Title
Physiological indicators of Driver Fatigue

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Abstract/Summary
Fatigue has major implications in transportation system safety. Investigating the psychophysiological links to fatigue can enhance our understanding and management of fatigue in the transport industry. This study examined psychophysiological changes in thirty-five subjects randomly assigned to a driver simulator task. Electroencephalography changes during fatigue were significantly different to the alert baseline ($p<0.01$). Delta and theta activity increased the most from fatigue during simulated driving. Heart rate was significantly lower after the driving task ($p<0.01$). Blink rate also changed in association with fatigue. We conclude that significant physiological changes occur during driver fatigue. The results are discussed in light of directions for future studies and for the development of a fatigue counter measure device.

Introduction

Fatigue has implications in road fatalities and is a major hazard in transportation systems. Brown (1), in a review of driver fatigue, defined fatigue as a subjectively experienced disinclination to continue performing the task at hand. Driver fatigue has been specifically defined as a state of reduced mental alertness that impairs performance of a range of cognitive and psychomotor tasks including driving (2). Fatigue can lead to drowsiness and sleepiness. The terms 'sleepiness' and 'fatigue' are used synonymously to mean sleepiness resulting from the neurobiological processes regulating circadian rhythms and the drive to sleep (3). For communication purposes we use the terms interchangeably in this paper.

Driver fatigue is an issue that is receiving increasing attention in the road safety field. It is a serious problem in transportation systems and a direct or contributing cause of many accidents and is believed to account for 35-45% of all vehicle accidents (4). Drivers may experience fatigue from the length of the journey, monotonous driving situations and the time of the day (5), irregular work schedules (6) and demands to meet delivery schedules (7). Analysis of accident data suggest that driver-related fatigue is implicated in road accidents, particularly at night (8,9) and during long driving hours (10,11). 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 (12). The literature is abundant with studies, which have sought to measure variables associated with fatigue. However, the search for a reliable indicator of fatigue is still elusive and conflicting results continue to be obtained. Despite the literature being variable and numerous physiological indicators found to be linked to fatigue (13,14), the EEG signal may be one of the most predictive and reliable (15,16). Drivers cannot maintain a high level of consciousness when they are mentally fatigued and this is indicative in the EEG, which is believed to show consistent and reliable changes during fatigue (17). A study of truck drivers reported cortical deactivation and increased sleepiness during the end hours of an all night driving shift (18). Ambulatory studies with nonprofessional drivers have also demonstrated cortical deactivation in response to continuous driving over monotonous and repetitive environments (19,20).

Therefore the present study examined the physiological changes during the transition from alert to drowsiness/fatigue in a driver simulator task. We also wanted to confirm the EEG band most sensitive to drowsiness. The findings from this study will be discussed in light of directions for future studies and the development of a fatigue countermeasure device.

Methods

Subjects/study protocol

Thirty-five subjects (26 males and 9 females) who were nonprofessional drivers, aged 21-52 (34 ± 21) years, were randomly assigned to the study which was approved by the institutional ethics committee. The study was conducted in a temperature-controlled laboratory as the subjects performed a standardized sensory motor driver simulator task. Caffeine, tea and food intake was restricted for 4 hours and alcohol for 24 hours before the study. Subjects were sleep deprived for approximately two hours the night before. The study was conducted at approximately the same time of the day. The driver simulator equipment consisted of a car frame with steering wheel, brakes, accelerator, gears and speedometer with a video display. The driving task consisted of 5-10 min of active driving, followed by approximately two hours of driving (speed < 80 km/hr) till the subjects showed physical signs of fatigue. Simultaneous physiological measures were obtained during the driving task. These consisted of electroencephalography (EEG) and electro-occulogram (EOG). Nineteen channel monopolar EEG was recorded according to the International 10-20 system (21). Left eye EOG was obtained with electrodes (Red dot, Ag/AgCl, Health Care, Germany) positioned above and below the eye. The EOG and EEG data were linked in time. The EOG signal was used to identify blink artifact in the EEG data as well as changes in blink types such as small and slow blink during fatigue. Sitting brachial blood pressure (BP) was measured using a standard mercury sphygmomanometer, and heart rate (HR) was recorded before and after the driving session. Physical signs of fatigue were identified using a video image of the driver's face, linked in real time with the physiological measures. Specific facial features characteristic of fatigue observed during the driving task

included changes in facial tone, blink rate, eye activity and mannerisms such as nodding and yawning. The video image, which showed the physical signs of fatigue and the corresponding EOG changes (22) were used to validate the EEG changes, associated with fatigue. Fatigue levels before and after the driving task was evaluated by a scale created specifically for this research study called the 'fatigue state question'.

