processes involved in the processing of relevant visual cues during driving and on peripheral autonomic activity. We hypothesized that longer RTs would be better related to high time constraint conditions than with control conditions when drivers should stop at traffic-lights [36]. We also expected larger electrodermal and cardiac responses during conditions with time constraint than during control. Changes in affective state may be accompanied by specific physiological responses [3], [4], [41] and [42]. During pre-stimulation, we expected larger decrease in HR under high time constraint conditions than during control conditions [30], [31], [32] and [33]. We finally hypothesized that traffic-light change may elicit greater prefrontal cortical activations under high time constraint conditions, especially in the ventromedial part and in the ACC [10] and [40]. Likewise, increased emotional load may be correlated with a modulation of activity in cortical areas controlling attention (dorsolateral prefrontal cortex, DLPFC – [10], [43], [44] and [45]) and in visual areas [36]. Due to close relationships between cortical areas and peripheral activity, increased activity in the right ACC may activate the sympathetic system thus eliciting stronger responses from the autonomic nervous system [46], [47] and [48]. Conversely, the left hemisphere is involved in ANS inhibition. Therefore, higher activity from the left brain might result in lower autonomic responses [46], [49] and [50].

2. METHODS

Participants were confronted with driving sessions using a driving-simulator fitted to a MEG setting. The normal driving condition (ND) was considered the reference. Participants had to follow directions indicated by signs on the roadside. In the normal driving condition, drivers had to abide by the traffic law, and to particularly respect traffic lights. The conditions eliciting time constraint also included a scenario, e.g. driving a friend to the train station when there is little chance to catch the train due to both insufficient time and heavy traffic, or delivering a fragile package while being late. Under these conditions, traffic lights went frequently from green to orange, normally requiring the driver to stop.

2.1 Participants

Six healthy men, aged from 20 to 30 years (mean=27.33, SD=2.09) took part voluntarily in this experiment after giving their informed consent. The local ethic committee gave its approval to the experimental design. All participants were naive to the purposes and expected results of the experiment. None were under medications or had cardiac diseases that may influence physiological activity. None of them reported any mental pathology. They had a driving license for at least 3 years with normal or corrected to normal vision.

Deviant behaviors were assumed as exclusion criteria. The experimenters checked in real-time whether the participants showed deviant driving behaviors: we especially checked if they followed the lane and drove on the right side. We never observed deviant driving behavior.

2.2 Experimental Design: Procedure and Instructions

We recorded both magnetoencephalographic and autonomic activities with the aim of assessing how drivers managed high strain conditions, i.e. managing changes in traffic lights while being under time pressure.

Participants drove either on a single or 2-lane road in an urban environment and were confronted with 18 different randomly-controlled driving scenarios of about 5 minutes each. When necessary, participants could take short breaks (1-3min) between blocks in order to reduce blinking. At the experiment's midpoint, a longer break (10-15min) was imposed. Participants underwent one or two 5 min-training sessions before starting the experiment. During each experimental session, traffic lights randomly turned from green to orange between 107 and 115 times (i.e. ~30% of all traffic lights, mean=111.17, SD=2.86). All traffic lights were on the right side of the road and could turn from green to orange when the vehicle approached them at about 30m, otherwise the lights remained green and the driver was free to move forward. Signal switching was controlled by the speed of the vehicle in order to standardize the conditions for all participants. In rare cases, the signal was already red when perceived by the driver. While the main aim of the experiment was to study decision making when the traffic light changed from green to orange, several other experimental conditions were completed to prevent drowsiness and habituation across time. Several lights remained green when the drivers' car was approaching. Light changes were organized in a way that could not be predictable by the drivers. Thus, they always were faced an unexpected situation. For 9 of the scenarios, drivers were subject to normal driving (ND). In the 9 other scenarios, participants were confronted with conditions inducing time constraint (TCD). The order of the ND and TCD conditions was counterbalanced among participants. In the ND, drivers only had to respect the traffic law: they were especially required to stop when the signal changed from green to orange. No additional instructions were given. Thus, ND was the control condition. Under TCD, drivers had to respect both the traffic law and a scenario inducing high load, particularly time pressure, encouraging them to drive faster than they normally would.

2.3 Behavioral Analysis

2.3.1 Reaction Time (RT) Data Recordings and Analysis

RT was the time duration between signal change and the first action on the pedals, i.e. the moment the participants remove their foot from the accelerator pedal. Distribution of RT is usually not Gaussian and is more consistent with Poisson's law. There is thus higher probability that the inverse of RT (1/RT) would follow a Gaussian law. We thus tested this hypothesis using the Shapiro-Wilk test. We also compared 1/RT between ND and TCD using t-test. In this analysis, we did not include data associated with traffic lights violation (drivers who did not stop when the signal changed from green to orange, with or without associated braking).

2.3.2 Traffic Lights Violation

The rate of traffic lights violation in both ND and TCD was also considered a behavioral dependent variable. We performed simple regressions to assess the impact of lights violation on both central and autonomic activities (under the condition in which some traffic lights were not respected, i.e. under TCD).

2.4 MEG Acquisition and Analysis

To record cortical activities during driving sessions, participants were required to drive a virtual car using a driving simulator fitted with MEG environmental constraints, i.e. adapted to a nonmagnetic environment. This simulator was equipped with a steering wheel, a turning indicator, an accelerator and a brake pedal. The experiment was conducted at the MEG Centre (CERMEP, Bron, France). At first, and prior to scanning, head coils were placed on the nasion and on both left and right pre-auricular points, thus enabling continuous head localization recording. Then, the location of these coils and the head-shape of each participant were digitized with Polhemus (Polhemus Inc., Vermont, USA).

MEG recordings were performed using a whole-head MEG system (Omega 275, CTF, VSM MedTech Ltd.) with 275 radial gradiometers over the scalp and 33 reference channels for ambient field correction. Signals were digitized at a sampling rate of 300Hz and were recorded continuously applying band-pass filtering from 0 to 75Hz. Vertical and horizontal eye movements (electro-oculogram, EOG) were also recorded for artifact control. A marker was automatically triggered as early as traffic lights turned from green to orange to help along data analysis. Before starting data processing, we removed trials with excessive eye blinks, muscular or electromagnetic artifacts and head movements from further analysis. We initially selected few blinks manually to create a template. Then, we used the template to mark blinks automatically with a feedback to control whether the template worked adequately. We then checked that no blink occurred within both the [-5s/-4s] window (before light change) and the [0s/1s] window (just after light change), i.e. in the time window of interest used for Synthetic Aperture Magnetometry analyzes. Muscle activity rejection was carried out manually. Epochs of MEG signal for which head movements exceeded 1cm on the 3 coils were consistently suppressed. After rejection, we preserved a mean of 42 (SD=10.26) and 30 (SD=12.37) responses to traffic lights changes per participant for ND and TCD conditions, respectively.

