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Experimental framework for simulators to study driver cognitive distraction: brake reaction time in different levels of arousal

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Abstract

Distraction has the potential to degrade driving performance and may have serious consequences for road safety. There is a number of research in this area and most studies concentrate on perception errors as a result of visual distraction, so much so that NHTSA has issued driver distraction guidelines to address visual and manual sources of distraction. Cognitive distraction occurs when attention is withdrawn from the processing of information necessary for the safe operation of a vehicle and seems to be qualitatively different from those associated with visual distraction.
Among those sources of distraction, the cognitive one is the most difficult the to assess because of the problems associated with the observation of what a driver's brain, as opposed to hands or eyes is doing.
Despite many published standards, that specify a number of methods for evaluating the visual and manual demand of secondary task interactions, there are currently no published standards that explicitly and exclusively apply to cognitive distraction. In this paper is presented an experimental framework, developed within DRIVE IN2 project (DRIVEr Monitoring: Technologies, Methodologies and IN-vehicle INnovative systems for a safe and eco-compatible driving), based on a driving simulator and car--following paradigm, with the lead vehicle that brakes suddenly when a driver in a loop system, that analyzes in real time EEG signals, detects boot very high and very low level of engagement or arousal. As driving simulator, also the Sim-Panda has been used, developed in the project, the first prototype for testing driver monitoring systems in safety conditions and in a real car.

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Neuro-feedback for controlling the lead vehicle is obtained by the SDK (Suite Development Kit) of Neuro-Headset Emotiv EPOC, that uses proprietary metrics, that looks for distinct brainwave characteristics that are universal in nature and do not require signature-building or individual baselining. The first is “Engagement”, characterized by increases in beta and attenuated alpha waves, and the other is “Excitement”, associated with arousal and overall physiological response.
To study cognitive driver distraction, reaction time is evaluated, measuring time elapsed between sudden braking lead vehicle and response from drivers. Results are interpreted comparing brake reaction time recorded when the two metrics are booth above or below specific thresholds, obtaining indications of a driver’s ability to quickly and safely respond to the sudden appearance of a threat.
Reaction time measures show a great deal of consistency, and our preliminary results report that drivers responses to a lead braking vehicle are the slower, the higher is the attention they are paying to the roadway, as the drivers that are engaged in secondary-vehicle activities.

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Keywords: neurofeedback; driving simulation; EEG; brake reaction time; arousal; car following

1. Introduction

Driving a car, a train or an airplane is a complex behavior that involves correlated cognitive factors, which may include attention, perception, visuomotor integration, working memory, and decision making. Occasionally driver and pilots lapse into awareness states that are incompatible with the demands of the task, so these latter can be characterized as “hazardous” and could lead to catastrophic consequences. Just to cite some examples, Young and Hashemi (1991) showed that driver fatigue may play a role in about 40% of truck accidents, and states with reduced situational awareness have been found to be a major contributor to Controlled Flight Into Terrain (CFIT) accidents (Shappell and Wiegmann, 1997).

Those states are defined by Lawrence (2002) in an official NASA report as “Hazardous States of Awareness” (HSAs) and obviously tends to most frequently occur under specifics conditions.

Hazardous states of awareness can be differentiated into six related constructs:

- Blocks
- Task-Unrelated Thoughts
- Lapses and Slips
- Mental Fatigue
- Boredom
- Complacency

Boredom is a physiological state associated with arousal (Berlyne, 1960) and has been defined by O'Hanlon (1981) as feeling of displeasure caused by a conflict between habituation and sustained effort to maintain an adequate level of arousal to effectively perform the task.

In boredom and mental fatigue, receptivity to events deteriorates with exposure to a steady, prolonged task and the arousal level tends to be lower than the level required to achieve adequate safety performance, with increase in lapses, mental blocks, errors, and detection failures in monitoring tasks.

Both fatigue and boredom seem to be mechanisms aimed to protect the Central Nervous System (CNS) from becoming overloaded by impulses from the peripheral sense organs, like eyes or vestibular system. (Kroemer and Grandjean, 1997)

The psychological construct of a block was introduced by Bills (1931) to refer to subjects that occasionally take a very long time to name certain colors. Blocks are related to low arousal, boredom and attentive processing, although there are evidences that frequency of blocks increases over time and with repetitive tasks (Manly et al., 1997).

