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Driver fatigue: Electroencephalography and psychological assessment

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Abstract

Fatigue has major implications for transportation system safety; therefore, investigating the psychophysiological links to fatigue could enhance our understanding and management of fatigue in the transport industry. This study examined the psychophysiological changes that occurred during a driver simulator task in 35 randomly selected subjects. Results showed that significant electroencephalographic changes occur during fatigue. Delta and theta activity were found to increase significantly during fatigue. Heart rate was significantly lower after the driving task. Blink rate also changed during the fatigue task. Increased trait anxiety, tension–anxiety, fatigue–inertia and reduced vigor–activity were shown to be associated with neurophysiological indicators of fatigue such as increased delta and theta activity. The results are discussed in light of directions for future studies and for the development of a fatigue countermeasure device.

Descriptors: Driver fatigue, Electroencephalography, Electro-oculogram, Countermeasure, Mood, Anxiety

Fatigue has major implications in road fatalities and is believed to present a major hazard in the transportation industry. The early introduction to the subject by Grandjean (1979, 1988) defined fatigue as a state marked by reduced efficiency and a general unwillingness to work. Later, Brown (1994) 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 during a range of cognitive and psychomotor tasks including driving (Williamson, Feyer, & Friswell, 1996). Fatigue generally impairs human efficiency when individuals continue working after they have become aware of their fatigue state.

Before we continue to discuss driver fatigue, it is important to clarify terms denoting fatigue. Recently, investigators have used the terms sleepiness and fatigue interchangeably (Dinges, 1995; Torsvall & Åkerstedt, 1987). The terms *sleepiness* and *fatigue* are used synonymously to refer to sleepiness resulting from the neurobiological processes that regulate the circadian rhythm and the need to sleep (Dinges, 1995). Although the term *sleepiness* has a more precise definition than *fatigue* (hence the latter is not preferred by many sleep specialists), the term *fatigue* is widely used to indicate the influence of long working periods, reduced rest, and being unable to sustain a certain level of task performance (Dinges, 1995). These aspects of fatigue overlap extensively with sleepiness and its effect on performance and, consequently, for communication purposes we use the terms interchangeably in this paper.

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Driver fatigue is receiving increasing attention in the road safety field. It is a serious problem in transportation systems, and is believed to account for 35–45% of all vehicle accidents (Idogawa, 1991). Drivers may experience fatigue as a result of the length of a journey, from monotonous driving situations and the time of the day (Horne & Reyner, 1995b), from irregular work schedules (Åkerstedt, Kecklund, Gillberg, & Lowden, 2000), and demands to meet delivery schedules (Hartley & Arnold, 1994). Analysis of accident data suggests that driver-related fatigue is implicated in road accidents, particularly at night (Haworth, Heffernan, & Horne, 1989; Mackie & Miller, 1978) and during long driving hours (Hamelin, 1987; McDonald, 1984). As well as increasing the likelihood that drivers will fall asleep at the wheel, fatigue could also impair driving ability such as maintaining road position and speed (Mackie & 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 & Heath, 1992).

The literature is abundant with studies that have sought to measure fatigue, including performance, perceptual, electrophysiological, psychological, and biochemical based measurements. 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 being linked to fatigue (Riemersma, Sanders, Hildervanck, & Gaillard, 1977; Stern, Boyer, & Schroeder, 1994), EEG could potentially be one of the most predictive and reliable techniques for detecting changes in alertness and vigilance (Horne & Reyner, 1995a; Lal & Craig, 2001a, 2001b). Drivers cannot maintain a high level of alertness when they are mentally fatigued and this has been shown to be associated with significant changes in delta, theta, and alpha activity (Lal & Craig, 2000a, 2000b). A study of truck drivers also reported cortical deactivation and increased sleepiness during the end hours of an all-night driving shift (Kecklund & Åkerstedt, 1993). Ambulatory studies with nonprofessional drivers have further demonstrated cortical deactivation in response to continuous and monotonous driving (Brookhius & De Waard, 1993; De Waard & Brookhius, 1991). Furthermore, researchers have also found associations between EEG delta, theta, alpha, beta, and sigma waves during driving (Caille & Bassano, 1977; Lal & Craig, 2000a, 2000b; Torsvall & Åkerstedt, 1983, 1987). However, most previously published studies on EEG changes during fatigue have found varying results that could be due to methodological differences and limitations. A robust experimentally controlled study is required to identify and clarify the EEG changes that occur during different levels of fatigue while driving.