The regions of interest (ROI) were the prefrontal cortex and particularly the dorsolateral prefrontal cortex (DLPFC), the anterior cingulate cortex (ACC) and the ventro-median (VM) cortex (including the orbitofrontal part). We also focused on the occipital and motor cortices activities. We investigated the right and left side of the brain separately, with the exception of the motor cortex where the region of interest was on the left side. We investigated PFC and occipital cortex activities in the γ-band (30-50Hz - [40]) while we focused in the β-band to study motor cortex activity (13-35Hz - [51]). Depending on whether we consider the γ-band (e.g., on the PFC and occipital cortex) or the β-band (e.g. on motor cortex), activation could either be related to ERS (event related synchronization) or ERD (event related desynchronization). Indeed, this depends on both the number of neurons still available for synchronization, which might be activated by experimental conditions, and the level of excitability of neurons at rest. In brain areas where we studied the γ-band, the cortical excitability level at rest is low, many neurons being thus still available for synchronization. Accordingly, activation corresponded to ERS and increase of power corresponded to cortical activation. However, in brain regions where we examined the β-band, the cortical excitability level at rest is high, few neurons being available for synchronization. Thus, in this frequency band, ERD and therefore a decrease of power is induced by cortical activation [51].

We used a beamforming technique and virtual sensors for data processing. We assessed the spatio-temporal dynamics of cerebral processing, i.e. where and when brain activity changes occurred. Indeed, we performed Synthetic Aperture Magnetometry (SAM) analysis and applied paired t-tests to compare the [0s/1s] active time-window after light change to the [-5s/-4s] control time-window. ND and TCD conditions were processed separately. Each condition and each side of each ROI were associated with the most significant selected voxels (Figure 1).

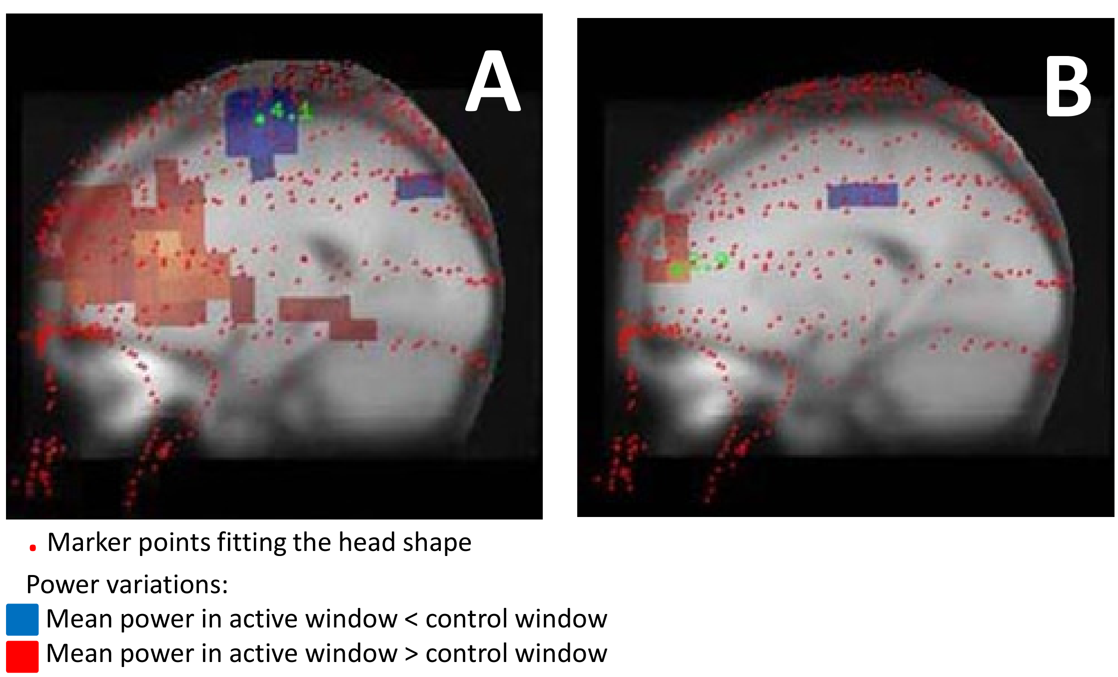

FIGURE 1: Two examples of maximal activations: for the motor cortex (A) and the VM cortex (B). A blue volume (A) is associated with a mean power in the active window lower than that in the control window. A red volume (B) is related to a mean power in the active window greater than that in the control window.

Then, we determined virtual sensors to process power variations (nanoAmpère-meter/T) for the selected voxels between [0s/1s] and [-5s/-4s] time-windows (Figure 2). We then based data analysis on this power variation measure using a single value per condition and ROI.

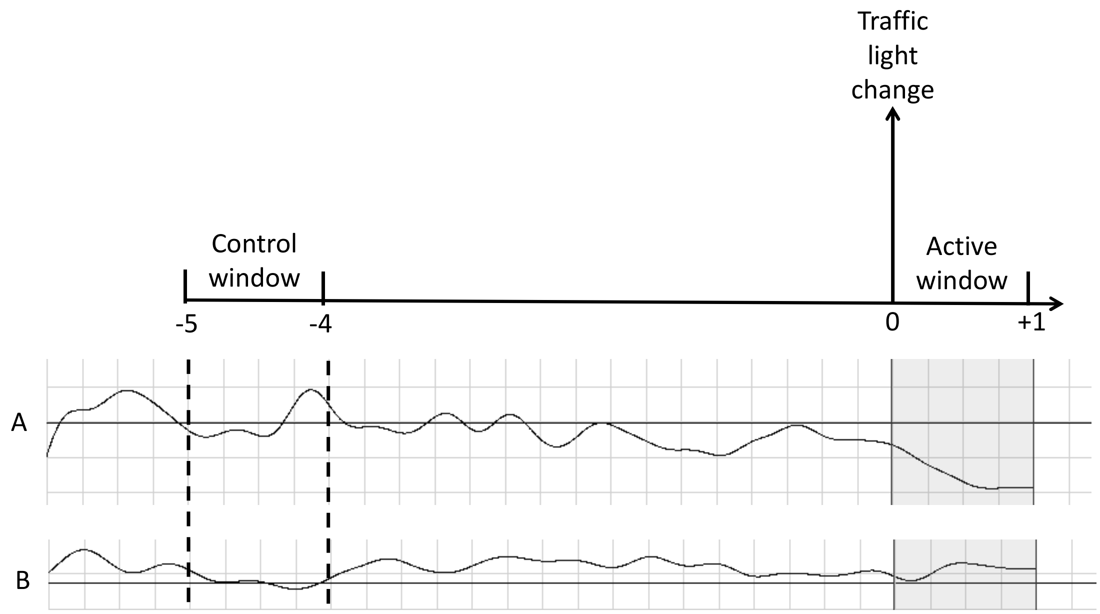

FIGURE 2: MEG analysis. 0 indicates the exact time of light change from green to orange. We determined virtual sensors for each maximum to study the mean power in the [0s/1s] active window (following the light change) in relation with the mean power in the [-5s/-4s] control window (before the light change). Virtual sensor A shows that the mean power is lower in the active than in the control window. Conversely, virtual sensor B indicates that the mean power is greater in the active as compared with the control window.

