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Monitoring driver fatigue using a single-channel electroencephalographic device: A validation study by gaze-based, driving performance, and subjective data

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ABSTRACT

Driver fatigue can impair performance as much as alcohol does. It is the most important road safety concern, causing thousands of accidents and fatalities every year. Thanks to technological developments, wearable, single-channel EEG devices are now getting considerable attention as fatigue monitors, as they could help drivers to assess their own levels of fatigue and, therefore, prevent the deterioration of performance. However, the few studies that have used single-channel EEG devices to investigate the physiological effects of driver fatigue have had inconsistent results, and the question of whether we can monitor driver fatigue reliably with these EEG devices remains open. Here, we assessed the validity of a single-channel EEG device (TGAM-based chip) to monitor changes in mental state (from alertness to fatigue). Fifteen drivers performed a 2-h simulated driving task while we recorded, simultaneously, their prefrontal brain activity and saccadic velocity. We used saccadic velocity as the reference index of fatigue. We also collected subjective ratings of alertness and fatigue, as well as driving performance. We found that the power spectra of the delta EEG band showed an inverted U-shaped quadratic trend (EEG power spectra increased for the first hour and half, and decreased during the last thirty minutes), while the power spectra of the beta band linearly increased as the driving session progressed. Coherently, saccadic velocity linearly decreased and speeding time increased, suggesting a clear effect of fatigue. Subjective data corroborated these conclusions. Overall, our results suggest that the TGAM-based chip EEG device is able to detect changes in mental state while performing a complex and dynamic everyday task as driving.

1. Introduction

Electroencephalography (EEG)-metrics are among the most reliable contemporary methods to assess cognitive states (Di Stasi et al., 2015a). EEG recording devices have dramatically developed in the last ten years thanks to technological progress (Minguillon et al., 2017), making ubiquitous acquisition of brain activity not only possible, but inexpensive (Borghini et al., 2014; Picot et al., 2008; Wang et al., 2015). These new devices, which are user-friendly, portable, and low-cost, have increased the use of EEG-metrics in daily-life situations (for a review, see Minguillon et al., 2017).

The EEG recording device "TGAM headset" (ThinkGear ASIC module, NeuroSky Inc., San Jose, CA, USA) is a single-channel, dry electrode, wireless signal transfer system (see Fig. 1B) that has received considerable attention from the general public (Dance, 2012; Bilton, 2013) and the neuroscientific community (e.g. Johnstone et al., 2012; Rogers et al., 2016) because of its set of features that make it an ideal wearable EEG system: the low intrusiveness of the equipment, the robustness of the sensor technology, and the wireless measurement solution (Gramann et al., 2011). Furthermore, since it has been validated for scientific use for assessing variations in the cognitive state (Johnstone et al., 2012), neural-engineering researchers have started

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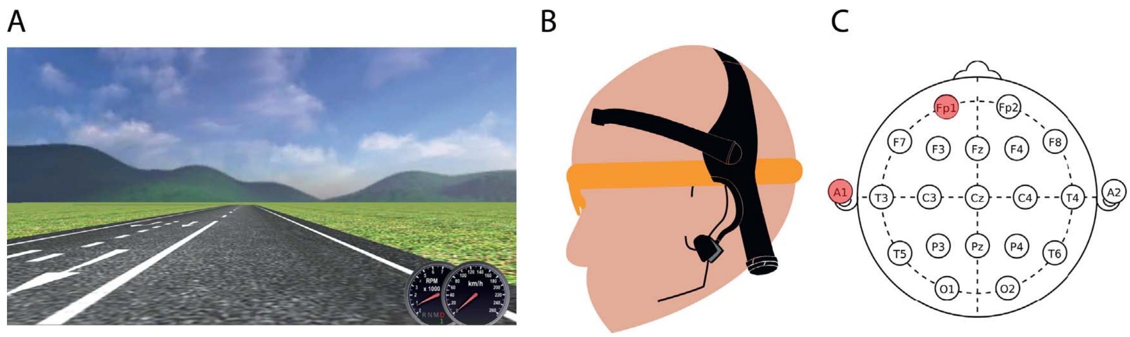

Fig. 1. A) A screenshot taken from the driving simulator. The speedometer gauges were displayed during the simulation. B) The configuration used to record EEG (black headset) and eye movements (orange element). C) The EEG device uses a monopolar montage with a single frontal dry electrode placed at Fp1, and uses the left *ear*-lobe as the reference/ground. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

developing EEG-based applications for daily-life (Minguillon et al., 2017), including for road safety (Morales et al., 2015).