It has also been suggested that fatigue may be experienced differently by drivers due to differing personalities and temperament (Brown & Eng, 1967). Lal et al. (1998) have shown that mood and anxiety levels can influence task performance and outcomes. Other studies have indicated associations between brain activity and psychological factors such as anxiety (Heller, Nitschke, Etienne, & Miller, 1997). However, research on the psychological links to fatigue and EEG is scarce and the subject needs further investigation.

Consequently, this investigation presents the results of a study that examined the physiological changes occurring during the transition from an alert to a fatigue state during a driver simulator task. A major goal of this research was to identify the EEG frequency bands most sensitive to fatigue. Psychological factors such as anxiety, mood, and perceived control and their associations with fatigue were also studied. A final goal of this paper was to explore the implications of the data for the development of a fatigue countermeasure device.

Methods

Participants and Study Protocol

Thirty-five participants (26 men and 9 women), who, at the time of the study, were nonprofessional drivers, were recruited from a large tertiary institution and the local community and were randomly assigned to the study. They had a mean age of 34 ± 21 years (range 21–52). All gave written consent for the study, which was approved by the institutional ethics committee. To qualify for the study, participants had to have no medical contraindications such as severe concomitant disease, alcoholism, drug abuse, and psychological or intellectual problems likely to limit compliance. This was determined during the initial interview on a separate day prior to the study.

The study was conducted in a temperature-controlled laboratory in which participants performed a standardized sensory motor driver simulator task. Caffeine, tea, and food intake were restricted for 4 hr and alcohol for 24 hr before the study. All participants recruited in the study stated that they were sleep deprived due to their current work demands. Prior to entering the study, participants reported average daily sleep periods of 6 hr. Participants were further instructed to sleep 2 hr less than their daily sleep period the night before the study. This request for less sleep the night before the study was to enhance the chance of the participants fatiguing during their performance of the continuous and monotonous driving task. Before the study, participants reported compliance with all given instructions. Furthermore, they all reported similar sleep periods of 4 ± 1 hr the night before the study. The study was conducted at the same time of the day (noon period) for each participant. 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 participants were asked to breath 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 participant with the driver simulator, followed by a 10-min break. Following this, participants performed Stage 1 (baseline) of the experimental task, which constituted 10–15 min of active driving, which included many road stimuli at various speeds. This was followed by Stage 2, which involved up to 2 hr of monotonous driving (very few road stimuli, speed <80 km/hr) or until the participants showed physical signs of fatigue.

Simultaneous physiological measures were obtained during the driving task. These consisted of electroencephalogram (EEG) and electro-oculogram (EOG). Nineteen-channel EEG was recorded according to the International 10-20 system (Fisch, 1991). A monopolar montage was used, that is, EEG activity was recorded in relation to a linked-ear reference. 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. Sitting brachial blood pressure (BP) measured using a standard mercury sphygmomanometer and heart rate (HR) were 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. 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 (according to Belyavin & Wright, 1987 and Santamaria & Chiappa, 1987a). The video image, which showed these physical and EOG signs of fatigue, was used to validate the EEG changes associated with fatigue. The study was concluded when specific video 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. The identification of these physical signs of fatigue from the video had excellent reliability, demonstrated by a high interobserver and intraobserver agreement (88% between three trained observers).

Anxiety, mood states, and perceptions of personal control were evaluated prior to the driving task. Trait anxiety and state anxiety were measured using the Spielberger State–Trait Anxiety Inventory which has high reliability and validity (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983). The Profile of Mood States (POMS) provided a measure of six mood states: tension–anxiety, depression–dejection, anger–hostility, vigor–activity, fatigue—inertia, and confusion–bewilderment (McNair, Lorr, & Droppleman, 1971). The POMS is a trait measure and its response is stable over at least a week and has a high reliability and validity (McNair et al., 1971). Locus of control of behavior (LCB), an outcome efficacy measure, provided a measure of the participant's perception of the relation between events and behavior (Craig, Franklin, & Andrews, 1984). LCB has been shown to have high reliability and validity (Craig et al., 1984). The State Anxiety Inventory was readministered at the end of the driving study protocol. All these questionnaires have been shown to have high reliability and validity. A scale created specifically for this research study called the "fatigue state question" also evaluated fatigue levels before and after the driving task, and asked the participants to respond to the following: "Presently I feel fatigued (tired, drowsy)." The choice of response ranged from 1, *not at all*, to 2, *slightly*, to 3, *moderately*, to 4, *markedly*. Reliability of this scale was tested in a separate group of 20 nonfatigued participants who did not participate in the current driving study, but completed the question before and after an interval of 2 hr. During the 2 hr, participants were attached with the electrodes as reported in the current study and performed the driver simulator task. Their response did not change significantly after the 2 hr, indicating adequate reliability and validity of this scale.

