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Review

A critical review of the psychophysiology of driver fatigue

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Abstract

Driver fatigue is a major cause of road accidents and has implications for road safety. This review discusses the concepts of fatigue and provides a summary on psychophysiological associations with driver fatigue. A variety of psychophysiological parameters have been used in previous research as indicators of fatigue, with electroencephalography perhaps being the most promising. Most research found changes in theta and delta activity to be strongly linked to transition to fatigue. Therefore, monitoring electroencephalography during driver fatigue may be a promising variable for use in fatigue countermeasure devices. The review also identified anxiety and mood states as factors that may possibly affect driver fatigue. Furthermore, personality and temperament may also influence fatigue. Given the above, understanding the psychology of fatigue may lead to better fatigue management. The findings from this review are discussed in the light of directions for future studies and for the development of fatigue countermeasures. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Electroencephalography; Electro-occulogram; Driver fatigue; Countermeasure; Anxiety; Mood

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1. Introduction

The purpose of this review was to understand better the psychophysiological aspects of driver fatigue and its applications for a fatigue countermeasure. Even though previous reviews exist on indicators and countermeasures for driver fatigue (Stern et al., 1994; Brown, 1994, 1997), there have been no thorough reviews on psychophysiological associations, especially neurophysiological changes associated with fatigue. The aim of the present review is to first, identify from the existing literature the potential of using psychophysiological factors such as electroencephalography as an indicator of fatigue, and second, to assess the practicability of a countermeasure based on detecting physiological changes during fatigue. This review encompasses a range of subject areas, including concepts and theories of fatigue, driver fatigue, and psychophysiological indicators and countermeasures of driver fatigue. Furthermore, the methodology and experimental designs employed in fatigue based research have never been critically assessed. This review will provide a critical discussion on the designs used, discuss the findings in the light of directions for future studies, as well as provide insights into the use of countermeasures for preventing fatigue-related accidents.

The present modern technological society relies upon 24-h operations or shift-work in industries such as transportation, health care, manufacturing industries, military, aviation and many public services. People exposed to shift-work can have major disruptions in sleep and circadian rhythms (Åkerstedt et al., 1987; Rosekind et al., 1994). Circadian disruption and sleep deprivation can also lead to reduced waking alertness, impaired performance, worsened mood and fatigue (Bonnet, 1985). Fatigue during driving is a serious problem in transportation systems and is believed to be a direct or contributing cause of road related accidents (Gander et al., 1993). For instance, road related injury costs billions of dollars (Donovan et al., 1994) with studies suggesting that fatigue is responsible for up to 20–30% of road fatalities (Camkin 1990). Fatigue or sleepiness is frequently reported in night-time drivers (Torsvall and Åkerstedt, 1987) and is thought to be a major factor in accidents occurring in monotonous driving conditions (Horne and Reyner, 1995c). Analysis of accident data suggest that fatigue is implicated in road accidents, particularly at night (Mackie and Miller, 1978; Haworth et al., 1989; Kecklund and Åkerstedt, 1993) and in situations in which driving hours are very long (McDonald, 1984; Hamelin, 1987). In 24 h operations and with widespread automation, risks of fatigue-related accidents are increased (Dinges, 1995). Furthermore, having sleep disorders will more than likely result in higher levels of fatigue and therefore increase risks of accidents. For example, drivers who suffer from hypersomnia have increased risks of being involved in car accidents. Patients with diurnal hypersomnia due to sleep apnea, perform poorly on cognitive testing (e.g. perception, communication and ability to perceive new information) and show psychomotor impairment, especially during tests that require a high level of attention and concentration (Bonnet, 1985; Kales et al., 1985; Findley et al., 1986).

A major problem is the phenomenon of mental fatigue. Driving or working for a sustained period of time can increase fatigue, reduce productivity, and alter cardiovascular and neurophysiological functions (Smith, 1981; Schliefer and Okogbaa, 1990; Okogbaa et al., 1994). However, little attempt has been made to examine driving task performance and neurophysiological and cardiovascular activity over a continuous period of time (e.g. minute by minute). Such an assessment could provide valuable information and form the basis for the development of a fatigue countermeasure device. However, the area of in-vehicle technological countermeasures to fatigue needs research, furthermore, there have been few attempts to review this area critically. This review will, therefore, critically assess studies that have investigated psychophysiological indicators of driver fatigue and its use in countermeasure devices. The usefulness of electroencephalography (EEG) as a measure of fatigue will be specifically discussed.

2. Fatigue

It is important to note that fatigue is the transitory period between awake and sleep and if uninterrupted, can lead to sleep. The literature has not been particularly helpful in defining the term fatigue with a lack of an agreed definition. Grandjean (1979, 1988) defined fatigue as a state marked by reduced efficiency and a general unwillingness to work. In 1994, Brown defined fatigue as a disinclination to continue performing the task, and that it involved an impairment of human efficiency when work continued after the person had become aware of their fatigued state. To better define the term fatigue it is helpful to note that it can be classified into physical and mental categories. Mental fatigue is believed to be psychological in nature whereas physical fatigue is considered synonymous with muscle fatigue.

2.1. Mental fatigue

Mental fatigue is believed to be a gradual and cumulative process and is thought to be associated with a disinclination for any effort, reduced efficiency and alertness and impaired mental performance (Grandjean, 1979, 1988). It should be understood that many factors could influence mental fatigue such as nutrition, physical health (Wisner, 1981), environment, physical activity (Sjoberg, 1980) and recuperation periods (Okogbaa et al., 1994). The major symptom of mental fatigue is a general sensation of weariness, feelings of inhibition and impaired activity. Generally, there is no desire for physical or mental effort and there is an associated heavy, drowsy feeling. A feeling of weariness is not unpleasant if one is allowed to rest, but it can be distressing if an individual cannot relax. At any moment a person is in one particular functional state, somewhere between the extremes of sleep and of a state of alarm. According to Grandjean (1979), the states range from deep sleep, light sleep, drowsy, weary, hardly awake, relaxed, resting, fresh, alert, very alert, stimulated and a state of alarm. In this context, mental fatigue is a functional state, which grades in one direction into sleep, and in the other direction into a relaxed, restful condition, both of which are likely to reduce attention and alertness.

2.1.1. Mental fatigue and boredom

When defining fatigue, it is important to discuss the association between fatigue and boredom, since one may affect or instigate the other. Some authors have considered boredom to be a special type of fatigue because boredom is caused by a reduction of the activation level of the brain (Grandjean, 1979). It has been shown that a stream of impulses from the sensory organs, combined with feedback to the cerebral cortex, stimulate the reticular activating system, maintaining the central nervous system (CNS) in a high state of readiness. When stimuli are few, the stream of sensory impulses diminishes, reducing the level of activation of the cerebrum, thereby raising the chances of inducing a fatigued (or bored) functional state.