Data acquisition and statistical analysis

The EEG and EOG data was acquired using a physiological monitor (Neurosearch-24, Lexicor, America). Data was sampled at 256 Hz. A fast fourier transform was performed on the EEG data using a spectral analysis package (Exporter, Lexicor, USA). The EEG was defined in terms of frequency bands including delta (0-4 Hz), theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) (21). For each band the average EEG magnitude (μV) and maximum amplitude (μV) were computed. Amplitude was defined as the maximum or peak spectral amplitude within a band's frequency range. Magnitude was the sum of all the amplitude in a band's frequency range. Drowsiness was classified into transitional (between awake and absence of alpha), transitional-post transitional (which has characteristics of both), post transitional (early Stage 1 of sleep) and arousal phases (emergence from drowsiness) (22). The EEG data was compared for these phases to an alert baseline. Statistical analysis package Statistica (for Windows, V 5.5, 1999, StatSoft, USA) was used for subsequent data analysis. A sample size calculation using the EEG changes in all frequency bands provided a sufficient statistical power (1-β) of >0.9 based upon an effect size of >0.9. The differences between 'office' BP and HR measured before and after the driving task were compared using paired Student's *t* test. The fatigue phases were compared to an alert baseline using a repeated measures analysis of variance (ANOVA). A post hoc analysis using a Scheffe test was used to determine where the differences existed in the comparison of the means. The significance level was set at *p*<0.05 for all analysis performed. Results are reported as mean and standard deviation of differences.

Results

All subjects completed the study and had an average pre-study BP of 119 ± 13/74 $\pm$ 9 mm Hg (systolic/diastolic). The BP after the study did not change significantly from baseline, 117 ± 10/75 $\pm$ 9 mm Hg. Heart rate was significantly different (t=5.9, df=34, p<0.01) from before (68 ± 11 beats/min) to after the driving task (62 ± 10 beats/min). The average time to the transition to fatigue was 6 ± 3 min. The self reported fatigue questionnaire identified subjects as slightly fatigued before the study and moderately to extremely fatigued after the study. Table 1 shows the mean EEG activity for the five phases i.e. an alert baseline, transitional phase o fatigue, transitional-post transitional, post transitional and an arousal phase. The ANOVA analysis on the amplitude and magnitude data revealed overall differences between the five phases tested. The effects for amplitude were: delta (F=238, df=4, 72, p<0.0001), theta (F=103, df=4,72, p<0.0001), alpha (F=95, df=4,72, p<0.0001) and beta (F=62, df=4,72, p<0.0001). Magnitude results were: delta (F=157, df=4,72, p<0.0001), theta (F=142, df=4,72, p<0.0001), alpha (F=85, df=4,72, p<0.0001), beta (F=77, df=4,72, p<0.0001).

Table 1 The average EEG activity during the alert baseline, transitional phase to fatigue, transitional-post transitional, post transitional and the arousal phase

EEG Band	Alert	Transition to Fatigue	Transitional-Post transitional	Post-Transitional	Arousal
Amplitude (μV)					
Delta	8.5 ± 1.91	10.2 ± 2.75	10.8 ± 2.20	13.9 ± 0.58	10.4 ± 0.59
Theta	2.8 ± 0.71	3.5 ± 1.02	3.1 ± 0.83	3.56 ± 1.00	2.9 ± 0.78
Alpha	2.2 ± 0.19	2.4 ± 0.26	2.4 ± 0.19	2.5 ± 0.25	2.3 ± 0.19
Beta	1.6 ± 0.08	1.7 ± 0.10	1.8 ± 0.10	1.8 ±0.09	1.6 ±0.09
Magnitude (μV)					
Delta	24.8 ± 6.13	30.3 ± 9.27	30.3 ± 7.18	37.5 ± 8.69	30.1 ± 8.61
Theta	8.8 ± 2.20	11.1 ± 3.07	9.7 ± 2.43	11.1 ± 2.80	9.2 ± 2.54
Alpha	8.3 ± 0.71	9.0 ± 0.86	8.9 ± 0.68	9.5 ± 0.81	8.7 ± 0.72
Beta	8.0 ± 0.36	8.36 ± 0.52	9.0 ± 0.40	8.6 ± 0.39	8.0 ± 0.41