Data Acquisition and Statistical Analysis

The EEG and EOG data were acquired using a 24 channel physiological monitor (Neurosearch-24, Lexicor, USA). The EEG and EOG were sampled at 256 Hz and then segmented into epochs of 1-s duration. The total sample time was individually determined, continuing until 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, USA). A 4-term Blackman–Harris window and a 2 Hz cut-off high-pass filter were used that significantly reduced low frequency artifact as low frequency signals are attenuated. The EEG 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 average EEG magnitude (in microvolts) was computed as an average of the 19 channels (representative of the entire head). Magnitude was defined as the sum of all the amplitudes (EEG activity) in a band's frequency range. The EEG of drowsiness/fatigue was classified into the first appearance of transitional phase (between awake and absence of alpha), transitional to posttransitional phase (which has characteristics of both phases), and posttransitional phase (early Stage 1 of sleep) followed by an arousal phase (emergence from drowsiness; Santamaria & Chiappa, 1987a). For each phase, 30 successive EEG spectra were generated using FFT and were averaged to form 30-s means to derive the EEG magnitude in the four EEG bands. Previous studies have reported reliable changes during fatigue and brain functional states from EEG data spanning 15 s to 1 min (Gillberg, Kecklund & Åkerstedt, 1996; Torsvall & Åkerstedt, 1987). During fatigue many such "microsleep" cycles ranging from transitional through to the posttransitional phases followed by intermittent arousal periods may occur. These phases were classified according to the simultaneous video analysis of the facial features and the EEG activity that are believed to be specific to each phase (Santamaria & Chiappa, 1987a). The first complete cycle constituting the three fatigue phases followed a self-arousal phase were analyzed for each participant. The EEG data in the fatigue phases (Stage 2 of the driving task) were then compared to the EEG data in the alert baseline (Stage 1 of the driving task).

Statistical analysis package Statistica (for Windows, V 5.5, 1999, StatSoft, USA) was used for data analysis. A sample size calculation 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 adequate for all comparisons performed. The differences between "office" BP and HR measured before and after the driving tasks were compared using paired Student's t test. The EEG changes in the fatigue phases were compared to an alert baseline using a repeated measures analysis of variance (ANOVA). A post hoc analysis for comparison of means using the Scheffé test was used to determine specifically where differences existed in the fatigue phases. The response to the self rated "fatigue state question" before and after the driving task was compared using a nonparametric Wilcoxon matched pairs test. The total score for each psychological measure was correlated with the EEG changes during the "transitional phase" to fatigue using Pearson's correlation. Finally, multiple regressions were used to identify which of the psychological variables shown to have a significant association to fatigue contributed uniquely to the EEG variability. Because the psychological analysis in this study was exploratory, for the correlations, all significant results at a p value of $<.05$ are reported. Results are reported as mean and standard deviation of differences.

Results

All subjects completed the study and had an average prestudy BP of 119 ± 13 (systolic) and 74 ± 9 mmHg (diastolic), (mean ± *SD*). The BP after the study (117 ± 10 (systolic) and 75 ± 9 mmHg (diastolic)) did not change significantly from baseline. Heart rate was significantly different, $t(34) = 5.9$, $p < .01$, from before (68 ± 11 beats/min) to after the driving task (62 ± 10 beats/min). The average time to the initial transitional phase of fatigue as identified from the EEG and video analysis was 66 ± 3 (range: 61–73) min. The average times for the subjects to reach the first transitional to posttransitional phase and posttransitional phase were 68 ± 4 (61–75) min and 71 ± 5 (61–80) min, respectively. These phases were followed by self-arousal by the subjects at 74 ± 6 (62–84) min. The total time a subject remained in the transitional phase was 2 ± 2.3 (0.2–8.1) min, in the transitional to posttransitional phase for 3 ± 2.2 (0.2–8.3) min and in the posttransitional phase for 3 ± 1.9 (0.6–9.3) min. It should be noted that a number of these microsleep cycles occurred in all the subjects until the study was terminated, at which stage all the subjects were verbally aroused after 120 min of driving.

The ANOVA analyses on the magnitude data from the average of the response across the entire head revealed overall differences between the five phases tested (alert baseline, transitional phase, transitional–posttransitional, posttransitional, and an arousal phase). The effects for the EEG magnitude were: delta, $F(4,72) = 157$, $p < .0001$, theta, $F(4,72) = 142$, $p < .0001$, alpha, $F(4,72) = 85$, $p < .0001$, and beta, $F(4,72) = 77$, $p < .0001$. Figure 1 shows the mean EEG magnitude for the five phases tested.

