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Reproducibility of the spectral components of the electroencephalogram during driver fatigue

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Abstract

Objective: To date, no study has tested the reproducibility of EEG changes that occur during driver fatigue. For the EEG changes to be useful in the development of a fatigue countermeasure device the EEG response during each onset period of fatigue in individuals needs to be reproducible. It should be noted that fatigue during driving is not a continuous process but consists of successive episodes of 'microsleeps' where the subject may go in and out of a fatigue state. The aim of the present study was to investigate the reproducibility of fatigue during driving in both professional and non-professional drivers.
Methods: Thirty five non-professional drivers and twenty professional drivers were tested during two separate sessions of a driver simulator task. EEG, EOG and behavioural measurements of fatigue were obtained during the driving task.
Results: The results showed high reproducibility for the delta and theta bands (r>0.95) in both groups of drivers.
Conclusions: The results are discussed in light of implications for future studies and for the development of an EEG based fatigue countermeasure device.

Keywords: Neurophysiology; EEG; Reproducibility; Fatigue; Reliability coefficients; Driving

1. Introduction

Driver fatigue is receiving increasing attention in the road safety field. It is believed to be a serious problem in transportation systems and a direct or contributing cause of many accidents, and has been shown to account for nearly 20–30% of road accidents (The Parliament of the Commonwealth of Australia, 2000). Fatigue is major problem in road safety because it: (a) increases the likelihood that drivers will fall asleep at the wheel and (b) decreases one's ability to maintain essential sensory motor skills such as maintaining road position as well as appropriate speed (Mackie and Miller, 1978). During fatigue, the decreased physiological arousal, slowed sensorimotor functions and impaired information processing can diminish a driver's ability to respond effectively to unusual or emergency situations (Mascord and Heath,

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1992). Recently, in a review from the International consensus meeting on fatigue and risk of traffic accidents, Åkerstedt and Haraldsson (2001) identified disturbed sleep, working at the low of the circadian rhythm and sleep apnea as some of the factors associated with fatigue related accidents. These authors also described countermeasures for fatigue such as implementation of electronic devices for fatigue detection. Åkerstedt and his group have pioneered some important investigations into fatigue and sleepiness and identified the detrimental consequences of shiftwork and night driving on fatigue and its effects in professional drivers (Åkerstedt, 1988; Åkerstedt et al., 1987, 1991; Kecklund and Åkerstedt, 1993; Torsvall and Åkerstedt, 1987). If indicators of fatigue can be developed, they may be used to provide drivers with useful feedback about the onset of fatigue and their possible deterioration in driving ability and ability to maintain road safety.

While numerous physiological indicators are available to measure levels of fatigue and alertness, the EEG signal may be one of the most predictive and reliable (Artaud et al., 1994; Lal and Craig, 2002a). Drivers cannot maintain a high level of consciousness when they are mentally fatigued and this is paralleled by consistent and reliable changes in the EEG. In our recent controlled laboratory-based driver simulator studies, we consistently found increases in delta and theta activity during transition from an alert state to fatigue (Lal and Craig, 2001a,b,2002a). From the results of our previous studies in professional and non-professional drivers (Lal and Craig, 2002a,b), we suggest that when persistent delta and theta waves appear, a rest period should be considered before the subjects become severely fatigued. Another study of truck drivers also reported cortical deactivation and increased sleepiness during the end hours of an all night driving shift (Kecklund and Åkerstedt, 1993). Furthermore, we have previously shown that EEG measures could be useful as the basis for a driver fatigue countermeasure device (Lal and Craig, 2002a; Lal et al., in press). However, for the EEG changes that occur during driver fatigue to be utilised in the development of a countermeasure device, the EEG response during the onset of fatigue in individuals needs to be highly reproducible. It should be noted that fatigue during driving is a process that involves successive episodes of 'microsleeps' where the subject may go in and out of a fatigue state (Harrison and Horne, 1996). The reliability of the EEG response during two episodes of a performance task has been shown recently (Fallgatter et al., 2002). Others have shown good test–retest reliability of EEG power, however lesser reliability has been reported for EEG coherence during various cognitive tasks (Fernandez et al., 1993; Harmony et al., 1993). In another study, poor reproducibility of theta and beta amplitude has been found during a simple motor task (Burgess and Gruzelier, 1997), however this study was about topography and not EEG amplitude changes. Also another prominent paper in this area demonstrated acceptable test–retest stability and internal consistency reliability in resting alpha asymmetry (Tomarken et al., 1992). However, analysis with other frequency bands indicated some degree of variability as a function of band and region. Others report stable EEG amplitude reliabilities for all bands except delta in healthy older adults (Pollock et al., 2002). However, no study to date has tested the reproducibility of EEG magnitude response during different episodes of driver fatigue. Therefore, the aim of this study was to assess the reproducibility of EEG changes that occur in two separate episodes of fatigue in professional and non-professional drivers.