The physiological aspects of boredom are associated with low levels of stimulation, a regular repetition of identical stimuli, or with mental or physical demands (Grandjean, 1979). This leads to a functional state of the CNS characterized by a reduction in the level of cerebral activation, accompanied by feelings of weariness and sleepiness, decreased vigilance, disinclination for the task and a decline in alertness. These symptoms are very similar to a state of fatigue. It is therefore understandable if researchers make no fundamental distinction between fatigue and boredom as both of these conditions indicate a lowered activation level of the brain. For example, the decline in performance and the feeling of tiredness during long hours of driving can be signs of fatigue or boredom. There are many such examples in traffic conditions which can be simultaneously boring and fatiguing. In such cases the distinction between boredom and fatigue is considered arbitrary (Grandjean, 1979).

2.2. Physical fatigue

The phenomenon of reduced performance of a muscle after stress is called muscular fatigue and is characterized by reduced muscular power and movement. Muscular fatigue contributes to impaired co-ordination and increased chances of errors and accidents (Grandjean, 1979). During muscular contraction, chemical changes occur to provide energy. In a stressed muscle, energy reserves (sugar and phosphorous) are depleted while lactic acid and carbon dioxide increase and the muscular tissue becomes acidic (Grandjean, 1979). Physical fatigue is a complex phenomenon influenced by numerous psychophysiological factors and has been linked with: (1) a decline in alertness, mental concentration and motivation; (2) reduced work output; (3) weaker and slower muscular contractions; (4) muscular tremor and localized pain; (5) loading of respiratory, circulatory and neuromuscular functions; (6) a decrease in the frequency of the electromyogram (EMG) signal; (8) a decrease in duration of sustained isometric exertions and endurance time; (9) increased lactate accumulation; and (10) increased core temperature (Basmajian and De Luca, 1985; Åstrand and Rodahl, 1986). Hard physical work before driving can also increase the risks of experiencing fatigue during driving, such as in cargo drivers who perform manual lifting.

2.3. Fatigue and performance

There is an emerging recognition that a sleepiness/fatigue state contributes to deterioration in performance, which may lead to errors and increase the risk of accidents. Nilsson et al. (1997) believe that fatigue is a major contributing factor to errors made by drivers. Performance over time, such as that required during driving, usually requires greater cognitive effort than physical effort (Brown, 1994). Cognitive effort involves sustained vigilance, selective attention, complex decision making and occasionally automatized perceptual–motor control skills. According to Miller and Mackie (1980), long hours of continuous driving, a monotonous driving environment and driving during the night and early morning hours leads to driver performance degradation. In addition, Adkins (1964) has shown that the changing levels of arousal produced by circadian rhythms can also affect corresponding variations in performance. Fatigue incurred by driving during that part of the day when physiological activity is increasing would be influenced by an improvement in performance. In contrast, fatigue incurred by driving during times of the day when physiological activity is diminishing will act synergistically with the deterioration in performance.

In professional drivers, fatigue may be quite severe before routine driving performance is noticeably affected. It is important to note that at lesser levels of fatigue, decreases in physiological arousal, slowed sensorimotor functions and impaired information processing can still diminish a driver's ability to respond to unusual and emergency situations (Mascord and Heath, 1992). Therefore, to measure the impact of fatigue on driver performance, researchers need to utilize not only direct indices of driving (such as steering control and speed maintenance), but also to test perceptual, motor and cognitive skills associated with driving performance (Williamson et al., 1996). Crawford (1961) has argued that the most appropriate index of driver fatigue would be some sort of a physiological measure. For example, electroencephalography measures have been used to quantify performance changes (Harmony et al., 1996), and studies have found increases in delta activity to be related to attention to internal processing during the performance of a mental task. Others report increases in EEG theta activity associated with performance decrements during a monotonous task Horváth et al., 1976). It is therefore critical in our round the clock operational environment to understand the impact of fatigue and to develop strategies and countermeasures to detect fatigue in order to optimize performance and maintain an adequate margin of safety.

2.4. Fatigue, vigilance and circadian rhythms

Since fatigue affects attention and performance, it is important to consider 'vigilance' with which it overlaps. In neurobiological research the terms vigilance and arousal are used interchangeably (Benson et al., 1974). As discussed in Parasuraman et al. (1998), vigilance may refer to a general state of wakefulness that is characterized as arousal or alertness. Both physical and mental fatigue can produce impairments in vigilance and task performance (Davies and Parasuraman, 1982). Known environmental factors affecting vigilance are noise, vibration, ambient temperature, frequency and a variety of stimulation and environmental pollutants. For example, the after effect of noise on performance has been termed 'cognitive fatigue' and may result from situations in which high attentional demands are needed in the presence of such stressors (Davies and Parasuraman, 1982). This suggests that environmental factors such as higher levels of noise during driving can lead to driver fatigue. Davies and Parasuraman also suggest that sleep deprivation produces feelings of increased sleepiness and fatigue, and this process seems to be related to circadian rhythms. Circadian rhythms are biological clocks and normally have a period of about 24 h. Disruption to the circadian rhythm can upset physiological factors such as motor activity, body temperature, sleep/ wakefulness, hormonal secretions, blood pressure, and work performance (Rosekind et al., 1994) and therefore, should be an important consideration in the study of driver fatigue.

2.5. Driver-related fatigue

Any activity if pursued long enough, will be associated with a difficulty in maintaining skilled performance and this is true for driving. Driver fatigue has been defined as a state of reduced mental alertness, which impairs performance of a range of cognitive and psychomotor tasks, including driving (Williamson et al., 1996). Previously, Brown (1994) reviewed factors that contributed to driver fatigue such as length of work, time for rest and the amount of continuous sleep in the 24-h cycle. He concluded that driver fatigue is largely due to prolonged and irregular working hours. This current review attempts to form a logical extension of the review by Brown by highlighting the psychophysiological links to driver fatigue.

A study of truck drivers reported cortical deactivation was associated with increased sleepiness during the end hours of an all night driving shift (Kecklund and Åkerstedt, 1993). Ambulatory studies with nonprofessional drivers have also demonstrated cortical deactivation in response to continuous driving over monotonous and repetitive environments (De Waard and Brookhius, 1991; Brookhius and De Waard, 1993). In some studies, reported sleepiness was so severe that there were incidents of falling asleep during the night shift (Kogi and Ohta, 1975; Åkerstedt et al., 1983). Under controlled laboratory conditions, fatigue can be observed in some subjects after only 60 min of driving or during vigilance tasks (Skipper and Wierwille, 1986; Galinsky et al., 1993). Wiener (1984) suggested that performance decrements in on-road studies might be attributed to reduction in vigilance or to increased driver fatigue. Harris (1977) suggests that decrements in vigilance have a substantial role in vehicle accidents.