In the post hoc analyses, the magnitude observed in all the phases were compared to the alert baseline. The analyses identified the transitional phase, transition–posttransitional and posttransitional phases to be significantly different from the alert baseline, all $F\text{s}(4,72) > 62$, $p\text{s} < .01$. The difference in EEG activity during the different phases of fatigue compared to the alert baseline is summarized in Table 1. During the initial phase of transition to fatigue, the largest change in magnitude, compared to the alert baseline, was found in the delta and theta bands, $F(4,72) = 157$, $p < .0001$, and $F(4,72) = 142$, $p < .0001$, respectively (see Table 1). The magnitude changes in the alpha and beta bands were also significantly different from the baseline, $F(4,72) = 85$, $p < .0001$, and, $F(4,72) = 77$, $p < .0001$, respectively.

Table 1 shows that the increased delta and theta levels persisted or increased further as fatigue progressed and maximum changes compared to the baseline were observed during the posttransitional phase, $F(4,72) = 77$, $p < .0001$, and, $F(4,72) = 142$, $p < .0001$, respectively. Alpha increased the most during the posttransitional phase, $F(4,72) = 85$, $p < .0001$. Beta activity was found to be

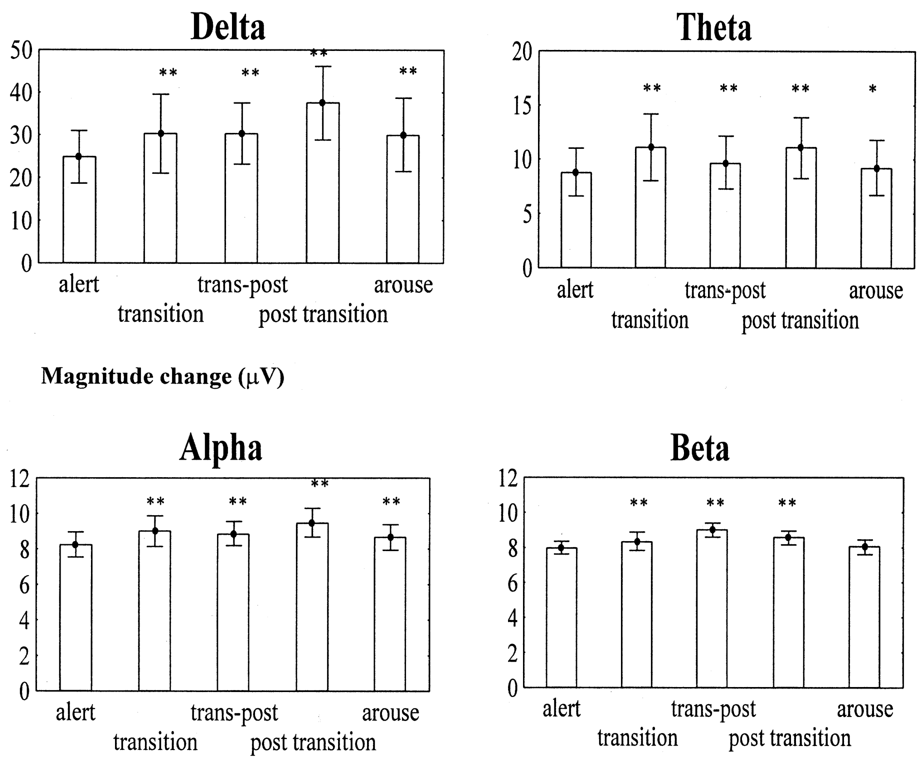

Figure 1. The mean and standard deviation of the EEG magnitude (in microvolts) response during driver fatigue across all 19 channels. The magnitude changes are shown during an alert phase and varying phases of fatigue. $*p < .05$, $**p < .0001$ ($n = 35$).

maximal during the transitional to posttransitional phase, $F(4,72) = 77$, $p < .0001$. On arousal from fatigue, the EEG activity came close to that observed during the alert baseline (refer to Figure 1), especially for theta and beta activity.

During the transitional phase to fatigue, maximum delta activity was observed in the frontal and central regions of the brain (7.6 ± 22.17 μV and 4.1 ± 17.88 μV, respectively). Theta activity was highest in the frontal and parietal regions (3.0 ± 5.07 μV and 2.3 ± 1.76 μV, respectively). Alpha activity was maximum in the frontal and occipital regions (0.79 ± 1.87 μV and 0.75 ± 2.04 μV, respectively), and beta was maximum in the parietal and occipital regions (0.46 ± 1.53 μV and 0.55 ± 2.19 μV).