We performed t-tests to assess the difference between ND and TCD regarding the power variation values obtained for each ROI, i.e. left and right (L/R) DLPFC, L/R VM cortex, L/R anterior cingulate cortex, L/R motor cortex, and L/R occipital cortex. We finally performed simple regressions to study the effect of lights violation on brain activity under the TCD condition (i.e., on the power variation value for each ROI). We normalized TCD power variations as compared with those from ND by computing the difference between both conditions, for each side of each ROI.

2.5 ANS Data Recording and Analysis

We used a system designed by the team "Microsensors and Biomedical Micro-Systems" of the National Institute of Applied Sciences of Lyon (INSA, Lyon) to record ANS activity ([35], e-motion device). This is an integrated device for simultaneous and real-time recordings of both electrodermal and cardiac activities. Electrodermal activity (EDA) and instantaneous heart rate (IHR) were continuously recorded and were the two dependent variables. ANS variables give a close estimation of participants' physiological arousal especially through the sympathetic branch. We selected larger time-windows for ANS responses analysis than for MEG responses as ANS responses occurred within longer periods of time. We thus extended the time-window to [-10s/5s]. Due to its sensitivity to motor preparation, we observed HR responses from 10 s before stimulus onset until 5s after. Electrodermal responses would probably occur after the traffic light changed and were thus studied in the post-stimulus period: the electrodermal responses which began in the 5s time-window after stimulus onset were considered and quantified by their amplitudes and durations (see Figure 3). We aimed at processing, as much as possible, the same trials for ANS and CNS analysis with the exception of those including artefacts, which were removed from the dataset.

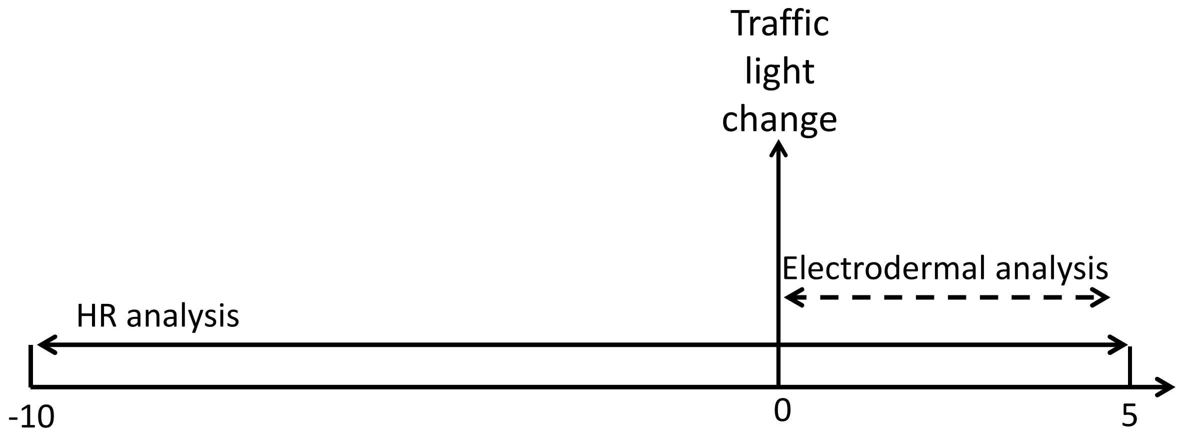

FIGURE 3: ANS analysis. 0 indicates the exact time of light change from green to orange. We processed ANS activities (HR and electrodermal activities) by using a [-10s/5s] window of interest. We processed cardiac activity within a [-10s/5s] window of interest (both pre- and post-stimulation cardiac responses were studied) and EDA within a [0s/5s] window of interest (we only considered electrodermal responses after stimulation).

EDA was measured with 5 µA DC current and recorded using 50 mm^2 unpolarizable Ag/AgCl electrodes (Clark Electromedical Instruments, Edenbridge, UK). Thus, the current density was 10 $µA/cm^2$, as recommended by the international standards. The EDA sampling rate was 20 Hz. We used a low-pass analog filter during the acquisition and no high-pass filter. The cut-off frequency was 1 Hz. We detected ANS responses manually with reference to event markers positioning [52]. We then computed skin resistance response amplitude during the post stimulation period using the tools provided by the software. As skin resistance amplitude is likely to be sensitive to strong variations in basal values, we simultaneously processed response duration through the Ohmic Perturbation Duration (OPD). The OPD is measured from the sudden drop after the stimulus was triggered until the exact point where the slope started recovering its initial level again without any fluctuation [53] and [54]. OPD is thus defined as the time-period during which the individual remains under the influence of the stimulus. In sum, only electrodermal responses occurring within the 5s-period time window after stimulus onset were considered [55]. We processed response amplitude and duration.

HR was recorded from three silver electrodes placed in the precordial position thus recording ECG. The time of occurrence of the R-waves could thus be determined. The time-interval between two consecutives R-waves of the ECG (the D2 derivation signal) was processed electronically and delivered in the form of IHR. The smallest appreciable variation was 0.5 of a bpm and the calibrated scale ranged from 0 to 200 bpm. The IHR signal was directly extracted from the ECG at the level of sensors. Therefore, the IHR was an analog signal and data acquisition was then carried out at 20 Hz. By this method, HR increase or decrease could easily be detected and quantified as a reliable indicator of strain [2] and [19]. IHR enabled the observation of HR variation across time, especially decrease in HR usually occurring during the preparation phase of motor response. IHR is also likely to increase in response to decision making [21]. We thus computed the difference between the lowest IHR value during the 5s preceding the light change and the mean IHR pre-stimulation values, averaged during the 10s-period preceding stimulus onset, as shown by Figure 4. A 5s-delay prior to stimulus was taken by Stern [26] as an index of attention (i.e. readiness to act). We processed increase in HR by measuring the difference between the highest IHR value within the 5s following stimulus onset (light change) and HR baseline value (averaged within the 10s pre-stimulation time-window). We finally computed the difference between the highest IHR value within the 5s post-stimulation time window and the lowest IHR value in the 5s pre-stimulation time window as an index of mental effort and physiological arousal. All indicators related to IHR are summarized in Figure 4.