2.6. Driver fatigue, arousal and psychological determinants

The concept of arousal is important in the area of driver fatigue. For regulation of cortical arousal, there are multiple ascending pathways from the sub-cortical nuclei; each associated with varying neurotransmitters and neuromodulators (Parasuraman et al., 1998). The basal forebrain cholinergic and the locus coerulus noradrenergic systems may be important for maintaining vigilance and phasic alertness to stimuli as required for safe driving. Parasuraman et al. reported that sleep deprivation reduces detection rates on vigilance tasks. This has major implications for those drivers performing shift-work, who consequently have disturbed circadian rhythms. These authors further suggest that vigilance decrement is due to neural habituation which has been linked to general arousal. Such habituation is generally observed under passive conditions such as driving on similar routes.

It has also been suggested that fatigue could be experienced differently by drivers having different personality and temperament (Brown and Eng, 1967). In a previous study, Lal et al. (1998) showed that environmental stimuli and psychological factors affect cognitive task performance where anxiety had an adverse effect. Mood type and expectation were also related to task outcome. Recently, Lal and Craig (2000a,b) found strong associations between driver fatigue and negative mood states such as increased fatigue–inertia and decreased vigor–activity and increased anxiety. Other studies have also indicated associations between brain activity and psychological factors such as anxiety (Heller et al., 1997). However, research on the psychological links to driver fatigue is still exploratory and is an important area that needs further investigation.

2.7. Fatigue and the professional driver

Professional drivers regularly deliver freight and passengers over long distances. Evidence suggests that these drivers present an increasing problem for road safety (Fuller, 1980; Miller and Mackie, 1980). They may be at risk from fatigue, because generally they are not free to determine their work schedules, which often involves irregular hours of work. The irregular shifts may force them on occasions to continue driving during troughs in their circadian rhythm, so that performance may decline to sub-optimal levels. Irregular work schedules will also negatively influence the periods available for rest and sleep. Based on a review of 2000 commercial drivers and an in-depth study of 18 drivers for several weeks, Miller and Mackie (1980) attributed driving fatigue to irregular schedules and work demands placed on commercial drivers. They believed accidents were directly related to the development of fatigue. In a recent international conference on driver fatigue Åkerstedt et al. (2000) suggested that different recovery periods from fatigue were required, based on the number and duration of irregular work hours performed and the level of disturbance in the circadian rhythm.

A review on truck and bus driver fatigue showed that irregular driving schedules produced greater subjective fatigue, physiological stress, and performance degradation than did regular work hours (Mackie and Miller, 1978). The influence of irregular schedules and physical work on the performance and fatigue of commercial drivers (with emphasis on bus and truck drivers) may be summarized as follows (Miller and Mackie, 1980): (1) irregular schedules cause greater subjective fatigue, stress, and performance degradation than regular schedules; (2) there is cumulative fatigue after six consecutive days of driving; (3) pairs of truck drivers engaging in round-the-clock sleeper operations show earlier and/or greater signs of fatigue than single drivers; (4) heavy cargo handling as well as long driving stints increases fatigue; (5) during irregular operations the driver must at some time drive during those hours of the night when circadian reduction in physiological arousal are substantial; (6) for all classes of drivers, degradation in driving occurs sooner than current regulations allow (which is 10 h); and (7) furthermore, professional drivers with irregular schedules do not always obtain 8 h of continuous sleep.

Furthermore, the driving cabs of professional drivers' are likely to cause other stressors that interact with fatigue, such as heat, noise and vibration. The importance of these factors was demonstrated by Storie's (1984) Storie (1984) study of motorway accidents. In this study, fatigue was implicated in 11% of the accidents with 62% of the accidents occurring after driving less than 100 miles.

3. Indicators of fatigue

The literature is abundant with studies which have sought to measure variables associated with fatigue and these include performance, perceptual, electrophysiological, psychological and biochemical measurements. However, the search for a reliable indicator of fatigue is still elusive even though the technology for measuring these factors have greatly improved over the past 20 years. Conflicting results continue to be obtained with many studies having poor experimental designs and insufficient subjects to achieve adequate statistical power. Furthermore, factors such as time of day, and the influence of drugs and alcohol have not been accounted for. We will now briefly discuss the different approaches that have been used to measure fatigue.

3.1. Electroencephalography (EEG)

While numerous physiological indicators are available to measure level of alertness, the EEG signal may be one of the most predictive and reliable (Erwin and Al, 1973; Volow and Erwin, 1973; Artaud et al., 1994). Prior to describing the use of EEG as a fatigue indicator, it is important to understand its origin and measurement. The EEG is generated by inhibitory and excitatory postsynaptic potentials of cortical nerve cells. These potentials summate in the cortex and extend through the coverings of the brain to the scalp (Fisch, 1991). The rhythmical activity in the EEG represents postsynaptic cortical neuronal potentials, which are synchronized by the complex interaction of large populations of cortical cells. Rhythmical EEG activity is thought to arise mainly from the interaction between cortical neurons and organizing impulses from subcortical pacemakers.

To obtain EEG measurements during fatigue and drowsiness, data is collected in the transition period from wakefulness to the onset of sleep (Wright et al., 1995). Such an assessment of physiological changes may lead to a better understanding of sequences and events occurring during fatigue. It should be noted that studies on fatigue and drowsiness do not need to assess all stages of sleep but only the phase between awake and sleep onset (Stage 1 of sleep). Several methods are used to quantify EEG signals and have been described by Fisch (1991) and Cacioppo and Tassinary (1990). The electrical activity of the brain is classified according to rhythms, which are defined in terms of frequency bands including delta, theta, alpha and beta (Fisch, 1991). The following describes these EEG bandwidths, which are somewhat arbitrary since many EEG contain waves and frequencies extending across the range of these bands.

3.1.1. Delta activity

These are slow waves between 0.5 and 4 Hz. Delta waves have been shown to be present during transition to drowsiness and during sleep.

3.1.2. Theta frequency

The theta rhythm is an activity within the frequency range of 4–7 Hz. Theta rhythms are associated with a variety of psychological states including hypnagogic imagery, and low levels of alertness during drowsiness and sleep and as such has been associated with decreased information processing. They replace the alpha components at the onset of sleep (Grandjean, 1988).