In the post hoc analyses all the phases were compared to the alert baseline for the magnitude and amplitude data. The analysis identified that the transitional phase, transition to post-transition and post-transition phases were different to the alert baseline (p<0.01). The amplitude and magnitude changes from the alert baseline, during the different fatigue phases are summarized in Table 2. During the initial phase of transition to fatigue, the largest change in amplitude, compared to the alert baseline, was found in the delta and theta bands (1.7 ± 0.84 μV and 0.8 ± 0.31 μV, respectively; p<0.05). Similarly, the change in magnitude for the delta and theta bands were 5.5 ± 3.14 μV and 2.3 ± 0.87 μV, respectively; p<0.05 (see Table 2). Comparatively, the amplitude changes in the alpha and beta bands were smaller (0.3 ± 0.07 μV, p<0.05 and 0.03 ± 0.02 μV, ns, respectively). The magnitude changes were 0.8 ± 0.15 μV and 0.4 ± 0.16 μV, p<0.05 respectively.

Table 2 shows that the increased delta and theta levels persisted or increased further as fatigue progressed and maximum change was observed during the post transitional phase (amplitude: 5.4 ± 0.62 µV and 0.76 ± 0.29 µV respectively and magnitude: 12.7 ± 2.56 µV and 2.3 ± 0.60 µV, p<0.05, respectively). Alpha changed the most during the post transitional phase (amplitude: 0.4 ± 0.06 µV and magnitude: 1.2 ± 0.10 µV, p<0.05, respectively). Beta was maximum during the transitional-post transitional phase (amplitude: 0.2 ± 0.01 µV and magnitude: 1.01 ± 0.04 µV, p<0.05 respectively). On arousal from fatigue the amplitude and magnitude changes came close to that seen during the alert baseline (see Table 1), especially for theta and beta activity.

Table 2 The average change in EEG amplitude and magnitude during drowsiness compared to an alert baseline

EEG Band	Transitional	Transitional-Post transitional	Post-Transitional	Arousal
Amplitude (µV)				
Delta	1.68 ± 0.84**	2.26 ± 0.29**	5.36 ± 0.62**	1.90 ± 0.65**
Theta	0.75 ± 0.31**	0.32 ± 0.12**	0.76 ± 0.29**	0.13 ± 0.07
Alpha	0.25 ± 0.07**	0.19 ± 0.003**	0.38 ± 0.06**	-0.11 ± 0.002**
Beta	0.03 ± 0.02	0.19 ± 0.01**	0.11 ± 0.003**	0.01 ± 0.01
Magnitude (µV)				
Delta	5.45 ± 3.14**	5.50 ± 1.05**	12.67 ± 2.56**	5.24 ± 2.48**
Theta	2.31 ± 0.87**	0.90 ± 0.23**	2.26 ± 0.60**	0.45 ± 0.34*
Alpha	0.75 ± 0.15**	0.63 ± 0.03**	1.24 ± 0.10**	0.40 ± 0.01**
Beta	0.37 ± 0.16**	1.01 ± 0.04**	0.57 ± 0.03**	0.04 ± 0.05

Note The results are reported as mean ± sd, * p<0.05, ** p<0.0001

During transition to fatigue delta activity increased the most from baseline values in the frontal and central regions of the brain (7.6 ± 22.17 µV and 4.1 ± 17.88 µV, respectively). Theta activity increased the most in the frontal and parietal regions (3.0 ± 5.07 µV and 2.3 ± 1.76 µV, respectively). Alpha activity showed substantial increases in the frontal and occipital regions (0.79 ± 1.87 µV and 0.75 ± 2.04 µV, respectively), while beta increased the most in the parietal and occipital regions (0.46 ± 1.53 µV and 0.55 ± 2.19 µV). The fast eye movements and the conventional blinks during the alert phase; were replaced by no eye movements and small fast rhythmic blinks during drowsiness. Some physical mannerisms associated with onset of fatigue were yawning and head nodding. On arousal from the fatigue state subjects generally showed single vertical eye movements and the conventional blinks apparent during the alert phase mostly reappeared.