From a physiological point of view, Makeig and Inlow (1993) have found that blocks are related with an increased delta activity in the electroencephalogram (EEG), and Smith and Nutt (1996) reported a connection between blocks and activation level of Sympathetic Nervous System (SNS) with clonidine, that reduces the noradrenaline release at the presynaptic level, increasing the incidence of blocks whereas a noradrenaline agonist reverses the effect. Giambra (1993) described the state of Task-Unrelated Thoughts (TUTs) or Mind Wandering (MW) as a form of daydreaming, with thoughts that swap between topics. It seems that a TUT may reflect a failure of the selective attention mechanism, that is source of random but infrequent sampling of irrelevant cognitive channels by the attention filter.

Spectral electroencephalographic analyses and evoked related potential results suggest a decreased alertness and sensory processing during mind wandering, with theta (4–7 Hz) and delta (2–3.5 Hz) EEG activity that increase during mind wandering, whereas alpha (9–11 Hz) and beta (15–30 Hz) decreased (Braboszcz and Delorme, 2011)

There are several definitions of mental fatigue, certainly transportation safety well knows its effects.

The widespread concept of fatigue is related to a decrease in performance measurable by spending time on task. (Bartlett, 1943) Main effect of mental fatigue is a weakening of the ability to allocate attentional resources to task performance that cause a performance decrement when the workload exceeds the available supply.

Norman (1981) and Reason (1984) defined slips as those actions that do not agree with a person's intentions and lapses as intention failures that are not necessarily apparent in behavior.

Performances on repetitive or habitual tasks, especially when sustained for long time or under low cognitive workload, can considerably decrease because the familiar and routine nature of the task promotes a failure of attentive monitoring and an automatic execution of stimulus – response sequences with only a sporadic attentional check.

The term complacency refers to a failure to properly monitor the actions of a machine or computer, that is widely used in aviation to describe when a pilot doesn't adequately check the cockpit instruments or aircraft subsystems (Parasuraman, 1993).

In lasts years, complacency has become very significant in many other transportation domains, where automation is being increasingly implemented, especially in automotive field since of introduction of Advanced Driver Assistance Systems (ADAS), as Adaptive Cruise Control (ACC), that could lead to a condition of excessive trust of drivers in the automated subsystem that doesn't allow them to adequately monitor the road scenario. (DeWaard and Brookhuis, 1999)

Today, etiologies of HSAs have been clarified by many research conducted by the aviation community, actual researches should focus on developing of tools and insights, and not only recognition, even for classification of the various HSAs, so that new countermeasures could be developed.

2. Physiology-driven Virtual Reality Adaptive Stimulation (VRAS)

Biofeedback is just a quantitative measure of a bodily function, as blood pressure, heart rate, skin temperature and can be seen as a visual, audio or haptic real time information. (Norris, 1986)

Neurofeedback is a type of biofeedback that is based on evaluation of firing, intensity, and location patterns of brainwaves, extremely indicative of the kind of subject's brain state.

Virtual reality is a rapidly evolving and very promising technology, that allows for the possibility to study subjects, with suitable ecological validity, by simulating an interactive environment with stereoscopic visual displays, auditory input and haptic feedback.

Simulated driving environments have been used to understand the neuronal underpinnings of factors involved in the reduction of driving performance produced by distraction, with the advantage that virtual reality allows simulations of driving tasks that would be impractical, dangerous, unethical, or even impossible in real contexts.

Thus, virtual reality technologies, being compatible with many physiological measuring techniques, have been widely used by researchers to evaluate the cognitive elements involved in driving behavior and to study how driving performance is affected by distraction. (Strayer and Johnston, 2001; Allen et al., 2009)

Measurements of brain function, obtained by Walter et al. (2001) during simulated driving, showed that cerebellum and fronto-parietal areas, brain regions deputed respectively to fine-control in movement execution and related to visual attention, were highly active during simulated driving.

Physiology-driven Virtual Reality Adaptive Stimulation (VRAS) blends biofeedback into Virtual Reality applications and are closed loop simulations that responds to physiological signals, as EEG frequency band ratio, to periodically modify the virtual task by modifying parameters, in automate way and in real time, while the task itself is being performed by the subject source of the biofeedback.

As stated by Ćosić et al (2007), physiology-driven VRAS includes:

- Time-synchronized stimuli generation;
- Acquisition of the subject's physiological response;
- Subject's emotional state estimation;
- Closed-loop control that leads to subsequent generation of new stimuli.