Table 2 shows the proportion of subjects categorized according to the facial characteristics and mannerisms identified from the

Table 1. *The Average Change in EEG Magnitude during Drowsiness Compared to an Alert Baseline*

	Magnitude (μV)			
EEG band	Transitional	Transitional–posttransitional	Posttransitional	Arousal
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*.
$*p < .05$; $**p < .0001$.

video as well as the driving performance in each phase. The fast eye movements and the conventional blinks during the awake, alert phase were replaced by slow or no eye movements and small fast rhythmic blinks during drowsiness. Some physical mannerisms prominent during the 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 reappeared.

Subjects had psychological trait scores in the normal range. The mean trait anxiety score was 36 ± 8.4 (normative scores for men: 36 ± 10.4 and women: 35 ± 10.6; Spielberger et al., 1983). Locus of control was 23 ± 8.6 (normative score: 28.3 ± 8.5; Craig et al. 1984), and total mood score was 44 ± 24.4 (the six individual scales tested were in the normative range). The prestudy state anxiety of 32 ± 11.6 was not different from the poststudy state anxiety, which was 31 ± 9.1. The Wilcoxon test on the self-reported "fatigue state question" data identified subjects as slightly fatigued before the study and moderately to extremely fatigued after the driving task, $T = 30$, $N = 35$, $p = .002$. Table 3 shows the number of subjects reporting different levels of fatigue in response to the "fatigue state question" and the mean score before and after the driving task.

The following correlation results are a typical representation for the EEG changes for the entire head. Table 4 shows all the individual psychological variables that significantly correlated with EEG activity [i.e., sum of EEG activity (magnitude) and peak EEG activity in the delta, theta, alpha, and beta bands] during the transitional phase of fatigue. The self-reported fatigue levels were significantly associated with delta, theta, and beta activity during fatigue. State and trait anxiety were significantly associated with delta activity during transition to fatigue. Tension–anxiety was

Table 2. *The Video and EOG Indicators of Fatigue and Lapses in Driving Performance*

Status	Frequency of episode (average)	Percentage of subjects
Alert/awake		
Frequent, gaze-associated fast eye movement in any direction		100
Conventional blinks of high amplitude		100
Mini blinks		100
Fatigue/drowsiness		
Transitional phase		
No eye movement		67
Yawns	1 yawn/5 min	23
Lane drifting		10
Other driving errors		5
Accidents (collisions)		2
Transitional to posttransitional phase, deeper drowsiness		
Small, fast, rhythmic blinks		46
Nodding	1 nod/10 s	23
Lane drifting		20
Other driving errors		15
Accidents (collisions)		25
Posttransitional phase, onset of Stage I of sleep		
Slow eye movement and slow blinks		100
Eyes half closed or closed		69
Lane drifting		50
Other driving errors		20
Accidents (collisions)		70
Arousal from drowsiness		
Single, vertical eye movement		100
Slow blinks disappear; replaced by conventional blinks		100

significantly associated with delta activity whereas fatigue–inertia correlated significantly with delta, alpha and beta activity. Vigor–activity was negatively correlated with delta changes during fatigue. Locus of control was significantly linked to theta activity.

To determine which psychological variables uniquely contributed to EEG changes associated with fatigue, only those variables that correlated significantly with the EEG activity during fatigue were entered into a standard multiple regression analysis. The multiple regressions that had an overall significance of $p < .05$ are shown in Tables 5, 6, and 7. Table 5 shows that the regression with peak EEG activity in the different bands for the frontal region was significant, $R = .59$, $R^2 = .35$, adjusted $R^2 = .21$, $p < .05$, for six psychological variables (trait anxiety, tension–anxiety, vigor–activity, fatigue–inertia and pre- and poststudy state anxiety), which together explained 35% of the variance in delta activity associated with fatigue. However, the only individual factor that was significant in the regression was fatigue–inertia, $p < .04$. Table 5 also shows that the magnitude effects; the regression was significant, $R = .41$, $R^2 = .16$, adjusted $R^2 = .11$, $p < .05$, for the frontal region with two variables (pre- and poststudy state anxiety) explaining 17% of delta variability during fatigue. Table 6 shows that 24% of theta variability in the temporal region of the brain was significantly, $R = .49$, $R^2 = .24$, adjusted $R^2 = .19$, $p < .01$, explained by Trait anxiety, $p = .04$, and poststudy fatigue status, $p = .03$. Table 6 also shows that trait anxiety, locus of control, and poststudy fatigue state explained 26% of theta variability in the central area of the brain, $R = .51$, $R^2 = .26$, adjusted $R^2 = 19\%$, $p < .02$. When all three variables were entered into the regression, only poststudy fatigue status was significant, $p < .05$. Table 7 shows that fatigue–inertia, $p = .04$, and prestudy fatigue status, $p = .006$, accounted for 33% of beta variability in the occipital region during fatigue, $R = .57$, $R^2 = .33$, adjusted $R^2 = 29\%$, $p < .01$.