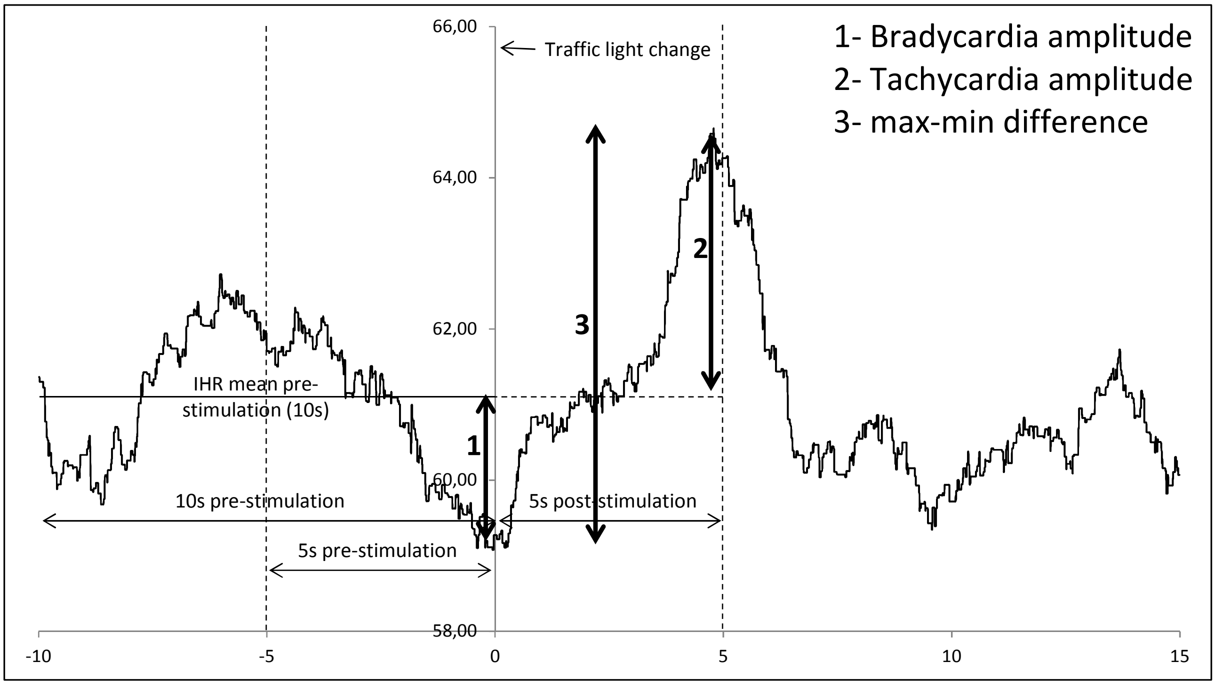

FIGURE 4: Description of HR indices through an example from the dataset. Decrease in IHR (1), increase in IHR (2) and max-min difference (3).

We used t-tests to compare electrodermal and cardiac indices under ND and TCD. We finally carried out simple regression analysis to test the effect of the rate of lights violation on the ANS indices.

2.6 MEG and ANS Relationships

Statistical analysis aimed at testing the effect of brain activities on ANS responses, as a function of both ND and TCD conditions. We thus used simple regressions to test the effect of power variation values in specific left and right brain regions of interest on ANS activity changes.

3. RESULTS

3.1 Behavioral Results

3.1.1 RT

The Shapiro-Wilk test confirmed that the distribution of 1/RT data was Gaussian in both ND ($W=0.89$, $p=.32$) and TCD conditions ($W=0.98$, $p=.93$). Then, t-test revealed significant difference in RT when comparing ND to TCD (mean difference=0.75, $t=3.46$, $p<.02$). Mean (SD) RT were 390ms (170) and 480ms (240) during ND and TCD, respectively.

3.1.2 Percentage of Traffic Lights Violation

Drivers respected all traffic lights changes under ND while 18% of traffic lights were violated under TCD. Figure 5 summarizes the rate of lights violation for each driver.

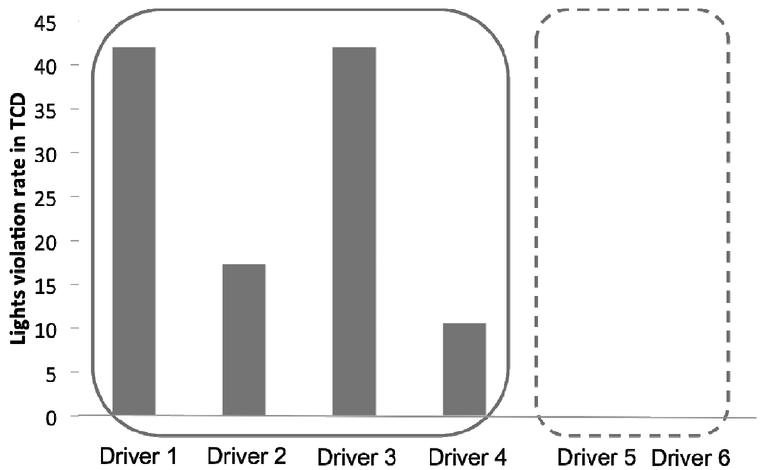

FIGURE 5: Proportion of lights violation rate in TCD. Under the ND condition, all traffic lights were respected.

3.2 MEG Results

We did not observe differences between ND and TCD conditions regarding the power variation values recorded for each ROI, i.e. L/R DLPFC, L/R VM cortex, L/R anterior cingulate cortex, L/R motor cortex and L/R occipital cortex. Regression analysis showed significant results only for the TCD condition. Under TCD, simple regressions revealed that the power variation in the left DLPFC marginally increased simultaneously with the rate of lights violation ($F(1,4)=5.46$, $p=.08$ - see Figure 6). The weak number of participants did not allow reaching statistical significance. Nevertheless, power calculation with alpha set at 0.05 and power at 0.80 gave a sample size of 9 participants to reach the significance.

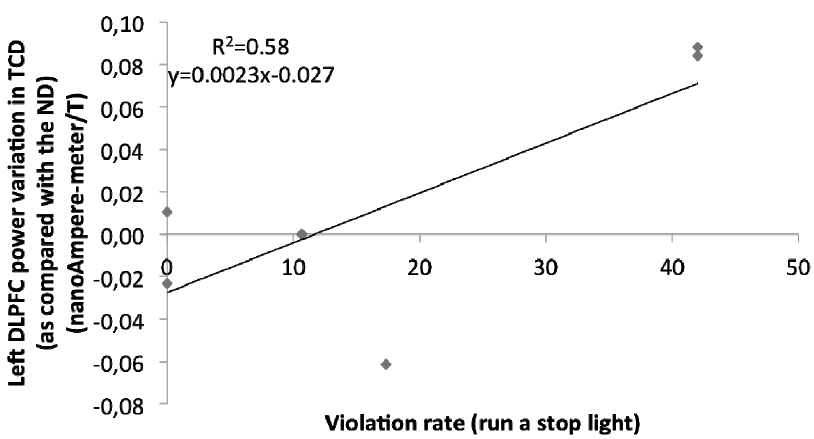

FIGURE 6: Left DLPFC power variation in TCD (as compared with ND) as a function of the lights violation rate.

Under the same condition, the power variation in the left motor cortex increased simultaneously with the rate of lights violation ($F(1,4)=10.17$, $p=.03$ - see Figure 7).