Biofeedback-driven VRAS is recently raised into a very promising technology, since technologies for detecting brainwaves, so as brain states, are becoming more reliable and accessible.

All that above, associated to a better understanding of where and what type of brainwaves corresponds to a specific activity, allows researcher to fully integrate brainwave biofeedback into a true, dynamic virtual reality stimulation, without clinician involvement and using inexpensive equipment, as gaming derived technologies, even if they are not specifically designed for EEG biofeedback.

3. Neurofeedback controlled car following framework

The proposed experimental framework aims to extend possibilities in studies design, by introduction of an On-Line Human-In-the-Loop Simulation System that can continuously monitor EEG signals, recognize some Hazardous States of Awareness based on EEG signals, and finally activate a specific event in the virtual driving scenario that requires an appropriate driver response, so much so that an outcome quantitative measure can be obtained.

This experimental methodology is based on the assumption that EEG Power Spectral Density (PSD) in the bands of interest (alpha, beta, delta and theta) significantly differ for the different arousal states, and that is possible to identify HASs by examination of metrics that reflects the spectral changes in spontaneous EEG.

To develop this experimental set-up, some off-line experiment has been conducted to identify, by one side the best conditions to induce in subject HSAs and by the other side the metrics that are much more suitable for HASs recognition.

The experimental procedure was then verified and validated by an experiment with a non-invasive, lightweight and wireless EEG headset and two driving simulators based on Sim-Racing derived technologies, racing simulations software for entertainment purpose and devices of high grade for game enthusiasts.

3.1. The experimental setup

A neurofeedback-driven adaptive VR stimulation is clearly based on a EEG sensors and an automatic signal analyzer, able to estimate in real time the subject's arousal state, that interact with a virtual reality system. This consists of at least two major components: a platform for stimuli presentation and a user interface able to record the subject's response. (Wang et al., 2014)

This framework uses an Emotiv Headset as EEG device (emotiv.com) and its Suite Development Kit (SDK) to provide neuro-feedback functionality to the interactive environment.

The experimental protocol has been developed and verified on the ReAsonably Priced Immersive Driving Simulator (RAPIDS) and the Sim-Panda of the Department Pharmacy of the University of Salerno (DIFARMA), both developed in the DriveIn2 Projects in cooperation with FIAT Chrysler Automobiles.

The RAPID Simulator has a curved screen with 180 degrees of field of view. The simulation physical engine is a specialized version of the popular software for entertainment "rFactor" (Image Space Incorporated) and the user interface is a modified version of commercial grade steering wheels, pedals and gearshift (ARC Team – Pavia).

The Sim-Panda Simulation Setup correspond to a real FIAT Panda car with right hand drive, equipped on left side with a full interface for driving simulator, so is possible to drive virtually in immersive scenarios by the inside of a real car.

In this experiment design, as usually done every time in EGG recording, both motion system and stereoscopic vision have been deliberately excluded not to create artefacts in EEG signals, due to head movements or other perceived cues.

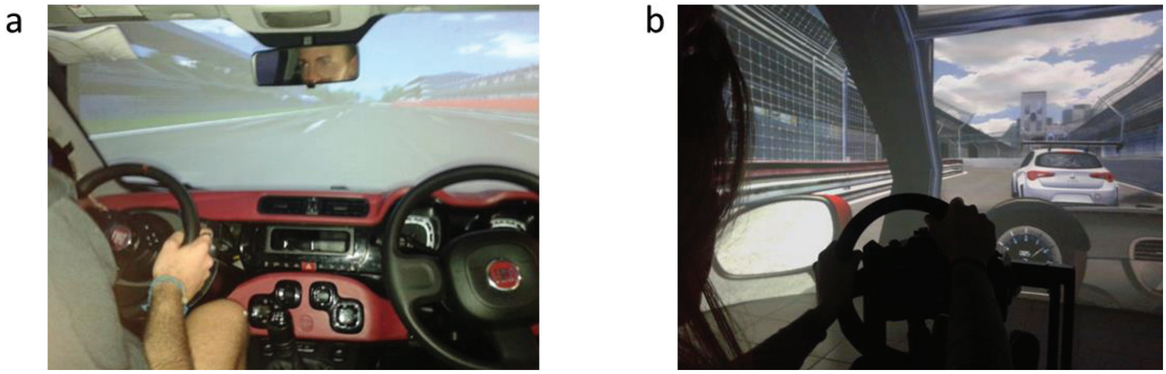

Fig. 1. (a) The Sim-Panda Simulation Setup; (b) The ReAsonably Priced Immersive Driving Simulator (RAPIDS).