Discussion

The EEG showed consistent and reliable changes associated with driver fatigue. In the present study, we found delta and theta

Table 3. *The Number (Percentage) of Subjects Responding to Individual Items on the Likert "Fatigue State Question" Immediately Before and After the Driving Task (n = 35)*

	Response to Fatigue State Item: "Presently, I feel fatigued (tired, drowsy)"				
	Not at all	Slightly	Moderately	Markedly	Mean
n (%) before driving	5 (14.3%)	14 (40%)	13 (37.1%)	3 (8.6%)	2.4 ± 0.85
n (%) after driving	1 (2.9%)	5 (14.3%)	23 (65.7%)	6 (17.1%)	3.0 ± 0.66

Table 4. *Significant Correlation Between EEG Changes and Psychological Variables*

Psychological measure	EEG band: Delta	Theta	Alpha	Beta
Associations with peak EEG activity				
Trait anxiety	.40/.02*	.35/.04*		
Poststate anxiety	.42/.01*			
Locus of control		.35/.04*		
Tension anxiety	.40/.02*			
Vigor–activity	−.44/.009**			
Fatigue–inertia	.39/.02*		.36/.03*	.43/.009**
Prestudy fatigue state	.37/.03*			.49/.003**
Poststudy fatigue state		.44/.009**		
Associations with sum of EEG activity (magnitude)				
Trait anxiety	.36/.03*			
Prestate anxiety	.40/.02*			
Poststate anxiety	.40/.02*			
Tension anxiety	.40/0,02*			
Vigor–activity	−.36/.03*			
Poststudy fatigue state	.40/.02*			

Note: Results are reported as correlation (r)/significance (p).
$*p < .05$; $**p < .01$.

magnitude increased significantly over the entire head during transition to fatigue by 22% and 26%, respectively. Alpha and beta activity was also found to increase but by a smaller degree (9% and 5%, respectively). The subjects remained in each of the transitional, transitional to posttransitional, and posttransitional phases for 2–3 min on average. For the duration of the study, the subjects went through many such microsleep periods. The EEG changes were shown to be associated with physical signs of fatigue as verified by the video analysis. Furthermore, as fatigue levels increased, greater numbers of subjects were prone to have driving related errors and accidents.

In previous fatigue based research, change in delta activity has received little or no attention due to the tendency for the low frequency signal to be influenced by artifacts from activities such as breathing and movement. However, with advancing technology that is capable of removing noise from the EEG, changes in delta can now be reported more reliably and this increases its potential to be used as a neurophysiological indicator of fatigue. The EEG theta activity also occurs in a variety of mental states including drowsiness. Deteriorated performance has been previously associated with increased theta and changes in alpha intensity and beta activity has also been shown to be altered (Townsend & Johnson, 1979; Wierwille & Ellsworth, 1994). Makeig and Jung (1995) also found changes in theta and alpha waves related to fatigue. In a

Table 5. *Multiple Regression Analysis of Psychological Association with Peak Delta Activity and Magnitude*

Regression summary for dependent variable: Frontal/Delta (peak activity); $R = .60$, $R^2 = .35$, Adjusted $R^2 = .21$, $p < .05*$, SE of estimate = 8.63, $n = 35$

	β	SE of β	B	SE of B	t	p
Intercept			0.42	13.65	0.03	.98
Trait anxiety	0.11	0.21	0.12	0.24	0.52	.61
Tension–anxiety	−0.42	0.32	−0.68	0.52	−1.30	.20
Vigor–activity	−0.19	0.23	−0.30	0.36	−0.84	.41
Fatigue–inertia	0.44	0.20	0.73	0.33	2.21	<.04*
Preestate anxiety	0.33	0.32	0.28	0.27	1.03	.31
Poststate anxiety	0.12	0.27	0.13	0.28	0.45	.66

Regression summary for dependent variable: Frontal/Delta; $R = .41$, $R^2 = .17$, Adjusted $R^2 = .11$, $p < .05*$, SE of estimate = 25.0

	β	SE of β	B	SE of B	t	p
Intercept			3.03	15.27	0.20	.84
Prestate anxiety	0.14	0.24	0.32	0.55	0.58	.58
Poststate anxiety	0.29	0.24	0.86	0.70	1.22	.23

Note: SE: standard error, β: the standard regression coefficient, B: unstandardized regression coefficient.
$*p < .05$.

