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Inter-hemispheric electroencephalography coherence analysis: Assessing brain activity during monotonous driving

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ABSTRACT

The current study investigated the effect of monotonous driving on inter-hemispheric electroencephalography (EEG) coherence. Twenty-four non-professional drivers were recruited to perform a fatigue instigating monotonous driving task while 30 channels of EEG were simultaneously recorded. The EEG recordings were then divided into 5 equal sections over the entire driving period for analysis. Inter-hemispheric coherence was computed from 5 homologous EEG electrode pairs (FP1–FP2, C3–C4, T7–T8, P7–P8, and O1–O2) for delta, theta, alpha and beta frequency bands. Results showed that frontal and occipital inter-hemispheric coherence values were significantly higher than central, parietal, and temporal sites for all four frequency bands ($p<0.0001$). In the alpha frequency band, significant difference was found between earlier and later driving sections ($p=0.02$). The coherence values in all EEG frequency bands were slightly increased at the end of the driving session, except for FP1–FP2 electrode pair, which showed no significant change in coherence in the beta frequency band at the end of the driving session.

1. Introduction

Fatigue has been identified as an occupational hazard for long-distance or professional drivers who are under pressure to reach the scheduled destination (Brown, 1997; Williamson & Boufous, 2007). Prolonged monotonous driving can cause fatigue, which impairs cognitive skills and affects the ability to monitor and assess the drivers' ability to monitor and assess their fitness to continue driving (Brown, 1997; Lal & Craig, 2002). Fatigue can be avoided if drivers are willing to stop driving to have a quick rest when feeling fatigued or unable to drive safely (Brown, 1994). However, most drivers would ignore obvious signs of fatigue and would continue driving (Smith et al., 2005). Therefore, automatic fatigue detection monitors would be useful to warn drivers of their fatigue levels and prevent accidents (Brown, 1994; Lal & Craig, 2001).

Several methods of fatigue detection have been researched, and the electroencephalography (EEG) has been found to be one of the most reliable fatigue indicators (Artaud et al., 1994). Several fatigue detection algorithms that utilise the different frequency bands of brain activities have been proposed (Eoh et al., 2005; Jap et al., 2007, 2009; Lal et al., 2003; Tietze, 2000). However, EEG coherence changes have not been researched in detail as a possible means for a fatigue detection technique.

The EEG coherence analysis is a non-invasive technique that can be applied to study functional relationships between spatially separated scalp electrodes and to estimate the similarities of waveform components generated by the mass action of neurons in the underlying cortical regions (French & Beaumont, 1984; Shaw, 1984; Wada et al., 1996a). EEG coherence is a statistical measure for the correlation of the spatially separated signals within a certain frequency band (Volf & Razumnikova, 1999), or in other words, it is a correlation analysis as a function of EEG frequency (Shaw, 1981). There are four frequency bands that are normally derived from EEG recordings, which are delta (0–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), and beta (13–35 Hz) (Fisch, 2000; Stern & Engel, 2005).

Several studies in the past have used EEG coherence analysis to investigate functional changes in different situations, such as in normal subjects when controlling simple and complex motor functions (Pulvermüller et al., 1995), in comparison between normal elderly and those with Alzheimer's disease (Kikuchi et al., 2002), and in effects of aging in normal subjects (Duffy et al., 1996).

Some studies have analysed EEG coherence during sleep (Armitage et al., 1993; Corsi-Cabrera et al., 1996; Dumermuth et al., 1983). During sleep, decreasing pattern of inter-hemispheric coherence from the waking state until sleep stage 4 was observed in all EEG frequency bands, although synchronisation of slow frequency bands was still considerably high (Banquet, 1983). However, there is still some controversy with other studies reporting that inter-hemispheric coherence increases during sleep (Dumermuth et al., 1983; Dumermuth & Lehmann, 1981).

Studies have also looked at EEG coherence while performing mental processing activities, while the subjects are in an alert state

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(Busk & Galbraith, 1975; Çiçek & Nalcaci, 2001; Gasser et al., 1987). Busk and Galbraith (1975) observed higher inter-hemispheric coherence with an increase of task difficulty, while practice reduced the inter-hemispheric coherence as a result of a decrease in task difficulty. Çiçek and Nalcaci (2001) supported the observation by Busk and Galbraith (1975) that greater bilateral alpha activity was correlated with higher performance.

However, only a few studies have looked at the effect of fatigue on EEG coherence. Changes in the inter-hemispheric coherence were observed during transition from alert state to light fatigue (Boldyreva & Zhavoronkova, 1991), which suggested an alteration of cerebral functional organisation between the two states (Wada et al., 1996b). Inter-hemispheric coherence was found to be significantly lower when subjects were in light fatigue state than during the alert state for alpha and beta frequency bands (Wada et al., 1996b). Boldyreva and Zhavoronkova (1991) also found decreased inter-hemispheric coherence when subjects are in a state of fatigue.

Although some studies in the literature have investigated the changes in inter-hemispheric coherence during light fatigue, little has been reported on changes in the inter-hemispheric EEG coherence during monotonous driving sessions. Hence, the aim of the current study was to investigate the inter-hemispheric EEG coherence changes during a monotonous driving task in light of future development of fatigue countermeasure system.