2. Methods

2.1. Subjects

Thirty-five subjects (26 males and 9 females), who were current non-professional drivers with an age of 34±21 (mean±S.D.) years, were recruited from a large tertiary institution and the local community and randomly assigned to the study. Twenty male professional truck drivers, with mean age of 44±11 (mean±S.D.) years were also recruited by advertisement placed in the local newspaper. After being given a comprehensive explanation about the investigation, all subjects provided written consent for the study, which was approved by the institutional ethics committee. To qualify for the study, subjects had to have no medical contraindications such as severe concomitant disease, alcoholism, drug abuse and psychological or intellectual problems likely to limit compliance. Health and psychological status was determined during the initial interview on a separate day prior to the study. All subjects were free of any medication and did not possess any personal or family history of neuropsychiatric disorders.

2.2. Experimental protocol

The study was conducted in a temperature-controlled laboratory in which subjects performed a standardized sensory motor driver simulator task. Subjects were asked to restrict caffeine, tea and food intake for 4 h and alcohol for 24 h before the study. Before the study subjects reported compliance with all given instructions. The study was conducted at approximately the same time of the day (noon period) for each subject. The driver simulator equipment consisted of a car frame with an in-built steering wheel, brakes, accelerator, gears and speedometer with a video display. The subjects were asked to breathe normally and restrict all unnecessary movements as much as possible during driving. Furthermore, the car frame was also designed to restrict movement. The initial driving task consisted of 10–15 min of driving to familiarize the subject with the driver simulator, followed by a 10-min break. Following this, subjects performed stage 1 (baseline) of the experimental task, which constituted 10–15 min of active driving that included exposure to varying road stimuli at various speeds. This was followed by stage 2 (very few road stimuli, speed <80 km/h), which involved two sessions of monotonous driving until the subjects showed physical signs of fatigue. The two driving sessions were interspersed by an interval of 2 h during which time the subjects were not involved in the driving task.

2.3. Data acquisition and statistical analysis

The EEG and EOG data were acquired using a 24 channel physiological monitor (Neurosearch-24, Lexicor, USA) simultaneously with the driving task. Nineteen channels of EEG data were recorded according to the International 10–20 system (Fisch, 1991). The EEG activity was recorded in relation to a linked-ear reference. The data was sampled at 256 Hz and divided into epochs of 1-s duration. The total sample time was individually determined, continuing till arousal from fatigue by a verbal interaction from the investigator. A fast Fourier transform was performed on the EEG data using a spectral analysis package (Exporter, Lexicor). A 4-term Blackman–Harris window and a 2-Hz cut-off high-pass filter were used to reduce low frequency artefact. The EEG activity was defined in terms of four frequency bands including delta (0–4 Hz), theta (4–8 Hz), alpha (8–13 Hz) and beta (13–20 Hz) (Fisch, 1991). For each band, the mean EEG magnitude (μV) was computed for the 19channels (representative of the entire head). Magnitude was defined as the sum of all the amplitude (EEG activity) in a band's frequency range. The transitional phase of fatigue was identified using the observational measures based on the video analysis (Santamaria and Chiappa, 1987a; Lal and Craig, 2002a), described below.

In order to test the reproducibility of the EEG changes that occur during fatigue, two transitional phases to fatigue (episode 1 and episode 2 of transition to fatigue) were randomly selected from the two separate driving sessions stated above, linked in real time to a video recording of the subject's face. The EEG data was averaged across the entire 19 channels for both groups of subjects (35 non-professional and 20 professional drivers) in order to derive a single value of EEG magnitude change. The reproducibility of EEG changes was then assessed across the entire brain during the two episodes of fatigue for both groups of drivers.

The transitional phases were classified according to the simultaneous video analysis of the facial features (Lal and Craig, 2002a) and the EEG activity that are believed to be specific to this phase (Lal and Craig, 2002a; Santamaria and Chiappa, 1987). Left eye EOG was obtained with electrodes (Red dot, Ag/AgCl, Health Care, Germany) positioned above and below the eye with a ground on the masseter. The EOG signal was used to identify blink artifact in the EEG data as well as changes in blink types such as the small and slow blinks that characterize fatigue.