Table 6. *Multiple Regression Analysis of Psychological Association with Peak Theta Activity*

Regression summary for dependent variable: Temporal/Theta; $R = .49$, $R^2 = 0.24$, Adjusted $R^2 = 0.19$, $p < .01**$, SE of estimate = 0.59, $n = 35$

	β	SE of β	B	SE of B	t	p
Intercept			0.61	0.62	0.98	.33
Trait anxiety	0.32	0.15	0.03	0.01	2.09	.04*
Poststudy fatigue	0.35	0.15	0.34	0.15	2.25	.03*

Regression summary for dependent variable: Central/Theta; $R = .51$, $R^2 = .26$, Adjusted $R^2 = .19$, $p < .02*$, SE of estimate = 0.72

	β	SE of β	B	SE of B	t	p
Intercept			0.96	0.76	1.26	.22
Trait anxiety	0.71	0.20	0.02	0.02	0.85	.40
Locus of control	0.24	0.20	0.02	0.02	1.21	.23
Poststudy fatigue	0.34	0.15	0.41	0.19	2.20	.04*

Note: SE: standard error, β: the standard regression coefficient, B: unstandardized regression coefficient.
$*p < .05$.

Table 7. *Multiple Regression Analysis of Psychological Association with Peak Beta Activity*

Regression summary for dependent variable: Occipital/Beta; $R = .57$, $R^2 = .33$, Adjusted $R^2 = .29$, $p < .002$**, SE of estimate = 0.47, $n = 35$

	β	SE of β	B	SE of B	t	p
Intercept			0.77	0.26	3.01	.005
Fatigue–inertia	0.31	0.15	0.03	0.01	2.07	<.05*
Prestudy fatigue	0.43	0.15	0.28	0.10	2.93	.006**

Note: SE: standard error, β: the standard regression coefficient, B: unstandardized regression coefficient.
*$p < .05$; **$p < .01$.

study of drivers subjected to monotonous tasks, mean EEG activity in the theta and alpha bands increased and higher theta activity accompanied performance impairment (Horváth, Frantik, Kopriva, & Meissner, 1976). The results from our study confirm findings of prior research that suggested that increased theta and alpha activity most likely reflects decreased cortical arousal during a monotonous task such as driving.

Another study recorded the EEG of 11 train drivers and found that sleepiness increased sharply during the night journey (Torsvall & Åkerstedt, 1987). They showed that alpha activity was clearly the most sensitive to sleepiness with delta and theta increasing by a lesser extent. Furthermore, in a field study, these investigators recorded EEG continuously during night and evening drives in a group of 18 truck drivers (Kecklund & Åkerstedt, 1993). The night group showed higher subjective sleepiness and lower performance with increased theta and alpha burst activity during the last few hours of driving. The EEG changes in the current study were shown to vary according to the cortical site being assessed. During the onset of fatigue, we observed that delta and theta activity were present mostly in the frontal, central, and parietal areas of the brain with some anterior alpha and posterior beta. Other researchers have similarly reported that during drowsiness, increases in slow wave activity occur, that is, progressive temporal, centrofrontal, and posterior theta and delta (Santamaria & Chiappa, 1987a). These investigators have also found a change in alpha distribution during drowsiness, that is, occipitoparietal alpha spread to anterior areas and became more centrofrontal and temporal alpha (Santamaria & Chiappa, 1987b). These results suggest that various areas of the brain behave differently during fatigue, and therefore it may be useful to utilize an electrode derivation that spans the surface of the head when studying this phenomenon.

Because there are rich sensory and motor connections between the eye and the brain, eye movement can also provide signs of fatigue. In our study, the fast eye movements and conventional blinks during alert were replaced by no eye movements and small fast rhythmic blinks during fatigue. During deeper drowsiness, slow blinks were seen in all the subjects. These results confirm the value of using EOG to identify the physical onset of fatigue. In a review on blink rate as a possible measure of fatigue, Stern et al. (1994) identified that not only blink rates but number of blinks and blink duration were also variables sensitive to fatigue effects. Others have also identified slow eyelid closure as a reliable estimate of the level of drowsiness (Wierwille & Ellsworth, 1994). In the present study, we also found that heart rate decreased significantly during fatigue (by 7 bpm), indicating an autonomic association. Heart rate has been shown to decrease during prolonged and monotonous driving (O'Hanlon & Kelley, 1977). However, more research is required in this area to better understand the autonomic changes associated with driver fatigue.