Discussion

Driver fatigue and physiological effects

The EEG showed consistent and reliable changes associated with driver fatigue. In the present study we found delta and theta amplitude increased significantly during transition to fatigue by 20% and 29% (p<0.0001); and magnitude by 22% and 26% respectively (p<0.0001). Alpha and beta activity also increased significantly though by a smaller degree (amplitude: 9% (p<0.0001) and 2% (ns) and magnitude: 9% and 5% (p<0.0001); respectively). The EEG changes were associated with physical signs of fatigue, which suggests that drivers cannot maintain consciousness in this state. The EEG theta activity occurs in a variety of mental states including drowsiness. According to Yamamoto and Matsuoka (23), when long lasting theta waves appear, a rest period should be considered before the subjects become fatigued. Deteriorated performance has been associated with increased theta and changes in alpha intensity while beta activity has also been shown to be altered (24,25). Makeig and Jung (26) also found changes in theta and alpha waves related to fatigue. In a study of drivers subjected to monotonous tasks, mean EEG activity in the theta and alpha bands increased and higher theta activity accompanied performance impairment (27). The results from our study confirms the increases observed in theta and alpha activity in the literature, which reflects a decreased cortical arousal that occurs during long monotonous tasks such as driving. However, in previous fatigue research, delta activity change has received little attention due to the low frequency signal being influenced by activities such as breathing and movement. However with advancing technology that is capable of removing noise from EEG signals, changes in delta can now be reported reliably and this increases its potential to be used as a neurophysiological indicator of fatigue.

Another study recorded the EEG of 11 train drivers and found that rated sleepiness increased sharply during the night journey (28). They showed that alpha activity was clearly the most sensitive to sleepiness with

delta and theta increasing by a lesser extent. The same group of investigators compared day and nighttime driving in nine professional drivers on a simulated truck driving task and found EEG associated with sleepiness was higher during night driving (29). Furthermore, in a field study, these investigators recorded EEG continuously during night and evening drives in a group of eighteen truck drivers (18). The night group showed higher subjective sleepiness and lower performance with increased theta and alpha burst activity during the last few hours of driving. In another study of night driving, EEG was recorded from a parieto-occipital derivation with amplification close to the electrodes (30). The results showed that unskilled drivers had increased power in the alpha band over the duration of the drive compared to skilled drivers. Sleep intruded while the drivers still had their eyes open, and it was accompanied by theta waves, sleep spindles (frequency of 11-15 Hz, duration of >0.5 sec (21)) and k-complexes (a transient EEG pattern of sharp positive wave followed by a negative wave, duration of >0.5 s described by (31)). Interestingly, the drivers had not been aware that they had been driving the car while asleep. The researchers concluded that the alpha band was sensitive to changes in alertness while the theta and delta bands were necessary for distinguishing lower levels of arousal. Others recorded EEG from four subjects during night driving (32). The EEG was recorded telemetrically via fronto-parietal and parieto-occipital derivations together with electro-occulogram (EOG). Towards the end of the driving, alpha bursts frequently appeared followed by theta waves. Others reported that during drowsiness, there are increases in slow wave activity i.e. progressive temporal, centrofrontal and posterior theta and delta and temporal alpha (22). Similarly, during onset of fatigue, we found that delta and theta activity was present mostly in the frontal, central and parietal areas of the brain with some anterior alpha and posterior beta. This is in accordance to the classification of drowsiness by some researchers who report appearance and increases in centrofrontal delta/theta with alpha during transition to drowsiness (22). The same investigators have also found a change in alpha distribution during drowsiness i.e. occipitopareital alpha spread to anterior areas and became more centrofrontal and temporal alpha (33). The results from our study and those of others indicate that the various areas of the brain behave differently during fatigue and therefore it may be useful to utilize an electrode derivation that spans the whole brain. Furthermore, we also found that the physical and physiological signs of fatigue was evident very soon after simulated driving (average 6 minutes). Other studies have observed marked indications of fatigue in some subjects after 60 minutes of driving or vigilance tasks (34).