Emotiv EEG is a Brain Computer Interface (BCI) that combine slow powered wireless communication with a good fidelity signal acquisition system.

The light weight of this consumer product, and the easy integration into existing applications via traditional input device emulation seem to make the Emotiv Headset and its SKD a very promising choice to integrate neurofeedback into adaptive virtual reality environments. In fact, detection outputs could be mapped to keystrokes which trigger events in the target application by the "EmoKey" module of the Emotiv SDK, so that detection of HSA events could be converted into signals that emulate traditional input devices.

EmoKey translates Emotiv detection results to predefined sequences of keystrokes, according to logical rules defined by the user through the EmoKey user interface. Such keystroke could be used to activate a key macro that could be useful to favor proper stimuli generation, as in our case to activate the brake on the lead vehicle.

The Trigger Conditions table in EmoKey contains user interface controls that allow to define logical conditions, determining when the corresponding rule is activated, related to metrics of Emotiv "Affectiv Suite" that reports real time changes in the subjective emotions experienced by the user.

Those Affectiv detections look for brainwave characteristics that are universal in nature and don't require an explicit training or signature-building step by of the user.

For our purposes, two Emotiv Affectiv metrics have been selected. The first one is "Long Term Excitement", characterized by activation in the sympathetic nervous system which relate to nervousness or agitation. The other one is "Engagement/Boredom" that is related to the level of alertness and to the conscious direction of attention towards task-relevant stimuli.

It is also characterized by increased physiological arousal and beta waves along with attenuated alpha waves.

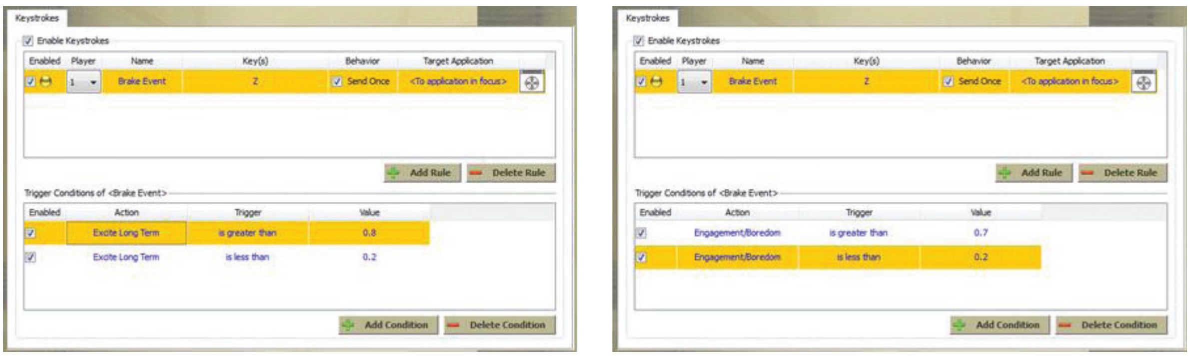

Fig. 2. Setting of the EmoKey rules that activate the braking of the lead vehicle.

Implementing an adaptive car following test by using a commercial software designed for entertainment purpose as rFactor, (one of the main Sim-Racing games title), is made possible by the characteristic multiplayer capability of this kind of software that allows to use one instance of rFactor to simulate the vehicle driven by the test subject and a second instance, on another pc connected in Local Area Network (LAN), to recreate the lead vehicle.

On this secondary computer vehicle controls have to be settled such as to properly respond to the key macro, in turn triggered by the keystroke evoked by Emotiv SDK, paying attention not to assign twice the same key.

In rFactor, it is strongly suggested to use full steering help and automatic gearbox in lead vehicle settings, and to properly set speed limiter by editing the corresponding track file in “GameData” folder.

To promote HSAs, could be desirable to choose a very long track, mainly straight, requiring at least 30 minutes to complete a lap. Brake reaction time measurements can be obtained in two ways. For both of them is necessary to install a “Telemetry Plugin” that enables data logging and eventual analysis with specific software, as MoTeC i2 and Wintax 4.