It should be noted that questionnaires cannot provide information on moment-to-moment fluctuations of sleepiness. Therefore, we employed both physiological and self-report measures in our study. The self-report results in our study revealed subjects were 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 as well as the EOG changes. For obvious reasons, it is important that fatigue studies incorporate an independent and reliable indicator of fatigue such as a video image of the face to verify fatigue status. Consequently, we used a video image of the driver's face, linked in real time with the physiological measures for drowsiness assessment. Very few studies have applied "facial expression" to fatigue research (Belyavin & Wright, 1987; Yabuta, Iizuka, Yanagishima, Kataoka, & Seno, 1985), and most studies do not provide independent validation of fatigue status. In the present study nearly two-thirds of the subjects had negligible eye movements and many were shown to have mannerisms such as yawning and nodding during fatigue. More than halfway through the driving task, slow blinks occurred in most subjects with episodes of eye closure. Furthermore, the transition to fatigue as shown by the video analysis was not an immediate process but included periods of fatigue and alert states that were also reflected in the EEG. Others have also found that the EEG change during falling asleep is not an immediate process, showing that fluctuations between wake and sleep periods occur, that is, successive microsleep episodes (Harrison & Horne, 1996).

The EEG changes found to occur during the transition to fatigue were shown to be associated with psychological factors such as anxiety and mood. In a recent study, Lal et al. (1998) showed that environmental stimuli and psychological factors such as mood and anxiety affect cognitive task performance. In the current study, increased levels of trait and state anxiety and negative mood states such as tension–anxiety and fatigue–inertia were associated with EEG fatigue indicators such as increased delta and theta activity. The results suggest that having higher levels of anxiety increases the potential for becoming fatigued. In our study, 17% of the variation in delta activity during transition to fatigue was accounted for by state anxiety. For a single psychological factor to explain at least a fifth of the variance in EEG delta during fatigue is impressive. The results also suggest that having a higher tension–anxiety level (indicating heightened musculoskeletal tension) is another factor that increases the risk of experiencing fatigue. The tension–anxiety mood subscale incorporates somatic tension as well as observable psychomotor manifestations such as "shaky" and "restless." It also refers to vague and diffuse anxiety states. Increased fatigue–inertia showed similar associations to fatigue. It represents a mood of weariness, inertia, and low energy levels. Not surprisingly, having less vigor–activity was also linked to increased delta activity, which occurs during fatigue. This factor suggests a mood of vigorousness and high energy. In addition, increased trait anxiety level was associated with theta increase and fatigue–inertia was associated with beta changes during fatigue. This suggests higher levels of anxiety; psychomotor tension, increased cognitive inefficiency and low energy levels may hinder performance through greater risks of experiencing fatigue. These findings suggest that an assessment of mood, anxiety, and fatigue levels would enhance strategies for fatigue management.

It is evident from the literature that numerous studies have been conducted on fatigue; however, some of the literature presents equivocal results due to several methodological reasons that include use of heterogeneous samples, insufficient subject numbers, the variable use of referential and bipolar EEG montages, testing of limited scalp sites and reporting activity in some EEG bands, which may not be an adequate representation of the brain function deactivation that occurs in a fatigue state (Lal & Craig, 2001b). Even though there is variability in the literature, some firm conclusions can be reached regarding EEG changes during fatigue. In a review of studies that came close to fulfilling some of the above criteria, the main EEG activities reported were increases in delta, theta, and alpha activity (Lal & Craig, 2000a; Torsvall & Åkerstedt, 1988), theta wave persistence (Yamamoto & Matsuoka, 1990), and appearance of grouped alpha waves (Ninomija, Funada, Yazu, Ide, & Daimon, 1993). Similarly, others reported increases in delta, theta, and beta activities (Kiroy, Warsawskaya, & Voynov, 1996) whereas others reported increases in only delta and theta (Makeig & Jung, 1996). In our present study, we found large increases in delta and theta during fatigue as well as smaller change in alpha and beta. Therefore, according to prior studies and our present research, fatigue is most likely associated with increases in slow wave EEG activities with smaller variations in alpha and beta activity. Because fatigue creates the potential for increased hazards in the transportation system, methods need to be developed to assess and counteract its effects. Previous research has noted the importance of developing technological driver-support systems, which have the potential to sense fatigue symptoms and either present appropriate warnings, or intervene directly (Brown, 1994). Such a device needs a well-researched physiological measure, which changes substantially enough to be used as a valid indicator of fatigue. Our current study, with a robust experimental design, identified consistent EEG changes during a monotonous driving task, suggesting that EEG could be used to detect fatigue in a countermeasure device.

Future Direction and Conclusions

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 that can detect changes during fatigue in the slow wave EEG activities such as in delta and theta. Our group is also conducting research on the development of miniaturized dry electrodes and EEG signal processing technology for the countermeasure device. In the next phase of our research, we plan to test the feasibility of the EEG-based fatigue countermeasure device in both the laboratory and field contexts. In conclusion, the electroencephalographic and psychological effects identified during driver fatigue provide useful insights for future development of a countermeasure device and fatigue management.

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