Since there are rich sensory and motor connections between the eye and the brain, eye movement can provide signs of drowsiness. In our study the fast eye movements and conventional blinks during awake were replaced by no eye movements and small fast rhythmic blinks during drowsiness. During deeper drowsiness, slow blinks were seen in all the subjects. These changes occurred in majority of the subjects indicating the potential of using EOG to identify the physical onset of fatigue. Others have also indicated that slow eyelid closure is a reliable estimate of the level of drowsiness (24). In the present study we also found that heart rate decreased significantly during fatigue (by 7 beats per minute, p<0.01), indicating an autonomic association. Heart rate has been shown to decrease during prolonged and monotonous driving (30). However, more research is required in this area to better understand the autonomic changes associated with driver fatigue.

Self-report in our study revealed subjects as slightly fatigued before and moderately to extremely fatigued after the driving test. The self-report measures were also linked to EEG indicators of fatigue such as delta, theta and alpha variability and EOG changes. Another study of night driving also found changes in the EEG alpha and theta bands; and the self-rated fatigue outcome paralleled the EEG data (35).

On the Methodology of Fatigue studies

It is evident from the literature that numerous studies have been conducted on fatigue, however, some of the literature presents equivocal results for several stipulated methodological reasons which include: (a) The variable use of referential and bipolar EEG montages. (b) The use of heterogeneous samples. (c) The use of insufficient subject numbers. (d) Omitting to report the sample size. (e) Testing limited scalp sites. Since not all brain regions exhibit the same changes, it is important to have electrodes, which span most of the cerebral cortex (36). (f) Only reporting activity in some EEG bands, which may not be an adequate representation of the brain function deactivation that occurs in a fatigue state. Even though there is variability in the literature, some firm conclusions can be reached regarding electroencephalography effects during fatigue. The review of studies that came close to meeting some of the above criteria, the main EEG activity reported were increases in delta, theta and alpha activity (37,38), theta wave persistence (23) and appearance of grouped alpha waves (39). Similarly, others reported increases in delta, theta and beta activities (40) while others reported increases in only delta and theta (41). In our present study we found large increases in delta and theta during fatigue as well as smaller change in alpha and beta. Therefore, from prior studies and our present research, fatigue is most likely to be associated with increases in slow wave activities with smaller variations in alpha and beta activity.

EEG as an indicator of fatigue in countermeasures

As few drivers are probably aware of their fatigue status (42), it would seem important that non-intrusive devices be developed which can alert the driver. Previous research has noted the importance of developing countermeasures, which have the potential to sense fatigue symptoms and present appropriate warnings (1). It is important to note that the detector of fatigue impairment must provide high detection capability with a low risk of false alarm, and the device should not be a hindrance or a nuisance to the driver. Such a device needs a well-researched physiological measure, which not only changes significantly, but also substantially enough to be

used as a valid indicator of fatigue. It is planned to use the EEG results from our study to develop such a device.

Conclusions and Recommendations

In our present study we have found significant changes in EEG, EOG and heart rate during driver fatigue. According to our study and the literature, EEG changes appear to be promising indicator of driver fatigue. There are also consistent changes in blink activity during fatigue. The major EEG changes reported during driver fatigue are increases in delta, theta and alpha activity. Therefore, a valid measure of fatigue such as the EEG seems promising for the development of a fatigue countermeasure device. The non-hindering nature of EEG complies with Desmond and Matthews (43) criteria for a fatigue countermeasure device: i.e., it must provide a valid indication of fatigue, rather than some type of performance impairment. In the future, such an enabling technology could be important in the transport environment that demands alertness and that involve multiple tasks competing for limited attention resources (44). Even though there is widespread discussion and appreciation of the feasibility of neurophysiological measures to derive reliable and unobtrusive assessments of the mental state, no convenient and effective fatigue countermeasure device yet exists for use in the transport industry. On this front, we are utilizing the results of the present study to develop a prototype fatigue countermeasure device, which can detect changes during fatigue in the slow wave EEG activities such as in delta and theta. In the next phase of our research we plan to test the feasibility of the EEG based fatigue countermeasure device in both a laboratory and real field-driving situation. Future research in the area of driver fatigue should also aim to negate the methodological limitations mentioned above. We believe our research makes a substantial contribution to better identification of the physiological changes that are associated with the transition from alert to a fatigue state in a driving situation.

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