The first method to determine brake reaction time requires to enable data acquisition on both lead and following vehicle computers and to synchronize data by introducing common markers in the two time-series overlapping them to given time intervals.

The second way, uses the same key macro to send a detectable marker to the following vehicle pc, as could be an impulsive and small action on the clutch pedal through the LAN that hosts the multiplayer session.

3.2. The experimental paradigm

The experimental protocol developed is based on an adapted event-related car following driving paradigm in witch subjects have to drive, in a natural way, following a lead vehicle that suddenly brakes at apparently random intervals.

Car following is a very common and widespread experimental paradigm used to study driver distraction, because it provides some quantitative measures that, as Brake Reaction Time (BRT) or Time Headway (TH), not simply reflects driver behavior and its arousal state, but are also directly related to real world safety issues.

Brake Reaction Time (BRT) is defined as the time between the onset of braking of the lead vehicle, as indicated to the following driver by the lighting up of the brake lights, and the first subsequent action of the brake pedal operated by the test subject. Furthermore, Minimum Tim Headway (MTH) is the lowest TH achieved by the simulator driver between the initial braking of the lead vehicle and its complete stop.

Subjects are just instructed to drive normally and to follow the lead vehicle of whose braking events are triggered by reaching of a given level of the Emotiv Affectiv metrics. For longitudinal control analysis, it seems to be desirable to instruct the driving subject to follow the lead vehicle at a “safe distance”, but BRT measurements could be much more reliable if driver is trained to follow the leader “as close as possible”.

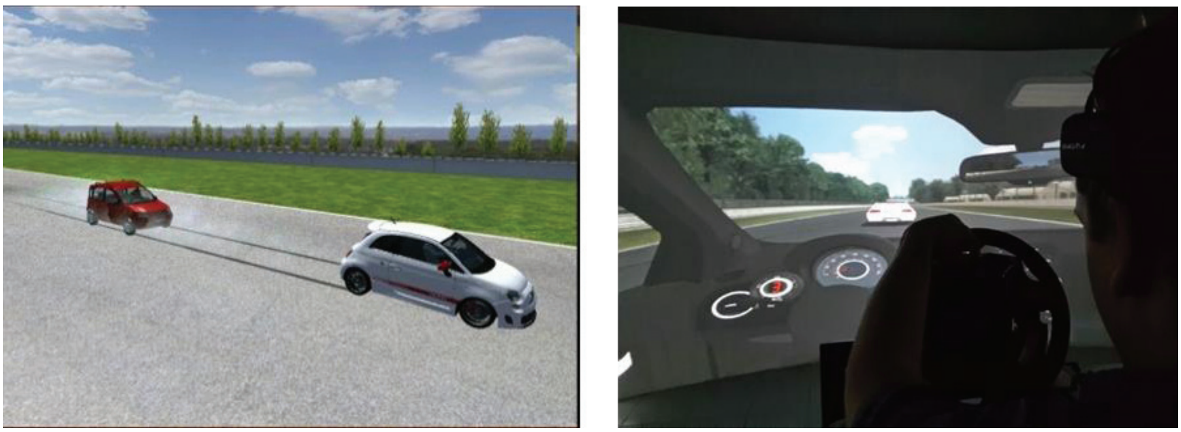

Fig. 3. Car following test.

4. Experimental validation of the framework

Tree healthy subjects, aged 23 to 36 years (two males and one female), with normal hearing and free from neurological and psychological disorders, participated in the experimental validation of the research protocol. They were introduced on how to manipulate the virtual car and practiced the simulator for about one hour to get familiar with it before the experiment started.

All participants were asked to read and sign the informed consent form before participating in the studies, and were instructed to follow the lead vehicle, that brakes hard and unexpectedly, “as close as possible” to favorite emergency brake response by the driver.

Emotiv Headset was then placed on the subject head, and the signal quality was verified, so the driver could start the simulation. In this experimental test the “Om Weg” track for rFactor was used, a 47 Km long racetrack released with the purpose “to race at maximum speeds for a prolonged time”. Brake Reaction Time measurement and visual inspection of the braking response was performed off-line on overlaps of synchronized data logs.

Each subject has repeated the car following task two times. In both the trials the braking of lead vehicle is triggered by two opposite EmoKey rules, applied to the same Affective metric, that defines two thresholds. In this way the leader brakes when the selected metric is above the higher or below the lower of the two specified thresholds, to obtain a comparison between high and low arousal states.