Statistical analysis package Statistica (for Windows, V 5.5, 1999, StatSoft, USA) was used for data analysis. A sample size calculation based on data from our previous studies (Lal and Craig, 2002a,b) using the EEG changes in all frequency bands, provided a statistical power $(1-\beta)$ of >0.9 based upon an effect size of >0.9 (according to Cohen, 1988). The statistical power was therefore more than adequate for all comparisons performed. We ran t-tests to identify differences between the sets of data. Pearson's correlation served to identify the association between the two different transitional phases.

2.4. Observational measures

Physical signs of fatigue were identified using a video image of the driver's face, linked in real time with the physiological measures. The video analysis served as an independent variable for fatigue assessment. Specific facial features characteristic of fatigue observed during the driving task that were used to identify fatigue included changes in facial tone, blink rate, eye activity and mannerisms such as nodding and yawning (Belyavin and Wright, 1987). The video image, which showed these physical and EOG signs of fatigue were used to validate the EEG changes associated with fatigue (Lal and Craig, 2002a). The study was concluded when specific physical signs appeared such as slow eye movement and slow blinks leading to eyes either half closed or fully closed together with mannerisms such as head drooped or continuous nods. Two independent observers assessed the reliability of identifying fatigue from the video recording. Both observers independently identified physical signs of fatigue from the same video recording. This was done in 10 randomly selected subjects. The identification of physical signs of fatigue from the video for inter-observer (r=0.88) and intra-observer variability (r=1.00) showed substantial agreement between the two observers (Lal and Craig, 2002a).

3. Results

3.1. The reproducibility of EEG during fatigue in non-professional drivers

All subjects completed the study. Table 1 shows the average EEG changes during the two separate episodes (episode 1 and episode 2) of transition to fatigue between the two driving sessions. The results of a t-test and correlations performed on the EEG changes in two episodes of transition to fatigue are shown in Table 2. Theta and beta were significantly different during two episodes of transition to fatigue between the two driving sessions (t=−8.42, df=34, p<0.001 and t=−8.20, df=34, p<0.0001, respectively); however, the differences were not large (moderate effect size for theta 0.5 and large effect size for beta=1.2). Delta and alpha bands were similar over the two fatigue episodes. However, all bands showed highly significant associations during the two episodes of fatigue (p<0.001 for all the bands).

3.2. The reproducibility of EEG during fatigue in professional drivers

Table 1 shows the average EEG changes during two separate episodes of transition to fatigue between the two driving sessions in the 20 truck drivers. The

Table 1
The average EEG activity during two different episodes of the transitional phase to fatigue in non-professional drivers and professional drivers

EEG band	Transition to fatigue (episode 1)		Transition to fatigue (episode 2)	
	np	p	np	p
Magnitude (μV)				
Delta	30.3±9.27	21.5±4.13	30.3±7.18	21.6±5.29
Theta	11.1±3.07	8.7±1.58	9.7±2.43*	9.1±1.70*
Alpha	9.0±0.86	7.9±0.59	8.9±0.68	7.9±0.62
Beta	8.4±0.52	9.0±0.55	9.0±0.40*	8.1±0.50*

The results are reported as mean±S.D.
np=non-professional drivers, p=professional drivers.
Bonferroni corrections have been applied so that the probability for rejection is p=0.01 (i.e., 0.05/4). (n=35).
* p<0.01.

Table 2
The results of a dependent sample t-test and Pearson's correlation on the intra-session EEG activity during the transitional phase to fatigue in non-professional and professional drivers

EEG band	Comparison of two episodes of transition to fatigue			
	t-Test		Correlation	
	np	p	np	p
Magnitude (μV)				
Delta	$t=-0.09$, $p=0.93$	$t=-0.20$, $p=0.85$	0.97/<0.0001	0.96/<0.0001
Theta	$t=8.42$, $p<0.0001$	$t=-8.84$, $p<0.0001$	0.99/<0.0001	0.99/<0.0001
Alpha	$t=1.09$, $p=0.29$	$t=0.49$, $p=0.63$	0.81/<0.0001	0.64/0.003
Beta	$t=-8.20$, $p<0.0001$	$t=9.97$, $p<0.0001$	0.76/<0.0001	0.71/0.001

Results of Pearson's correlation reported as (r)/significance (p).
Bonferroni corrections have been applied so that the probability for rejection is $p=0.01$ (i.e., 0.05/4). ($n=35$).

results of a t-test and correlation performed on the EEG changes during the two episodes of transition to fatigue are shown in Table 2. As found in the non-professional drivers, theta and beta activity were again more variable in the two episodes of transition to fatigue ($t=-8.84$, $df=34$, $p<0.0001$ and $t=9.97$, $df=34$, $p<0.0001$, respectively) in the professional drivers (moderate effect size of 0.3 and large effect size of 1.6, respectively). In addition, the EEG changes in all bands were highly correlated during the two episodes of fatigue ($p<0.01$).