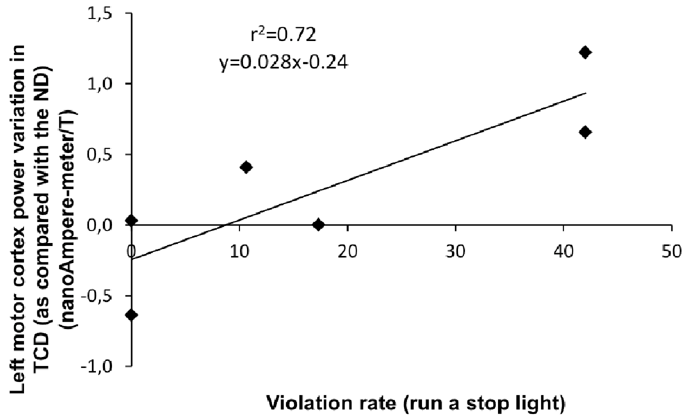

FIGURE 7: Left motor cortex power variation in TCD (as compared with ND) as a function of the lights violation rate.

3.3 ANS Results

Under TCD, simple regressions revealed that OPD decreased along with an increase of lights violation, however with a marginally significant p value (F(1,4)=6.25, p=.07). Power calculation with alpha set at 0.05 and power at 0.80 gave a sample size of 9 participants to reach significance.

We recorded larger HR decrease under TCD than under ND condition (mean difference=0.63, t=2.73, p=.04), during the 5s pre-stimulation period. Mean (SD) IHR values were -4.33 bpm (0.83) and -3.70 bpm (0.38) during TCD and ND, respectively.

3.4 Relationship between MEG Activities and Autonomic Activities

The ND is the only condition, which showed significant relationships between MEG and ANS data. Under this condition, we highlighted a negative relationship between electrodermal response amplitude and power variation in the left ACC, i.e. a decrease of response amplitude along with an increase of power variation in this brain area (F(1,4)=31.3, p=.005 - Figure 8A).

Under the same condition, we also observed a negative relationship between increase in HR and power variation in the left ACC (F(1,4)=11.9, p=.03 - Figure 8B).

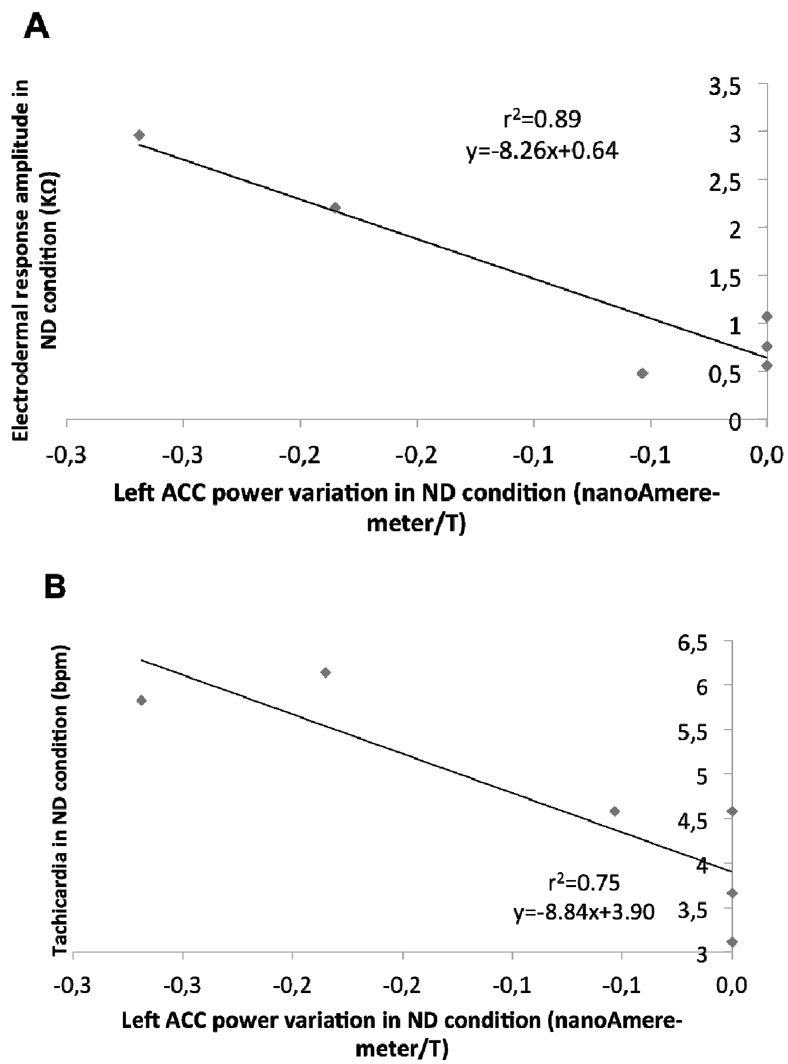

FIGURE 8: Electrodermal response amplitude (A) and HR increase (B) as a function of left ACC power variation. ANS activity is negatively correlated with central activity at the level of the left ACC.

4. DISCUSSION

As expected, we detected longer RTs when drivers stopped at traffic lights under high time constraint (TCD) than during normal driving (ND). Driving was more complex as the time allocated to process the same information, i.e. the traffic light switching from green to orange, was reduced under TCD condition [5]. While time pressure may accelerate information processing this could simultaneously be detrimental to response accuracy. Under TCD, respecting traffic law and scenario instructions contributed to making the decision-taking process a more difficult task and thus resulted in increased RTs. In the speed-accuracy trade-off, TCD resulted in taking more time to process the information although TCD simultaneously led four drivers out of six exhibiting higher rates of traffic-light violation while the 2 others respected all traffic lights. TCD would thus result in both increasing RT and sometimes disregard the traffic law, with the consequence of potentially impacting safety. Finally, TCD may have required an increase of top-down attention to select the relevant information and action, i.e. braking to stop at the red light or not [56]. Indeed, we observed a large rate for non-compliance with traffic-lights, i.e. from 0 to 42%. The expectancy theory [57] assumes that behavior results from conscious choices among alternatives whose purpose is to maximize utility and pleasure, on the one hand, and minimize pain and constraint, on the other. The majority of drivers, i.e. four out of six, did not wish to waste time by stopping at traffic lights and preferred to be on time. We may wonder whether this behavior is due to the fact that the experience was simulated. This would have encouraged the participants to less respect the Highway Code since no compliance with the traffic light has any consequences in terms of safety when driving a driving simulator. However, we do think that drivers' behavior would probably have been comparable under actual driving conditions. Indeed, two drivers respected the traffic law, even if they were involved in simulated conditions: they might intend to reach safely their destination despite time pressure. Driving behavior has also been shown as depending upon other parameters than driving itself. It might be thus explained by traffic culture and personality traits. Indeed, previous studies reported that people who show risky behavior in everyday life would be prone to take more risks while driving. For instance, they would tend to phone or send a text message while driving, thus believing that they have the ability to process two tasks simultaneously [58] and [59]. Other comparable behaviors have already been described, e.g. drivers who exhibit risky behaviors in daily life were also those who drive without wearing their seatbelt or after consuming alcohol, who were likely to drive faster, change lanes more frequently, spend more time in the left lane, and engage in more instances of hard braking and high acceleration events. Despite our experiment was simulated, drivers nevertheless kept in mind that risky behavior may impact safety. According to Megias et al. [60], emotional cues under high time constraints slow down participants' decision-making and make them less able to discriminate risky from not risky situations. Thus, task features are important factors in understanding risk behavior under high constraint conditions. Conversely, drivers respected all traffic-lights under ND condition and were thus more likely to stop at the traffic-light when they were not under high strain due to time pressure.