In each virtual driving session were recorded between 3 and 7 brake responses for each arousal state. The EmoKey rules used to activate the brake action of the lead vehicle in the two car following sessions are:

- Long Term Excitement: over 80% or under 20%
- Engagement/Boredom: over 70% or under 20%

Brake Reaction Times are analyzed by a one-way Analysis of Variance (ANOVA) with repeated measures.

Figure 4 shows the column plots of Reaction Times in the four different arousal conditions, engaged, bored, high and low general excitement (left to right).

The averaged RT of the trials within the engaged state across 3 subjects was about 1000 ms and close to the mean value recorded in boredom. Both minimum Time Headway (TH min) and RT with high long term excitement vary in a statistically significantly way respect to the trials with low arousal level.

Even though every subject responded to the brake of lead vehicle by instantaneously pressing the brake pedal on the simulated car, it seems that they are less responsive to unexpected stimuli.

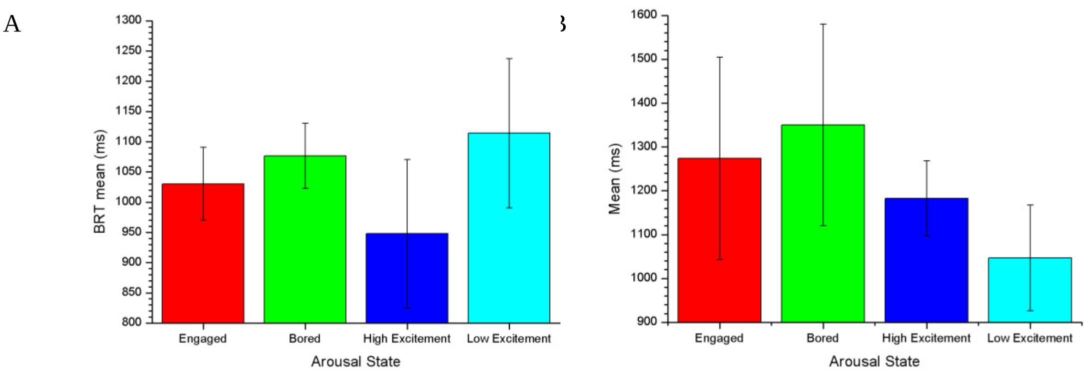

Fig. 4. (a) average Brake Reaction Time: (b) Average minimum Time Headway.

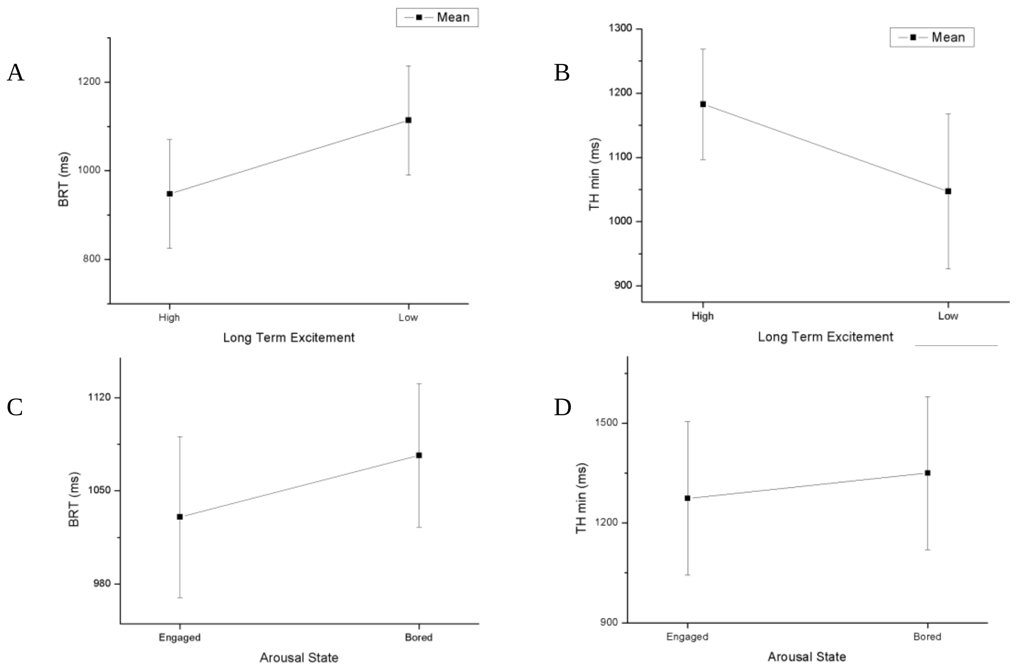

Fig. 5. (a, c) Mean comparison between arousal states relatively to both Brake Reaction Time; (b, d) minimum Time Headway.