3.1.3. Alpha waves

The alpha rhythm has a frequency range of 8–13 Hz, occurs during wakefulness, particularly over the occipital cortex, appears markedly at eye closure and decreases at eye opening and is highly attenuated during attention (Okogbaa et al., 1994). The alpha rhythms are present during an alert and relaxed state (Grandjean, 1988). A high alpha activity during a relaxed condition leads to a reduced readiness to react to stimuli. Though alpha wave activity is high during 'relaxed wakefulness' it should not be mistaken for a highly receptive state.

3.1.4. Beta waves

Beta waves are fast (13–30 Hz) EEG potentials associated with increased alertness, arousal and excitement (Grandjean, 1988). Beta activity has been reported to occur in humans while performing a reaction-time motor task (Sheer, 1988). Beta activity may also be indicated by its two components, beta 1 (13–25 Hz) and beta 2 (25–30 Hz). Others have also reported EEG bandwidths in terms of sigma waves, which approximately occur between 11.78–14.44 Hz and overlap with the alpha and beta bands (Trachsel et al., 1994).

In many previous studies the information obtainable from the EEG is limited due to the small number of scalp sites that are typically sampled. Using greater numbers of electrode positions would enhance research validity in this area. The 19-channel 10/20 montage system (Jasper, 1958) of electrode placement provides uniform coverage of the entire scalp and is commonly used for diagnostic purposes and in clinical and physiological research. The importance of testing most of these sites when assessing EEG changes during fatigue has been indicated previously (Wright et al., 1995). These authors found that not all brain regions exhibit the same EEG changes as is the common belief and not all brain regions change at the same time.

In our recent driver simulator study to investigate fatigue effects, we aimed to overcome these methodological limitations and found large increases in delta and theta during fatigue onset (Lal and Craig, 2000a). We studied the whole brain using the 19 channel 10/20 montage and found that slow wave activity was more likely to be present in the anterior, central and parietal regions of the brain.

3.2. The EEG as an indicator of drowsiness and performance

It has been known for many years that changes in brain arousal involve specific changes in oscillatory brain activity (Santamaria and Chiappa, 1987b; Steriade et al., 1988; Makeig and Inlow, 1993; Jung and Makeig, 1994; Lehmann et al., 1995). The literature abounds with EEG changes associated with fatigue but the results are quite variable. Variations in the EEG trace, such as increases in alpha and theta rhythms and reduction of beta waves, are interpreted as indicating states of weariness and sleepiness. With the onset of drowsiness, the alpha rhythm may attenuate or diminish for a few seconds, reappear again, and go through this alteration for a few minutes until the trains of alpha waves finally disappear at the onset of sleep (Markand, 1990). Other changes such as the distribution, amplitude and frequency of the alpha rhythm has also been emphasized (Santamaria and Chiappa, 1987b). It has been shown that there is an increase in the amplitude of the centrofrontal alpha (alpha wave activity spreading to the anterior regions) lasting 1–10 s, often occurring concurrently with a decrease in the amplitude of the occipital alpha rhythm (Santamaria and Chiappa, 1987b). Another change during drowsiness was the appearance or persistence of mid- or posterior-temporal alpha, lasting several seconds after occipital alpha had already disappeared. Recently, we found a similar pattern of change in alpha wave distribution during driver fatigue, that is occipital and parietal alpha spread to more anterior regions such as the centrofrontal and temporal regions (Lal and Craig, 2000a).

EEG is sensitive to fluctuations in vigilance and has been shown to predict performance degradation due to sustained mental work (Matousek and Petersen, 1983; Gevins et al., 1990). Associations between decreasing alertness and reduction in vigilance have been known to occur in the ongoing EEG (Roth, 1961; Makeig and Inlow, 1993). Changes in EEG with vigilance have generally shown that deterioration in performance is associated with increased theta and changes in alpha intensity (Davies, 1965; Morrel, 1966; Gale et al., 1977). Makeig and Jung (1995) also found that changes in alpha and theta waves were related to reduced performance and fatigue.

EEG theta activity occurs in a variety of mental states including the hypnagogic state experienced in drowsiness. According to Yamamoto and Matsuoka (1990), when long lasting theta waves appear, a rest period should be considered before the subjects become fatigued. Furthermore, lapses in alertness have been classified according to the quantity of alpha bursts and appearance of theta waves (Torsvall and Åkerstedt, 1987). Reduction in performance has been associated with increased theta and changes in alpha intensity while beta activity has also been shown to be altered (Townsend and Johnson, 1979; Wierwille and Ellsworth, 1994). In a prominent study by Åkerstedt et al. (1984) over a night of continuous activity in ambulatory subjects, alpha and theta activity was found to increase significantly through the night. Ratings of sleepiness also correlated with alpha and theta power.

3.3. EEG as an indicator of fatigue in transport

EEG has been used previously in fatigue related transport research but results have been variable. Howitt et al. (1978) showed that in-flight recorded EEG after sleep deprivation were not the same as those observed when the pilot had slept well. In our driver simulator study we found substantial increases in delta and theta activity and smaller increases in alpha activity during transition to fatigue (Lal and Craig, 2000a). Another study found a progressive increase of alpha waves in the EEG of motor vehicle drivers (Grandjean, 1979). Work done by Lemke (1982) showed that monitoring the EEG signal in both ‘on road’ and simulator situations indicated that this was a promising method for monitoring fatigue in drivers. Another study measured EEG during driving and subjected it to a Fast Fourier Transform frequency analysis and expressed it as power in the alpha and theta bands (Åkerstedt et al., 1982), since these bands would be most likely to indicate sleepiness (Loomis et al., 1937; Roth, 1961). Most of the increase was seen in the alpha band, mostly due to longer duration of eye blinks, sometimes turning into episodes of Stage 1 sleep (Åkerstedt et al., 1982).

Other researchers recorded EEG from four subjects during night driving (Caille and Bassano, 1977). 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 and sometimes sigma waves. Continuous driving at night has also been studied with continuous recording of the EEG (O’Hanlon and Kelley, 1977). EEG was recorded from a parieto–occipital derivation with amplification close to the electrodes. The results showed that unskilled drivers had increased power in the alpha band over the duration of the drive compared to skilled drivers. Sleep occurred while the drivers still had their eyes open. This was indicated by appearance of theta waves, sleep spindles (frequency of 11–15 Hz, duration of >0.5 s (Fisch, 1991) and k-complexes (a transient EEG pattern of sharp positive wave followed by a negative wave with a duration of >0.5 s (Bankman et al., 1992). Interestingly, the drivers had not been aware that they had been driving the car for some distance while asleep. It was also 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.