The major finding of the present experiment is that both conditions selectively impacted brain activation. During TCD, the activity increased in the γ-band, in the left DLPFC simultaneously with the rate of lights violation. The DLPC is known as being involved in complex cognitive processes, e.g. attention, working memory, anticipation and motor response selection [10], [43], [44] and [45]. The DLPFC activation under TCD confirms that this condition was more demanding. We also reported an increase of power variation in the β-band on the left motor cortex along with an increase of the rate of traffic lights violation. This is coherent with drivers' action when violating traffic light, as they probably did not brake. In similar driving conditions, Fort et al. [36] reported increased activation in the supplementary motor area. As in our study, drivers should stop at the traffic lights but no violations were reported, probably because drivers had no time constraint and were only instructed to drive at their own pace. We may thus conclude that the supplementary strain elicited by time pressure may have affected both drivers' behavior and the processing of relevant information.

We also observed that decrease in HR preceding traffic light perception was larger under TCD than under ND condition. Previous experiments reported that HR changes correlated with attention. HR decreases when attention is diverted towards the environment, i.e. when the attention is focused on cues of particular interest [21], [22], [25], [26], [27], [28] and [29]. Other data also showed that difficult task requiring the allocation of high attentional resources elicited larger HR deceleration during the fore-period [30], [31], [32] and [33]. In our study, drivers better focused their attention toward changes in the environment under TCD than under ND condition. This is well attested by HR responses. During TCD, they drove at higher speed than during ND and had to pay attention to both traffic light changes simultaneously with other environmental changes (i.e. other vehicles, pedestrians…). Avoiding risky situations, especially in the case of traffic light violation, thus required the allocation of more attention resources and resulted in larger HR decrease.

The aim of this experiment was finally to highlight the relationship between central and peripheral autonomic activities. High correlation between both would allow considering ANS activity as reflecting central processing and therefore that mental and emotional states of the driver could be monitored in real-time through peripheral variables of the ANS. Both EDR and HR response amplitude decreased while the power variation of the left ACC increased in the γ-band. Thus, both ANS indices decreased along with increasing activity in the left ACC [51]. We therefore observed a negative relationship between ANS and left-brain activities, especially in the left ACC. This is in accordance with previous studies reporting that the left hemisphere is involved in ANS responses inhibition. Indeed, several studies showed that damages in the left hemisphere increased ANS responses [46], [49] and [50]. Conversely, right hemisphere damages resulted in opposite effects [46], [49] and [47]. Likewise, Wittling et al. [61] revealed that parasympathetic activity is under the main control of the left hemisphere while sympathetic activity is mainly controlled by the right hemisphere. Critchley et al. [48] later confirmed the right hemisphere dominance over sympathetic activity, especially at the level of the right ACC, right insular and right OFC. Our results are hence consistent with previous papers highlighting the control of left ACC upon ANS responses inhibition. Therefore, ANS activity might be considered highly correlated with CNS activity. It may thus give reliable information regarding drivers' functional state while driving. ANS activity recordings in real-time (e.g. EDA or HR through non-intrusive sensors) might give relevant information to drivers if these could be used as feedback information. In the near future, this information could be interpreted by drivers as information linked with their own strain if they were directly available from an intelligent traffic system integrated to the vehicle through non-intrusive sensors. This information could help the drivers in deciding whether to stop or continue driving on the basis of the feedback provided [62], [63] and [64].

Behavioral and physiological variables actually showed that conditions inducing time constraint might have a detrimental impact on road safety. The strain added by time pressure was likely to influence drivers' behavior by increasing RT (in response to traffic light changes) and/or by increasing traffic lights violation (due to time-pressure). Additional strain elicited by time pressure showed that the cerebral processing of relevant information could be altered and that emotional state may interfere with decision-making. Respecting the traffic law as it should be, strongly interfered with the rate of traffic lights violation when the aim was to meet time constraints. We could transfer these results with caution to actual driving conditions as they were obtained under simulated driving conditions and therefore drivers' safety was not at stake. Other important features that should be considered are from drivers' personality traits, and their ability to handle driving conditions with time constraints. While improving road safety has made significant progress in terms of vehicles, equipment and infrastructure, the next step is to work on individual behavior, emotional characteristics of drivers and their implications in traffic safety. As expected, the comparison of the two driving conditions revealed the detrimental effects of TCD situations on driving safety. However, certain lines will have to be deepened. Future researches may differentiate autonomic and central activities depending on drivers' behavior (respecting or not of the Highway Code) or on personality traits (anxious, impulsive, calm). It will thus allow testing factors inducing the mental and/or emotional load while driving, i.e. either external (time pressure, environment requiring to be careful), internal (ruminations, negative thoughts) or both. From the results already obtained, along with future researches, we may expect to propose some recommendations in terms of driving safety to provide effective tools addressing attentional deficits (e.g. avoiding driving when the traffic is busy or by night; reducing speed thus allowing much time to select and process all relevant information from the road scene…). To be valid these recommendations will have to consider driver's psychological features, e.g., driving experience and age. The present study also showed that the autonomic nervous system activity might be a reliable, although indirect, indicator of the central nervous system activity. It is thus worth considering to use physiological signals embedded to intelligent traffic systems to assess drivers' mental and/or emotional states in real time. The ultimate goal would be to make these systems capable of advising the drivers according to their physiological and functional state (e.g. take a break as soon as possible). These may thus contribute to the reduction of critical driving situations due to attentional deficits and therefore to better prevent car crashes.

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6. REFERENCES

[1] A.W.K. Gaillard. “Comparing the concepts of mental load and stress”. Ergonomics, vol. 36, pp. 991-1005, 1993.

[2] H. Luczak and M. Göbel. “Signal processing and analysis in application”, in Engineering psychophysiology (Issues and Applications). R.W. Backs & W. Boucsein, Ed Lawrence Erlbaum Associates, 2000, pp. 79-110.

[3] W. Boucsein and R.W. Backs. “Engineering psychophysiology as a discipline: Historical and theoretical aspects”, in Engineering psychophysiology (Issues and Applications). R.W. Backs & W. Boucsein, Ed. Lawrence Erlbaum Associates, 2000, pp. 3-30.