4.1. Event Related Evoked Potential detection

During the development of this experimental framework, EEG data were collected and analyzed off-line to further investigation. Detaching all trials relative to boredom conditions, after a proper signal processing, we succeed in the observation and identification of the typical brain response to an unexpected stimulation: the so called Event Related Evoked Potential (ERPs). ERPs are brainwave that consist of a series of positive and negative voltage deflections, which are related to a set of underlying components, as the P300, that is known to reflect a higher cognitive response to unexpected or cognitively salient stimuli.

Figure 6 shows the ERP noted during those car following sessions. To our knowledge, it is the first time that ERP recordings are obtained in a virtual reality setup closely related to every day events that has important safety implications.

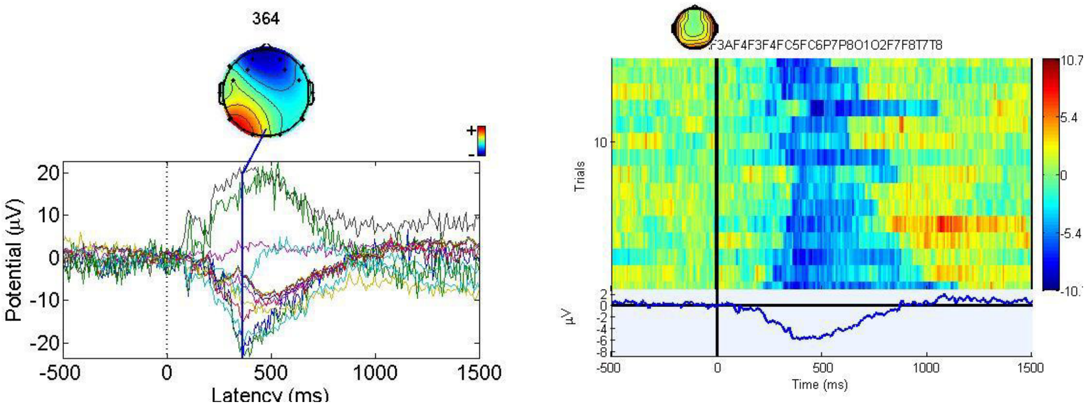

Fig. 6. Event Related Potentials evoked by the brake of lead vehicle on 15 trials.

5. Discussion

Simulations are increasingly adopted as solutions for automotive research, especially for developing driver monitoring systems and measuring acceptability of on-board devices. There are at least two ways in which neuroscientific techniques can be used to provide support research in virtual environments. Firstly, biofeedback methods in are general useful to assess reliability and ecological validity of simulation-based approaches. Furthermore, these methods are suitable to enhance the virtual environment adaptivity to the user by dynamically collecting brain activity and then use it a feedback to allowing the virtual scenario to be adapted to the user's interactions. Regarding the enhancement of simulation adaptivity, different ranges of Human-Computer Interaction (HCI) technologies and methods can be effectively integrated within Virtual Reality (VR) researches.

Amongst these biofeedback methods, neurosciences provide a new and relevant approach allowing for identifying the user's mind state. However, how neuro-feedback can be introduced into the simulation adaptivity is an emerging line of VR-related research, that not only increases measure reliability and controls of experimental conditions, but also provides a consistent solution for implementing adaptive agents in simulation studies.

The neuro-feedback most frequently used in VR environment is electroencephalography (EEG), mainly in due to reason its lightweight, noninvasive and unobtrusive nature. However, other neurophysiological methods, such as Functional Near-Infrared Spectroscopy (fNIRS), are also progressively used as a technique to assess and study brain activity in virtual environments. At the same time as these techniques are becoming better understood, their use is becoming increasingly prevalent in addressing important factors affecting the road safety, as human factor.

Neuro-feedback driven Virtual Reality Adaptive Stimulation could be extremely useful in developing of psychophysical model of the driver behavior or to investigate the neurological sources of dangerous behavior on the road.

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