Driver fatigue (i.e., under-aroused) is the most critical issue for transportation safety (National Transportation Safety Board, 2017), representing the main cause of motor vehicle crashes and traffic-related deaths (Touryan et al., 2016). Wearable EEG-based fatigue monitors have the potential to help drivers to assess their own levels of fatigue (Ko et al., 2015) and, therefore, to prevent the deterioration of driving performance (Dawson et al., 2014). Given its features, the TGAM headset should be suitable for use as a driver fatigue monitor. Unfortunately, since the pioneer case study by Yasui (2009), the question of whether the TGAM headset can monitor driver fatigue remains open. The few reports that have investigated this issue have not obtained conclusive results (see below), due to the inconsistencies and/or limitations in their methods/research designs. Examples of these limitations include 1) the *use of unfiltered/unprocessed EEG data* (Wan et al., 2013; Lin et al., 2015; He et al., 2015; Hsiao et al., 2015; He et al., 2016; Abdel-Rahman et al., 2015; He et al., 2014; Lim et al., 2014), 2) the *use of an imprecise operationalization of the construct* of *fatigue* – often confused with postprandial somnolence – (He et al., 2014, 2015), and 3) the *absence of (comparative) gold standard indices of fatigue* (Lim et al., 2014). All these limitations have compromised the potential utility of this wearable single-channel EEG device as a fatigue monitor.

Here, we present the first conclusive evidence about the sensitivity and validity of a single electrode EEG device (TGAM-based) as a driver fatigue monitor. We investigated the effects of a 2-h driving time – a common inducer of fatigue at the wheel (Wijesuriya et al., 2007; Di Stasi et al., 2012, 2016) – while we continuously monitored drivers' brain activity as well as their saccadic velocity. As saccadic velocity is a well-known fatigue index (Schmidt et al., 1979; Galley and Andres, 1996; Schleicher et al., 2008; Hirvonen et al., 2010; Di Stasi et al., 2016), we used it as a standard reference measure for fatigue. We also collected driver performance and subjective ratings of alertness and fatigue. We hypothesized that, during the 2-h driving session, participants would gradually experience higher levels of fatigue. EEG activity, recorded at the prefrontal cortex, as well as saccadic velocity, would reflect this phenomenon. Furthermore, we expected that participants would show poorer driving performance (i.e., increased speeding behavior) as the driving session progressed.

2. Material and methods

2.1. Ethical approval

We conducted the study in conformity with the Code of Ethics of the World Medical Association (WMA, Declaration of Helsinki) (WMA, 1964). The experiment was carried out under the guidelines of the University of Granada's Institutional Review Board (IRB approval #24/CEIH/2015).

2.2. Participants

Seventeen active drivers (mean age [± standard deviation, SD] = 25 ± 3.45 years, range 22–34; 12 men) volunteered to participate in this study. All participants had normal or corrected-to-normal vision and held a valid driver license (average number years of driving experience [± SD] = 5.94 ± 2.74 years). We asked participants to abstain from alcohol and caffeine-based beverages 24 and 12 h, respectively, before the driving session. Additionally, they had to get at least 7 h of sleep the night prior to the study. Thus, for screening purposes, we measured subjective levels of arousal using the Stanford Sleepiness Scale before the driving session (Hoddes et al., 1972) (see below): no participants scored more than 3, had they done so they would have been excluded from further testing (Connor et al., 2002; Morad et al., 2009; Di Stasi, et al., 2015a). No participants were excluded based on this criterion. Two participants suffered from simulator sickness and did not finish the driving session. Therefore, we finally analyzed data from 15 out of 17 participants (mean age ± SD = 24.33 ± 2.69 years, range 22–31; 10 men). From three of them, due to log system failures during the recording, we only analyzed performance and subjective data.

2.3. Experimental design

The study followed a within-subjects design with the Time-On-Driving (TOD) as the independent variable. Each experimental session consisted of four consecutive 30-min TOD blocks (TOD1[0–30 min], TOD2[30–60 min], TOD3[60–90 min], and TOD4[90–120 min]) (Di Stasi et al., 2012; Di Stasi, et al., 2015b). Participants did not rest between TOD blocks. We chose this temporal window to be close to the maximum TOD that professional drivers are allowed before a mandatory break (Vehicle and Operator Service Agency[VOSA], 2009). As dependent variables, we considered several psychophysiological (the EEG power spectra, as well as the saccadic peak velocity while driving), driving performance (the percentage of speeding time), and subjective indices (the perceived alertness and fatigue before and after the driving session).

2.4. Driving simulation and performance

We used the OpenDS 2.5 software (Math et al., 2013, OpenDS, Saarbrücken, Germany) to create the virtual environment. We developed a two-lane, rounded rectangle (curvature angle of $\pi/2$ rad) road scenario. The road was ~1.5 km long with a width of 8 m, and it was surrounded by an empty and monotonous grassy meadow (see Fig. 1A). Participants drove a middle-sized car for 2 h without breaks (i.e. without stopping the vehicle or restarting the engine) around the same road in sunny conditions and without any other traffic present (average number of laps ± SD = 62.2 ± 2.39). A speed limit of 60 km/h was