[4] W. Boucsein and R.W. Backs. “The psychophysiology of emotion, arousal, and personality: Methods and models”, in Handbook of digital human modeling: Research for applied ergonomics and human factors engineering. V. G. Duffy, Ed. Broca Raton US:CRC Press, 2009, pp. 35-31-35-18.

[5] A. Ninio, and D. Kahneman. “Reaction time in focused and in divided attention”. Journal of Experimental Psychology, vol. 103, pp. 394-399, 1974.

[6] C.S. Dula, B.A. Martin, R.T. Fox, and R.L. Leonard. “Differing types of cellular phone conversations and dangerous driving”. Accident Analysis & Prevention, vol. 43, pp. 187-193, 2011.

[7] T.C. Lansdown and A.N. Stephens. “Couples, contentious conversations, mobile telephone use and driving”. Accident Analysis & Prevention, vol. 50, pp. 416-422, 2013.

[8] M.A. Recarte and L.M. Nunes. “Mental workload while driving: Effects on visual search, discrimination, and decision making”. Journal of Experimental Psychology: Applied, vol. 9, pp. 119-137, 2003.

[9] C. Lemercier and J.M. Cellier. « Les défauts de l'attention en conduite automobile: inattention, distraction et interférence ». Le travail humain, vol. 71, pp. 271-296, 2008.

[10] A.R. Damasio. L'erreur de Descartes: la raison des émotions: Odile Jacob, 1995, 384 p.

[11] A.R. Damasio, B.J. Everitt, and D. Bishop. “The Somatic Marker Hypothesis and the Possible Functions of the Prefrontal Cortex [and Discussion]”. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, vol. 351, pp. 1413-1420, 1996.

[12] A. Bechara, H. Damasio, A.R. Damasio, and G.P. Lee. “Different contributions of the human amygdala and ventromedial prefrontal cortex to decision-making”. Journal of Neuroscience, vol. 19, pp. 5473-5481, 1999.

[13] A. Bechara, H. Damasio, and A.R. Damasio. “Emotion, decision making and the orbitofrontal cortex”. Cerebral Cortex, vol. 10, pp. 295-307, 2000.

[14] A. Bechara. “The role of emotion in decision-making: Evidence from neurological patients with orbitofrontal damage”. Brain and Cognition, vol. 55, pp. 30-40, 2004.

[15] A. Bechara and A.R. Damasio. “The somatic marker hypothesis: A neural theory of economic decision”. Games and Economic Behavior, vol. 52, pp. 336-372, 2005.

[16] M. Cella, S. Dymond, A. Cooper, and O. Turnbull. “Effects of decision-phase time constraints on emotion-based learning in the Iowa Gambling Task”. Brain and Cognition, vol. 64, pp. 164-169, 2007.

[17] A.W.K. Gaillard and A.F. Kramer. "Theoretical and methodological issues in psychophysiological research", in Engineering Psychophysiology (Issues and Applications). R. W. Backs & W. Boucsein, Ed. Lawrence Erlbaum Associates, 2000, pp. 31-58.

[18] X. Yu, J. Zhang, D. Xie, J. Wang, and C. Zhang. "Relationship between scalp potential and autonomic nervous activity during a mental arithmetic task". Autonomic Neuroscience, vol. 146, pp. 81-86, 2009.

[19] C. Collet, P. Averty, and A. Dittmar. "Autonomic nervous system and subjective ratings of strain in air-traffic control". Applied Ergonomics, vol. 40, pp. 23-32, 2009.

[20] C. Collet, C. Petit, S. Champely, and A. Dittmar. (2003). "Assessing Workload through Physiological Measurements in Bus Drivers Using an Automated System during Docking". Human Factors: The Journal of the Human Factors and Ergonomics Society, vol. 45, pp. 539-548, 2003.

[21] J.I. Lacey, J. Kagan, B.C. Lacey, and H.A. Moss. "The visceral level: situational determinants and behavioral correlates of autonomic response stereotypy", in Expressions of emotions in man. P. H. Napp, Ed. New York: International Universities Press, 1963, pp. 161-196.

[22] J.I. Lacey and B.C. Lacey. "Some autonomic-central nervous system interrelationships", in. Physiological correlates of emotion. P. Black, Ed. New York: Academic Press, 1970, pp. 205-227.

[23] T. Sosnowski, A. Bala, and A. Rynkiewicz. "Mental task demands and cardiovascular response patterns". Biological Psychology, vol. 84, pp. 264-271, 2010.

[24] B.L. Wilkes, C.J. Gonsalvez, and A. Blaszczynski. "Capturing SCL and HR changes to win and loss events during gambling on electronic machines". International Journal of Psychophysiology, vol. 78, pp. 265-272, 2010.

[25] M.G. Coles and C.C. Duncan-Johnson. "Cardiac activity and information processing: the effects of stimulus significance, and detection and response requirements". Journal of Experimental Psychology: Human Perception and Performance, vol. 1, pp. 418-428, 1975.

[26] R.M. Stern. "Reaction Time and Heart Rate between the GET SET and GO of Simulated Races". Psychophysiology, vol. 13, pp. 149-154, 1976.

[27] E.J.P. Damen and C.H.M. Brunia. "Changes in Heart Rate and Slow Brain Potentials Related to Motor Preparation and Stimulus Anticipation in a Time Estimation Task". Psychophysiology, vol. 24, pp. 700-713, 1987.

[28] H. Zimmer, G. Vossel, and W.D. Fröhlich. "Individual differences in resting heart rate and spontaneous electrodermal activity as predictors of attentional processes: effects on anticipatory heart rate decelaration and task performance". International Journal of Psychophysiology, vol. 8, pp. 249-259, 1990.

[29] V. De Pascalis, R.J. Barry, and A. Sparita. "Decelerative changes in heart rate during recognition of visual stimuli: effects of psychological stress". International Journal of Psychophysiology, vol. 20, pp. 21-31, 1995.

[30] B. Tursky, G.E. Schwartz, and A. Crider. "Differential patterns of heart rate and skin resistance during a digit-transformation task". Journal of Experimental Psychology, vol. 83, pp. 451-457, 1970.

[31] M.G. Coles. "Physiological activity and detection: the effects of attentional requirements and the prediction of performance". Biological Psychology, vol. 2, pp. 113-125, 1974.

[32] M.G. Coles and C.C. Duncan-Johnson. “Attention and cardiac activity: heart rate responses during a variable fore-period, disjunctive reaction time task”. Biological Psychology, vol. 5, pp. 151-158, 1977.

[33] A.W.K. Gaillard and J. Perdok. “Slow cortical and heart rate correlates of discrimination performance”. Acta Psychologica, vol. 43, pp. 185-198, 1979.

[34] A. Dittmar, H. Rada, G. Delhomme, E. Vernet-Maury, C. Collet, and R. Roure. “A multi-sensor system for the non-invasive measurement of the activity of the autonomic nervous system”. Sensors and Actuators B: Chemical, vol. 27, pp. 461-464, 1995.