2. Materials and methods

Twenty-four participants (12 males and 12 females, age range: 20–70 years, mean: 29.5 ± 12.4 years), who were non-professional drivers holding a current driver's license, were recruited to perform monotonous driving for the study. The Institute's Human Research Ethics approval was obtained. All participants had provided informed consent prior to participating in the study. In order to participate in the study, participants had to comply with the following: “no medical contraindications such as severe concomitant disease, alcoholism, drug abuse, and psychological or intellectual problems likely to limit compliance” (Craig et al., 1996).

This study was conducted in a temperature-controlled laboratory around noon ±1.5 h (starting at approximately 10–10:30 am to approximately 13:30 pm). Studies have shown that caffeine and alcohol intake can affect the brain activity (Kenemans & Lorist, 1995; Lumley et al., 1987). Therefore, nicotine, caffeine, tea, and food intake were restricted for approximately 4 h, while alcohol intake was restricted for 24 h prior to the study. Participants reported compliance with these instructions. A fatigue Likert scale questionnaire that asked the current state of the participants (alert, slightly drowsy, moderately drowsy, and markedly drowsy) was administered prior to and after the study.

The driving simulator used was Grand Prix 2 software (version 1.0b, 1996, Microprose Software, Inc., USA). The computer screen displayed other cars, driving environment, the current speed, and other road stimuli. The simulator consisted of a car frame with an in-built steering wheel, brakes, accelerator, and gears.

All participants were required to complete 2 types of driving sessions, which are the alert driving task for 10–15 min and the monotonous driving task for about 1 h. During the alert driving task, participants were provided a track that involved driving with many cars and other road stimuli. All other cars and road stimuli were removed for the monotonous driving task, and participants were asked to maintain a driving speed between 60 and 80 km/h.

Simultaneous physiological measurements were obtained during the two driving sessions, i.e., the alert and the monotonous driving sessions. The NeuroScan physiological recording system (Compumedics, Australia) was used to record the physiological data. Thirty channels of electroencephalography (EEG), sampled at 1000 Hz, were acquired simultaneously during both driving sessions. The international standard 10–20 system of electrode placement was applied (Jasper, 1958). A referential montage was used for acquiring data with the reference point located at the position between the midline central electrode (Cz), and the midline central parietal electrode (CPz). Vertical electrooculogram (VEOG) was also acquired and used to identify blink artefacts in the EEG recording.

The acquired EEG data of the active and monotonous driving sessions were segmented into 1-s epochs. The EEG recording for the monotonous driving session was divided into 5 equal sections of approximately 10 min per section. Sixty artefact-free epochs from the middle data segment of each monotonous driving section and active driving session were selected to compute the cross-power spectra or coherence between homologous inter-hemispheric electrode pairs. Five homologous inter-hemispheric electrode pairs were chosen to represent 5 different brain sites, which were frontal (FP1–FP2), central (C3–C4), temporal (T7–T8), parietal (P7–P8), and occipital (O1–O2) (refer to Fig. 1). Frequency bands, for which coherences were computed, were delta (1.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), and beta (13–35 Hz).

The coherence spectrum function, C_{xy}, for two given signals, x and y, is defined as, $C_{xy}(f) = |P_{xy}(f)|^2/(P_{xx}(f) \cdot P_{yy}(f))$, with f denoting frequency, and P power or cross-power (Achermann & Borbély, 1998). $|P_{xy}(f)|$ is the cross-spectrum between signals x and y, while $P_{xx}(f)$ and $P_{yy}(f)$ are the auto-spectrum of the signals x and y respectively (Guevara & Corsi-Cabrera, 1996).

Statistica software (for Windows, version 7, 2005, StatSoft Inc, USA) was used for the data analysis. One factor Analysis of Variance (ANOVA) was performed to identify significant differences between coherence values (dependent) at different electrode pairs (independent), as well as between the 5 sections during monotonous driving and the alert baseline (independent). This analysis was performed for all EEG frequency bands, delta, theta, alpha, and beta. Significant level was reported at $p < 0.05$.

3. Results and statistical analyses

The average driving time was 67 ± 11 min. Continuous and monotonous driving for approximately 30 min has been previously

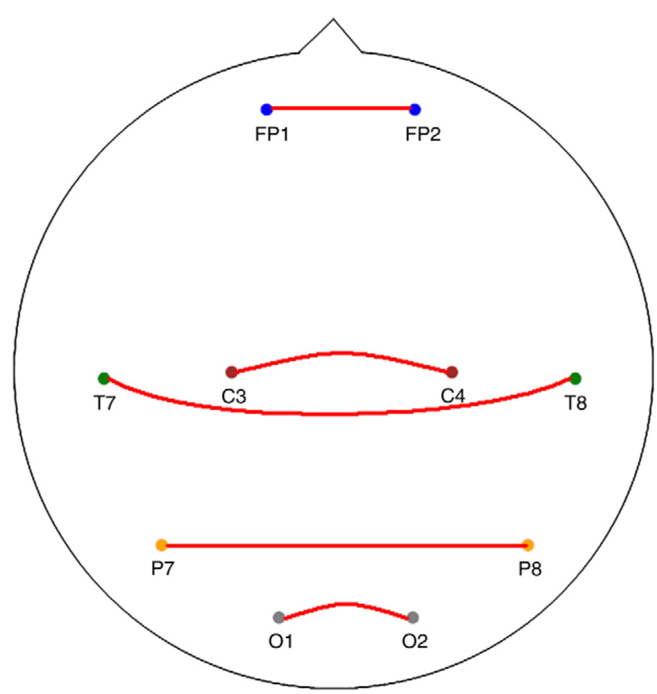

Fig. 1. Homologous inter-hemispheric electrode pairs.