Other studies recorded the EEG and EOG of 11 train drivers during a 4.5 h night or day trip, always along the same route (Torsvall and Åkerstedt, 1983). Drivers were allocated into ‘sleepy’ or ‘alert’ groups. During night driving, alpha power increased significantly above daytime levels in the sleepy group. These drivers also exhibited higher night trip alpha power than the alert group. The results were very similar for theta power and self-rated fatigue paralleled the EEG data. The authors concluded that night work was associated with increased sleepiness, and that the degree of sleepiness was reflected in the EEG spectral content mainly in the alpha and theta bands (Torsvall and Åkerstedt, 1983). Some of the above studies had small numbers of subjects and were not always conducted in controlled laboratory situations; therefore the findings must be treated with caution.

Furthermore, even though some definite trends have been found in delta, theta and alpha activity during fatigue, the results from different studies may be influenced by inter- and intra-individual variability in the EEG data. For example, EEG data is influenced by individual differences such as introversion–extroversion as well as the relationship between sex and spatial ability (Cacioppo and Tassinary, 1990). Furthermore, alpha is found to be variable between individuals, for example, it is seen in only about three-fourths of all individuals when they are awake and relaxed. When these individuals close their eyes and relax an immediate increase in alpha activity is produced. Alpha activity has been associated with particular levels of consciousness and awareness, and the reduction of alpha activity has been associated with sensory stimulation or mental activity. Furthermore, EEG theta activity may be age related and although it has been associated with hypnagogic imagery, rapid eye movement sleep, hypnosis and meditation, there is little understanding concerning its nature. During drowsiness there is a difference in alpha amplitude due to gender (Santamaria and Chiappa, 1987a). Furthermore, there are age-related differences in drowsiness. For example, during both drowsiness and arousal, centrofrontal delta/theta is more often seen as a dominant transition in young adults below 30 years, as are sharp vertex waves with alpha. Fatigue patterns are also affected by the degree of sleepiness between individuals with sleepier subjects being slightly older. Therefore, when assessing the EEG of drowsiness or fatigue, inter-individual factors need to be taken into account.

3.4. Other indicators of fatigue

While EEG is a measure of rhythmic oscillations in voltage, evoked potentials (EP), also called event-related potentials (ERP) are manifestations of brain activities that occur in preparation for or in response to discrete events (Cacioppo and Tassinary, 1990). Conceptually, ERPs are regarded as a manifestation of specific psychological processes. The low amplitude, high frequency waves of the EEG that are indicative of wakefulness are produced by a summation of potentials of thalamocortical neurons, which fire in a ‘tonic mode’ of depolarization (Coenen, 1995). In this mode, the transfer of information from the sense organs to the sensory cortex is facilitated. The transfer decreases during drowsiness when thalamocortical units are more hyperpolarized. Similar to EEG patterns, the ERP is dependent on the state of alertness. During waking, the components in ERP are moderate in amplitude, while during slow wave sleep larger responses are visible. Even though there are few studies in this area, more studies are now using the ERP changes as another neurological indicator of drowsiness and fatigue based tasks (Coenen, 1995; Schubert et al., 1998).

Another promising measure of fatigue and drowsiness is eye movement, assessed by EOG. Since there are rich sensory and motor connections between the eye and the brain, eye movement can provide valuable warning signs of drowsiness. Its predictive ability of arousal status is becoming accepted. Recently, we found that fast eye movement and conventional blinks in the alert state were replaced by no eye movement and small, fast rhythmic blinks during transition to fatigue in a driver simulator task) Lal and Craig, 2000a). These changes were quite prominent and occurred in the majority of subjects indicating the potential of EOG changes as an indicator of fatigue. Research has suggested that the disappearance of blinks and mini-blinks and relative quiescence in eye movement are the earliest reliable sign of drowsiness, preceding slow eye movement and alpha frequency and amplitude changes (Santamaria and Chiappa, 1987a). It is possible that the blink rate transition from wakefulness to drowsiness remains a valuable area of investigation into fatigue monitoring.

Heart rate (ECG) has been used as a physiological measure of workload especially during driving conditions. Heart rate has been shown to decrease during prolonged night driving (Riemersma et al., 1977). In our study we also found a significant and large decrease in heart rate during driver fatigue (Lal and Craig, 2000a). Others have reported changes in heart rate variability (HRV) and a feeling of fatigue associated with deterioration in driving (Harris et al., 1972). Another study found changes in HRV among drivers of motor vehicles after long test-drives (O'Hanlon, 1971). This change was interpreted as a sign of diminished alertness. The results indicate that heart rate changes have the potential for indicating driver fatigue (Hartley and Arnold, 1994). This area however needs further controlled investigation of the autonomic changes that occur during driver fatigue before any firm conclusion can be drawn about its potential to indicate fatigue.

Findings of some hormones or peptides related to sleep has been reported, but a review found no consistent evidence for a chemical indicator of a need to sleep (Borbely and Tobler, 1989). The development of sensitive microspectrometers that could analyze blood components with an ear-lobe sensor may lead to a physio–chemical indicator of fatigue (Nilsson et al., 1997). A recent review on sleep suggested that substances such as pregnanolone, melatonin and adenosin were associated with sleep, but it was also stated that the neurochemistry of sleep is complex and difficult to analyze (Finkbeiner, 1998). However, since the testing of biochemical parameters generally involves invasive techniques it may be disadvantaged as a tool for indicating driver fatigue.

Psychomotor tests that have been used to assess fatigue measure perception, cognitive interpretation and motor reactions. Tests include simulated driving, typing, reaction time tests etc. (Grandjean, 1979; Welford, 1968). In psychomotor tests, it is assumed that a reduction in performance is a sign of fatigue. Mental tests have also been used and involve tests of concentration (such as crossing-out tests), estimation tests (such as estimation of time intervals), and arithmetic sums. A disadvantage of psychomotor and mental tests is that they often make heavy demands on the subject, thereby raising the level of cerebral activity, which can temporarily mask any possible signs of fatigue (Grandjean, 1979).

Given that the subjective component of fatigue is very important, questionnaire investigations may therefore be important in the study of driver fatigue. Questionnaires can provide information about fatigue such as the time when fatigue appeared and factors contributing to fatigue. In a survey study of truck drivers, the results revealed that frequent signs of physical fatigue were back and leg pain (Milosevic, 1997). Other frequent signs were drowsiness, sleepiness, bad mood, irritability and eye pain. It should be pointed out that the answers were obtained at the end of driving, when these symptoms of fatigue are most prominent.