[35] A. Clarion, C. Ramon, C. Petit, E. McAdams, C. Gehin, and J.P. Bourgeay. “An integrated device to evaluate drivers' functional state in the field”. Behavior Research Methods, vol. 41, pp. 882-888, 2009.

[36] A. Fort, R. Martin, A. Jacquet-Andrieu, C. Combe-Pangaud, G. Foliot, and S. Daligault. “Attentional demand and processing of relevant visual information during simulated driving: A MEG study”. Brain Research, vol. 1363, pp. 117-127, 2010.

[37] L. Garnero, S. Baillet, and B. Renault. “Magnétoencéphalographie / électroencéphalographie et imagerie cérébrale fonctionnelle”. Annales de l'Institut Pasteur / Actualités, vol. 9, pp. 215-226, 1998.

[38] Y. Broche-Pérez, L.F. Herrera Jiménez, and E. Omar-Martínez. “Neural substrates of decision-making”. Neurologia. S0213-4853(15) 052-3. doi: 10.1016/j.nrl.2015.03.001, 2015.

[39] M. Balconi and C. Lucchiari. “Consciousness and arousal effects on emotional face processing as revealed by brain oscillations. A gamma band analysis”. International Journal of Psychophysiology, vol. 67, pp. 41-46, 2008.

[40] Q. Luo, D. Mitchell, X. Cheng, K. Mondillo, D. McCaffrey, and T. Holroyd. “Visual Awareness, Emotion, and Gamma Band Synchronization”. Cerebral Cortex, vol. 19, pp. 1896-1904, 2009.

[41] C. Collet, C. Petit, A. Priez, and A. Dittmar. “Stroop color–word test, arousal, electrodermal activity and performance in a critical driving situation”. Biological Psychology, vol. 69, pp. 195-203, 2005.

[42] H. Sequeira, P. Hot, L. Silvert, and S. Delplanque. “Electrical autonomic correlates of emotion”. International Journal of Psychophysiology, vol. 71, pp. 50-56, 2009.

[43] H. Yamasaki, K.S. LaBar, and G. McCarthy. “Dissociable prefrontal brain systems for attention and emotion”. Proceedings of the National Academy of Sciences, vol. 99, pp. 11447-11451, 2002.

[44] F. Dolcos and G. McCarthy. “Brain Systems Mediating Cognitive Interference by Emotional Distraction”. The Journal of Neuroscience, vol. 26, pp. 2072-2079, 2006.

[45] K. Kompus, K. Hugdahl, A. Ohman, P. Marklund, and L. Nyberg. “Distinct control networks for cognition and emotion in the prefrontal cortex.” Neuroscience Letters, vol. 467, pp. 76-80, 2009.

[46] K.M. Heilman, H.D. Schwartz, and R.T. Watson. “Hypoarousal in patients with the neglect syndrome and emotional indifference”. Neurology, vol. 28, pp. 229-232, 1978.

[47] T.P. Zahn, J. Grafman, and D. Tranel. “Frontal lobe lesions and electrodermal activity: effects of significance”. Neuropsychologia, vol. 37, pp. 1227-1241, 1999.

[48] H.D. Critchley, R. Elliott, C.J. Mathias, and R.J. Dolan. "Neural Activity Relating to Generation and Representation of Galvanic Skin Conductance Responses: A Functional Magnetic Resonance Imaging Study". The Journal of Neuroscience, vol. 20, pp. 3033-3040, 2000.

[49] P. Zoccolotti, D. Scabini, and C. Violani. "Electrodermal responses in patients with unilateral brain damage". Journal of Clinical Neuropsychology, vol. 4, pp. 143-150, 1982.

[50] G.P. Crucian, J.D. Hughes, A.M. Barrett, D.J.G. Williamson, R.M. Bauer, and D. Bowers. "Emotional and Physiological Responses to False Feedback". Cortex, vol. 36, pp. 623-647, 2000.

[51] G. Pfurtscheller. "The cortical activation model (CAM)". Progress in Brain Research, vol. 159, pp. 19-27, 2006.

[52] E. Salvia, A. Guillot, and C. Collet. "Autonomic nervous system correlates to readiness state and negative outcome during visual discrimination task". International Journal of Psychophysiology, vol. 84, pp. 211-218, 2012.

[53] E. Vernet-Maury, O. Robin, and A. Dittmar. "The ohmic perturbation duration, an original temporal index to quantify electrodermal responses". Behavioural Brain Research, vol. 67, pp. 103-107, 1995.

[54] C. Collet, E. Salvia, C. Petit-Boulanger. "Measuring workload with electrodermal activity during common braking actions". Ergonomics, vol. 57, pp. 886-896, 2014.

[55] M.E. Dawson, A.M. Schell, and D.L. Filion. "The electrodermal system", in Handbook of psychophysiology, vol. 2. J. T. Cacioppo, L. G. Tassinary & G. G. Berntson, Eds. Cambridge University Press, 2000, pp. 200-223.

[56] M. Corbetta, and G.L. Shulman. "Control of goal-directed and stimulus-driven attention in the brain". Nature Reviews Neuroscience, vol. 3, pp. 201-215, 2002.

[57] V.H. Vroom. Work and motivation. San Francisco, CA: Jossey-Bass., 1964, 331 p.

[58] N. Zhao, B. Reimer, B. Mehler, L.A. D'Ambrosio, and J.F. Coughlin. "Self-reported and observed risky driving behaviors among frequent and infrequent cell-phone users". Accident Analysis and Prevention, vol. 61, pp. 71–77, 2013.

[59] F. Cazzulino, R.V. Burke, V. Muller, H. Arbogast, and J.S. Upperman. "Cell phones and young drivers: A systematic review regarding the association between psychological factors and prevention". Traffic Injury Prevention, vol. 15, pp. 234–242, 2014.

[60] A. Megias, A. Maldonado, A. Candido, and A. Catena. "Emotional modulation of urgent and evaluative behaviors in risky driving scenarios". Accident Analysis & Prevention, vol. 43, pp. 813-817, 2011.

[61] W. Wittling, A. Block, S. Genzel, and E. Schweiger. "Hemisphere asymmetry in parasympathetic control of the heart". Neuropsychologia, vol. 36, pp. 461-468, 1998.

[62] C.L. Lisetti. "A user model of emotion-cognition", in UM99 Workshop on Attitude, Personality, and Emotions in User-Adapted Interaction, Banff Centre, Banff, Alberta, Canada, 1999, pp. 1-11.

[63] C.L. Lisetti, and F. Nasoz. "Affective intelligent car interfaces with emotion recognition", in 11th International Conference on Human Computer Interaction, Las Vegas, NV, USA, 2005, pp. 1-10.

[64] F. Nasoz, C.L. Lisetti, and A.V. Vasilakos. "Affectively intelligent and adaptive car interfaces". Information Sciences, vol. 180, pp. 3817-3836, 2010.