The Reliability of Sensing Fatigue from Neurophysiology

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Abstract

To date no-study has tested the reproducibility of electroencephalography (EEG) changes that occur during driver fatigue. For the EEG changes to be useful in the development of a fatigue sensing and countermeasure device the EEG response during each onset period of fatigue in individuals needs to be reproducible. The aim of the present study was to investigate the reproducibility of the EEG changes during fatigue in professional drivers in order to identify the feasibility of the EEG measure for a fatigue sensor. Twenty professional drivers were assessed during two separate sessions of a driver simulator task. EEG, eye activity and behavioural measurements of fatigue were obtained during the driving task. The results showed significant reproducibility for the EEG slow wave activity (r >0.95) and fast wave activity (r >0.60). The results have promising implications for the development of an EEG based fatigue-sensing device. The EEG changes during fatigue were reproducible and therefore, appear to be a promising neurophysiological measure, which can be incorporated into an on-line fatigue sensor.

1. Introduction

Driver fatigue has been shown to account for nearly 20-30% of road accidents [1]. Fatigue is a 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 [2]. The decrease in physiological arousal during fatigue, slowed sensorimotor functions and impaired information processing can diminish the driver's ability to respond effectively to emergency situations [3]. Recently, in a review from the International Consensus Meeting on Fatigue and Risk of Traffic Accidents, identified disturbed sleep, working at the low of the circadian rhythm and sleep apnea as some of the factors associated with fatigue related accidents [4]. If indicators of fatigue can be developed, they may be used to provide drivers with useful feedback about the onset of fatigue.

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 [5,6]. 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 [6, 7, 8]. From the results of our previous studies in professional and non-professional drivers [6, 9], we suggested that when persistent delta and theta waves appear, a rest period should be considered before the subjects become severely fatigued. However, for the EEG changes that occur during driver fatigue to be utilised in the development of a fatigue-sensing device, the EEG response during the onset of fatigue in individuals needs to be highly reproducible.

The reliability of the EEG response during two episodes of a performance task has been shown recently [10]. Others have shown good test-retest reliability of EEG power, however lesser reliability has been reported for EEG coherence during various cognitive tasks [11,12]. In another study, poor reproducibility of theta and beta amplitude has been found during a simple motor task [13], however this study was about topography and not EEG amplitude changes. To date, no-study 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 during fatigue in professional drivers.

2. Methods

Twenty male professional truck drivers, with a mean age of 44 ± 11 (mean ± SD) years were recruited by advertisement placed in the local newspaper. All truck drivers were irregular shift-workers. 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.

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 four hours and alcohol for 24 hours before the study. 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 initial driving task consisted of 10-15 minutes of driving to familiarize the subject with the driver simulator, followed by a 10-minute break. Following this, subjects performed stage 1 (baseline) of the experimental task, which constituted 10-15 minutes 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/hr), which involved two sessions of monotonous driving until the subjects showed physical signs of fatigue (based on video analysis, see below). The two driving sessions were interspersed by an interval of two hours during which time the subjects were not involved in the driving task.

The EEG and was 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 [14]. The data was sampled at 256 Hz and divided into epochs of 1-second duration. The total sample time was individually determined, continuing till arousal from fatigue by a verbal interaction from the investigator. 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) [14]. For each band the mean EEG magnitude (μV) was computed for the nineteen channels (representative of the entire head). The transitional phase of fatigue was identified using the observational measures based video analysis [6].

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 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. The transitional phases were classified according to the simultaneous video analysis of the facial features *(6)* and the EEG activity that are believed to be specific to this phase [6, 15].

The 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 *(6, 9)* using the EEG changes in all frequency bands, provided a statistical power (1-β) of >0.9 based upon an effect size of >0.9. The statistical power was therefore more than adequate for all comparisons performed. T-tests were performed to identify differences between the sets of data. Pearson's correlation served to identify the association between the two different transitional phases.

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 [16]. The video image, which showed these physical and EOG signs of fatigue were used to validate the EEG changes associated with fatigue [6]. 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 [6].

3. Results

Table 1 shows the average EEG changes during two separate episodes of transition to fatigue between the two driving sessions in the twenty truck drivers. The 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. Theta and beta activity were 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) (moderate effect size of 0.3 and large effect size of 1.6, respectively).

Table 1 The average EEG activity during two different episodes of the transitional phase to fatigue in professional drivers. Bonferroni corrections have been applied so that the probability for rejection is p=0.01 (i.e. 0.05/4). (n=20).

EEG Band Magnitude (μV)	**Transition to fatigue (episode 1)**	**Transition to fatigue (episode 2)**
Delta	21.5 ± 4.13	21.6 ± 5.29
Theta	8.7 ± 1.58	9.1 ± 1.70*
Alpha	7.9 ± 0.59	7.9 ± 0.62
Beta	9.0 ± 0.55	8.1 ± 0.50 *

The results are reported as mean ± sd, * $p < 0.0001$

In addition, the EEG changes in all bands were highly correlated during the two episodes of fatigue ($p<0.01$).

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 professional drivers. Bonferroni corrections have been applied so that the probability for rejection is $p=0.01$ (i.e. 0.05/4). ($n=20$).

EEG Band	**Comparison of two episodes of transition to fatigue**	
	t-test	**correlation**
Delta	t=-0.20, p=0.85	0.96/<0.0001
Theta	t=-8.84, p<0.0001	0.99/<0.0001
Alpha	t=0.49, p=0.63	0.64/0.003
Beta	t=9.97, p<0.0001	0.71/0.001

Results of Pearson's correlation reported as (*r*)/significance (*p*).

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 [15, 17], its stability over time has not been determined. While, studies that have investigated the reproducibility of EEG have mostly assessed EEG power effects [11, 18, 19], 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 [6] as well as the fact that it is a simpler parameter than power to utilise in a driver fatigue countermeasure device [6, 20], 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. The EEG activity in all bands was highly correlated between the two selected fatigue episodes. There were no significant differences in the delta and alpha magnitudes across the entire brain during the transitional phase to fatigue. 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 (0-4Hz) was filtered using a high pass filter. Theta and beta magnitude changes were more variable during the two episodes of fatigue, though differences were not large (order of 1 μV).

Others have also found good test re-test reliability in alpha and modest reliability in delta bands [18]. 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. This is encouraging as we have previously suggested that detection of slow wave activity during fatigue may form the basis of fatigue sensing and countermeasure device [20].

In the present study we tested EEG reproducibility utilising 30 sec records. It has previously been shown that 20 sec records are nearly as reliable as 40 sec or 60 sec records regarding the total EEG length used for frequency analysis [18,19]. It should be noted that the time between the test-retest intervals in our study was two hours. 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 [19], 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 [19], found EEG power to be similarly reproducible for short time intervals of 5 min as well as longer periods of 12-16 weeks. This finding is also consistent with the study by [18].

The EEG recording montage is another factor that has been reported to influence test-retest reliability [21]. 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 [19]. 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 [21]. The inter-electrode distance in our study was consistent at 6cm, 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-sensing device [20]. Future studies need to investigate the reproducibility of the EEG of fatigue using different EEG montage as well as longer test-retest intervals.

5. Acknowledgements

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