4. Discussion

There is a lack of research on the reproducibility of the EEG magnitude response during driver fatigue. Even though it has been shown that drowsiness and fatigue are associated with changes in the EEG frequency spectrum (Santamaria and Chiappa, 1987; Matousek and Petersen, 1983), its stability over time has not been determined. While, studies that have investigated the reproducibility of EEG have mostly assessed EEG power effects (Fernandez et al., 1993; Gasser et al., 1985; Salinsky et al., 1991), the present research investigated the reproducibility of the EEG magnitude changes in the delta, theta, alpha and beta bands. Since fatigue influences EEG magnitude considerably (Lal and Craig, 2002a) as well as the fact that it is a simpler parameter than power to utilise in a driver fatigue countermeasure device (Lal and Craig, 2002a; Lal et al., 2003), it seemed prudent to study the reproducibility of the EEG magnitude during fatigue. Results revealed that the EEG magnitude response in the two episodes of fatigue were closely associated for all four bands, i.e., delta, theta, alpha and beta in both professional and non-professional drivers. Furthermore, there were no significant differences in the delta and alpha magnitudes across the entire brain during the transitional phase to fatigue in both the non-professional and professional groups of drivers. This suggests that the delta and alpha activity during fatigue is stable and therefore reproducible across the entire brain. However, it should be noted that the stability observed in delta activity could be due to the fact that the signal in the delta frequency range (0–4 Hz) was filtered using a high pass filter. However, changes in theta and beta magnitude may be more variable during different episodes of fatigue; though differences were not large (of the order of 1 μV). The EEG activity in all bands was highly correlated between the two selected fatigue episodes in both groups of drivers.

Others have also found good test retest reliability in alpha and modest reliability in delta bands (Gasser et al., 1985). These authors suggested that the latter was probably due to the fact that slow activity is prone to be contaminated by eye movement artifact. In contrast, we found strong reliability coefficients between the two episodes of fatigue in slow wave activity and weaker reliability coefficients in alpha and beta activity in both driver groups. This is encouraging as we have previously suggested that detection of slow wave activity during fatigue may form the basis of a fatigue countermeasure device (Lal et al., 2003).

In the present study we tested EEG reproducibility utilising 30-s records. It has previously been shown that 20-s records are nearly as reliable as 40- or 60-s records regarding the total EEG length used for frequency analysis (Salinsky et al., 1991; Gasser et al., 1985). It should be noted that the time between the test–retest interval in our study was 2 h. For further verification of the reproducibility of the EEG of fatigue future studies would need to assess the subjects a few months apart. As may be expected, according to Salinsky et al. (1991), longer test–retest intervals increase the EEG variability it was important to identify the short-term stability of EEG during fatigue before investigating long-term stability. Long-term stability is a possibility as Salinsky et al. (1991), found EEG power to be similarly reproducible for short time intervals of 5 min as well as a longer periods of 12–16 weeks. This finding is also consistent with the results of Gasser et al. (1985).

The EEG recording montage is another factor that has been reported to influence test–retest reliability (Oken and Chiappa, 1988). In our study the EEG activity was recorded in relation to a linked-ear reference. Salinsky et al. (1991) reported higher reliability in linked ear compared to a central site reference montage and lower for temporal sites. These authors related montage effects to differences in inter-electrode distance. Oken and Chiappa (1988) observed higher variation in the longitudinal bipolar versus ipsilateral ear reference. The inter-electrode distance in our study was consistent at 6 cm, which perhaps reduces the montage variability effect observed in previous studies.

The high reliability coefficients found from the Pearson's correlation in delta and theta activity in the present study as well as the relatively small differences in the EEG magnitude for all bands promotes the usefulness of utilising slow wave activity changes in a fatigue countermeasure device (Lal et al., 2003). Future studies need to investigate the reproducibility of the EEG of fatigue using different EEG montage as well as longer test–retest intervals.

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