However, to maintain scientific validity, questionnaires alone should not be the sole indicator/identifier of fatigue symptoms. More objective measures need to accompany them for verification of fatigue. Questionnaire and survey research have limitations, for instance, it cannot provide moment-to-moment fluctuations of sleepiness. Also self-report techniques could hardly be considered to measure sleepiness per se. Survey research could also be prone to poor validity and reliability. In our study, the self-report measures on fatigue paralleled the changes in physiological indicators of fatigue such as EEG, EOG and heart rate (Lal and Craig, 2000a). The self-report questionnaires revealed subjects as slightly fatigued before the driving task and moderately to extremely fatigued after driving. It would therefore be preferable to include both self-report and more objective physiological measures when conducting fatigue related research.

3.5. Video indication of fatigue

Fatigue can also be assessed using a video image of a person's face (Belyavin and Wright, 1987). Experimenters can estimate the level of drowsiness based on characteristics such as facial tone, slow eyelid closure, and mannerisms such as rubbing, yawning and nodding. In a previous study we used a video image of the driver's face, linked in real time with physiological measures (Lal and Craig, 2000a). For obvious reasons, it is important when recording driver fatigue to incorporate an independent and reliable variable such as a video image of the face to verify fatigue status. However, very few studies have applied 'facial expression' to drowsiness research (Yabuta et al., 1985; Belyavin and Wright, 1987; Lal and Craig, 2000a).

4. Fatigue counter measures

In a special workshop on driver fatigue, the importance of a non-intrusive physiological detector of driver fatigue was raised (Camkin 1990; Haworth 1990). As few drivers are probably aware of their fatigue status (Birrell 1990), it would seem important that non-intrusive devices be developed and tested. 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). It is important to note that a detector of driver fatigue impairment must provide high detection capability with a low risk of false alarm, and the device should not be a nuisance for the driver. In other words, the device should not be too large and uncomfortable to wear and should not hinder driving.

A number of fatigue monitors have been developed and these include devices that sense eye closures as a sign of fatigue. Feedback is provided (in the form of a buzzer) to the driver (Haworth 1990), but this system has not been extensively tested. Head nodding monitors also exist however; this type of feedback may not alert the driver in ample time to prevent accidents and therefore, may not be useful for road safety application. Eye activity has attracted interest for monitoring driver sleepiness, especially with respect to developing in-car, remote devices. However, problems exist with monitors detecting eye activity. In 1995 Nissan reported a 5-year plan to produce a device using video images of the driver's face, the purpose being to extract eye blink rate and blink duration to detect drowsiness (Time, 1995). The Nissan strategy employed a video camera and a powerful computer for image processing. The video frame rate of 50–75/s would place a time resolution limit to between 13 and 20 ms at best, which may not be optimal to detect fine eye movements. Other disadvantages include high costs and the motorist may not be able to wear sunglasses while using the video system. However, the advantage of the Nissan system is that no device is attached to the driver.

According to Horne and Reyner (1995a), the most valid index of alertness in the driver is the EEG. Others also believe that the use of EEG is potentially the best for detecting vigilance while driving (Khardi and Vallet, 1994). We agree with these authors, based on our findings of substantial EEG changes during the onset of driver fatigue (Lal and Craig, 2000a). EEG has been used in fatigue monitors and has an advantage over indirect strategies of monitoring. Gevins et al. (1995) reviewed advances in the engineering of EEG recording systems that are small and easy to use and suitable for a number of environments. Development of signal processing algorithms and increasing the amount of information useful in the derivation of neurophysiological indices of mental load and fatigue was also assessed. Idogawa (1991) suggests that a fatigue accident can be predicted by observing an increase in the generation of grouped alpha waves and informing the driver automatically with an electrical or sound stimulus. Fukuda et al. (1994) described a system that automatically detects grouped alpha waves during drowsiness using moving average methods. However, further operation and evaluation of this device was not described.

A study by Khardi and Vallet (1994) claims that steering wheel reversals are a reliable indicator of sleepiness, with both the number and amplitude of these increasing with sleepiness. These investigators claimed that the number of reversals correlated significantly with the amount of theta and alpha activity appearing in the EEG. However the authors do not mention any further progress in the development or evaluations of such a device. Others have developed a drowsiness warning system, which also detects changes in the driver's alertness through steering behavior (Yabuta et al., 1985). Alertness was quantified by assessing brain activity and blinking. Their device detects the steering wheel patterns associated with drowsiness and emits a warning to the driver. The above studies provide some convincing examples of the feasibility of using neurophysiological measures to create an automated system to track and compensate for lapses in the alertness of human operators with EEG appearing to be the most promising.

A recent study described exposure to sound as a measure against driver drowsiness and fatigue (Landström et al., 1999). The system was based on time and frequency varied sound, generated for 3–7 s between 1 and 5 min periods. Positive results were found concerning the system for increasing wakefulness. The 'waking sounds' were not perceived as annoying by the driver. Practical countermeasures have also been suggested such as limiting driving time to a few hours and exercising during a break from driving. However, there is no substantive evidence in support of the efficacy of these approaches. Also, there is little evidence that countermeasures employed whilst driving, such as cold air and increasing the volume of the car radio could be of any benefit and may in fact distract sleepy drivers (Horne and Reyner, 1995b, 1999). Reyner and Horne (1998b) believe that major driving incidents are preceded by self-awareness of sleepiness long before subjects reached the stage of fighting sleep. According to these researchers, drivers should be educated about the effects of extreme sleepiness and the consequent high accident risk. Others have stated that in order for models of human neurobehavioral functions to be accurate and practical, they should be able to predict both cumulative effects (i.e. across days or weeks) and the influence of countermeasures such as napping and caffeine (Dinges and Achermann, 1999). Another method to alleviate sleepiness is to take pharmacological stimulants, caffeine being the most acceptable (Lorist et al., 1994; Lumley et al., 1987). According to Horne and Reyner, the only safe counter measure to driver sleepiness is to stop driving and take a break including a short nap or coffee (Reyner and Horne, 1998a; Horne and Reyner, 1999). However, very little systematic research has been conducted on the effects of caffeine on driving and the most notable study only showed certain aspects of driving to be marginally enhanced by caffeine (Regina, 1974).

5. Methodology of fatigue studies

Although many studies have been conducted on fatigue, especially driver related fatigue, much of the literature is 'noisy' for several methodological reasons including the following:

1. the variable use of referential and bipolar EEG montages, an issue, previously summarized by Broughton and Hasan (1995).
2. the use of heterogeneous samples with clinical problems and EEG abnormalities (Janati et al., 1986).
3. the use of insufficient subject numbers. Sufficient subjects are needed to reduce chances of Type II errors (the chance of accepting the null hypothesis when it is false) and to be able to generalize results to the broader population. Furthermore, difficulties during analysis can be caused by the inter- and even intra-individual variance in psychophysiological measures of drowsiness hence, it is important to have sufficient sample power in research for valid statistical outcomes.
4. omitting to report the sample size.
5. testing limited scalp sites, that is measuring fatigue from only one to three sites.

Since not all brain regions exhibit the same changes, it is important to have electrodes, which span most of the cerebral cortex (Wright et al., 1995).

6. 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.

6. Future direction and conclusions

This review indicates that fatigue is a prevalent and potentially dangerous transport related condition. Therefore, fatigue countermeasures are needed that could provide an important solution to fatigue related accidents. From the review of the literature and our recent study (Lal and Craig, 2000a), EEG appears to be a promising indicator of driver fatigue. The main EEG changes reported are increases in delta, theta and alpha activity during driver fatigue. 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 (1997) criteria for a fatigue countermeasure device, that is it must provide a valid indication of fatigue rather than some type of performance impairment. Furthermore, the stimulus delivered when the performance impairment due to fatigue is detected must successfully restore normal performance. In the future, such an enabling technology could be important in the transport, aviation, military and industrial environments that demand alertness and that involve multiple tasks competing for limited attention resources (Gevins et al., 1995).

Future research in the area of driver fatigue should improve on the methodological limitations mentioned above and should also aim to evaluate in more detail, the psychophysiological indicators of fatigue, especially EEG, state and trait anxiety, mood effects and self-reported physical and mental fatigue measures. If EEG is used, the electrodes should be chosen to cover the entire brain using the 19-channel EEG 10/20 montage system. The activity of the different EEG waves as well as the change in cortical distribution should be monitored during fatigue. An independent validation criteria for fatigue should be utilized such as video monitoring of changes in facial features to provide an objective indicator of fatigue. Furthermore, to date there have been no studies to identify whether the psychophysiological changes during fatigue are reproducible on different days. This area is worth investigating if a reliable countermeasure device is to be developed. The review also suggests psychological traits, such as anxiety and negative mood states, influence driver fatigue, indicating that personality and temperament may variably influence fatigue status. Investigation of psychological factors such as mood and anxiety and self reported fatigue measures with simultaneous measure of physiological parameters such as EEG would lead to better management of driver fatigue.

References

Adkins, S., 1964. Performance, heart rate, and respiration rate on the day-night continuum. Percept. Mot. Skills 18, 409–412.

Åkerstedt, T., Torsvall, L., Gillberg, M., 1982. Sleepiness and shiftwork: field studies. Sleep 5 (Suppl. 2), 95–106.

Åkerstedt, T., Torsvall, L., Fröberg, J.E., 1983. A questionnaire study of sleep/wake disturbances and irregular work hours. Sleep Research 12, 358(abstract.

Åkerstedt, T., Torsvall, L., Gillberg, M., 1984. Sleepiness in laboratory and field experiments. In: Koella, W.P., Rüther, E., Schulz, H. (Eds.), Sleep. Gustav Fischer Verlag, Stuttgart, pp. 88–89.

Åkerstedt, T., Torsvall, L., Gillberg, M., 1987. Sleepiness in shiftwork. A review with emphasis on continuous monitoring of EEG and EOG. Chronobiol. Int. 4 (2), 129–140.

Åkerstedt, T., Kecklund, G., Gillberg, M., Lowden, A., (2000). Days of recovery. The Fourth International Conference on Fatigue and Transportation, Australia.

Artaud, P., Planque, S., Lavergne, C., Cara, H., de Lepine, P., Tarrière, C., Gueguen, B.m (1994). An on-board system for detecting lapses of alertness in car driving. 14th E.S.V.Conference, Session 2-Intelligent Vehicle Highway system and Human Factors: (Munich, Germany).

Åstrand, P.O., Rodahl, K., 1986. Textbook of Work Physiology. McGraw-Hill, New York.

Bankman, I.N., Sigillito, V.G., Wise, R.A., Smith, P.L., 1992. Feature-based detection of the *K*-complex wave in the human electroencephalogram using neural networks. IEEE Trans. Biomed. Eng. 39 (12), 1305–1310.

Basmajian, J.V., De Luca, C.J., 1985. Muscles Alive. Williams and Wilkins, Baltimore.

Belyavin, A., Wright, N.A., 1987. Changes in electrical activity of the brain with vigilance. Electroencephalog. Clin. Neurophysiol. 66, 137–144.

Benson, H., Beary, J.F., Carol, M.P., 1974. The relaxation response. Psychiatry 37, 37–46.

Birrell, P., Sleep mechanisms and their relevance to driver fatigue. Road Traffic Authority. (1990). CR 2/90, Workshop on driver fatigue: report on proceedings. (Ed. M. Henderson).

Bonnet, M.H., 1985. Effect of sleep disruption on sleep, performance, and mood. Sleep 8 (1), 11–19.

Borbely, A.A., Tobler, J., 1989. Endogenous sleep-promoting substances and sleep regulation. Physiol. Rev. 69, 605–670.

Brookhius, K.A., De Waard, D., 1993. The use of psychophysiology to assess driver status. Ergonomics 36 (9), 1099–1110.

Broughton, R., Hasan, J., 1995. Quantitative topographic electroencephalographic mapping during drowsiness and sleep onset. J. Clin. Neurophysiol. 12 (4), 372–386.

Brown, I., 1994. Driver fatigue. Hum. Factors 36, 298–314.

Brown, I.D., 1997. Prospectus for technological countermeasures against driver fatigue. Accid. Analy. Prev. 29 (4), 525–531.

Brown, I.D., Eng, C., 1967. Car driving and fatigue. Triangle 8 (4), 131–137.

Cacioppo, J.T., Tassinary, L.G., 1990. Principles of Psychophysiology. Cambridge University Press, New York, USA.

Caille, E.J., Bassano, J.L., 1977. Validation of a behavior analysis methodology: variation of vigilance in night driving as a function of the rate of carboxyhemoglobin. In: Mackie, R.R. (Ed.), Vigilance. Plenum Press, New York, pp. 59–72.

Camkin, H., Introduction: fatigue and road safety. Road Traffic Authority. (1990). CR 2/90, Workshop on driver fatigue: report on proceedings. (Ed. M. Henderson).

Coenen, A.M., 1995. Neuronal activties underlying the electroencephalogram and evoked potentials of sleeping and waking. Neurosci. Biobehav. Rev. 19 (3), 447–463.

Crawford, A., 1961. Fatigue and driving. Ergonomics 4, 143–154.

Davies, D.R., 1965. Skin conductance, alpha activity and vigilance. Am. J. Psychol. 78 (2), 304–306.

Davies, D.R., Parasuraman, R., 1982. The Psychology of Vigilance. Academic Press, London.

De Waard, D., Brookhius, K.A., 1991. Assessing driver status: a demonstration experiment on the road. Accid. Anal. Prev. 23 (4), 297–307.

Desmond, P.A., Matthews, G., 1997. Implications of task-induced fatigue effects for in-vehicle countermeasures to driver fatigue. Accid. Analy. Prev. 29 (4), 515–523.

Dinges, D.F., 1995. An overview of sleepiness and accidents. J. Sleep Res. 4 (Suppl 2), 4–14.

Dinges, D.F., Achermann, P., 1999. Commentary: future considerations for models of human neurobehavioral function, Journal of Biological Rhythms 14 (6), 598–601.

Donovan, J., de Looper, M., Thompson, S., Cerasani, K., Searle, L., (eds). (1994). Australia's Health: The fourth biennial health report of the Australian Institute of Health and Welfare. Australia: Australian Government Publishing Service.

Erwin, C.W., Al, Psychophysiologic indices of drowsiness. 1973; Detroit, Mich: International Automotive Engineering Congress.

Findley, L.J., Barth, J.T., Powers, D.C., 1986. Cognitive impairment in patients with obstructive sleep apnoea and associated hypoxemia. Chest 90, 686–690.

Finkbeiner, A.K., 1998. Getting through the sleep gate. The Sciences 8/9, 14–18.

Fisch, B.J., 1991. Spehlmann's EEG Primer, Second revised and enlarged edition. Elsevier Science BV, Amsterdam, The Netherlands.

Fukuda, C., Funada, M.F., Ninomija, S.P., Yazy, Y., Daimon, N., Suzuki, S., Ide, H., (1994). Evaluating Dynamic changes of driver's awakening level by grouped alpha waves, *IEEE*, 1318-1319.

Fuller, R.G.C., 1980. Effect on HGV drivers of different work demands. In: Oborne, D.J., Lewis, J.A. (Eds.), Human Factors in Transport Research. Academic Press, London, pp. 117–125.

Gale, A., Davies, R., Smallbone, A., 1977. EEG correlates of signal rate time in task and individual differences in reaction time during a five-stage sustained attention task. Ergonomics 20, 363–376.

Galinsky, T.L., Rosa, R.R., Warm, J.S., Dember, W.N., 1993. Psychophysiological determinants of stress in sustained attention. Hum. Factors 35, 603–614.

Gander, P.H., Nguyen, D., Rosekind, M.R., Connell, L.J., 1993. Age, circadian rhythms, and sleep loss in flight crews. Aviat., Space Environ. Med. 64 (3), 189–195.

Gevins, A.S., Bressler, S.L., Cutillo, B.A., Illes, J., Fowler-White, R.M., 1990. Effects of prolonged mental work on functional brain topography. Electroencephalog. Clin. Neurophysiol. 76, 339–350.

Gevins, A., Leong, H., Du, R., Smith, M.E., Le, J., DuRousseau, D., Zhang, J., Libove, J., 1995. Towards measurement of brain function in operational environments. Biol. Psychol. 40, 169–186.

Grandjean, E., 1979. Fatigue in industry. Br. J. Internal Med. 36, 175–186.

Grandjean, E., 1988. Fitting the Task to the Man. Taylor and Francis, London.

Hamelin, P., 1987. Lorry driver's time habits in work and their involvement in traffic accidents. Ergonomics 30, 1323–1333.

Harmony, T., Fernandez, T., Silva, J., Bernal, J., Diaz-Comas, L., Reyes, A., Marosi, E., Rodriguez, M., 1996. EEG delta activity: an indicator of attention to internal processing during performance of mental tasks. Int. J. Psychophysiol. 24, 161–171.

Harris, W., 1977. Fatigue, circadian rhythms and truck accidents. In: Mackie, R.R. (Ed.), Vigilance: Theory, Operational Performance and Physiological Correlates. Plenum Press, New York, pp. 133–147.

Harris W., Mackie R.R., Abrams C., Buckner D.N., Harabedian A., O'Hanlon J.F., Starks J.R. (1972). A study of the relationship among fatigue, hours of service and safety of operations of truck- and bus-drivers. Human Factors Research Inc. California, Report No. 1727-2.

Hartley, L.R., Arnold, P.K., 1994. Indicators of fatigue in truck drivers. Appl. Ergonomics 25 (3), 143–156.

Haworth, N., Current countermeasures and areas for countermeasures development. Road Traffic Authority. (1990). CR 3/90, Workshop on driver fatigue: report on proceedings. (Ed. M. Henderson).

Haworth N.L., Heffernan C.J., Horne E.J. (1989). Fatigue in truck accidents. Victorian Road Freight Industry Council. Australia, Report No. 3.

Heller, W., Nitschke, J.B., Etienne, M.A., Miller, G.A., 1997. Patterns of regional brain activity differentiate types of anxiety. J. Abnorm. Psychol. 106 (3), 376–385.

Horne, J.A., Reyner, L.A., 1995a. Driver sleepiness. J. Sleep Res. 4 (suppl 2), 23–29.

Horne, J.A., Reyner, L.A, Falling asleep at the wheel, (1995b). Report for UK Department of Transport.

Horne, J.A., Reyner, L.A., 1995c. Sleep related vehicle accidents. Br. Med. J. 310, 565–567.

Horne, J., Reyner, L., 1999. Vehicle accidents related to sleep: a review. Occup. Environ. Med. 56 (5), 289–294.

Horváth, M., Frantik, E., Kopriva, K., Meissner, J., 1976. EEG theta activity increase coinciding with performance decrement in a monotonous task. Activitas Nervosa Superior (Prague) 18 (3), 207–210.

Howitt, J.S., Hay, A.E., Shergold, G.R., Ferres, H.M., 1978. Workload and fatigue in-flight EEG changes. Aviat. Space Environ. Med. 49 (10), 1197–1202.

Idogawa, K., 1991. On the brain wave activity of professional drivers during monotonous work. Behaviormetrika 30, 23–34.

Janati, A., Kidawi, S., Nowack, W.J., 1986. Episodic anterior drowsy theta in adults. Clin. Electroencephalogr. 17, 135–138.

Jasper, H.H., 1958. The ten-twenty electrode system of the International Federation. Electroencephalogr. Clin. Neurophysiol. 10, 371–375.

Jung, T., Makeig, S., (1994). Estimating level of alertness from EEG, IEEE, 1103-1104.

Kales, A., Caldwell, A.B., Cadieux, R.J., et al., 1985. Severe obstructive sleep apnoea. II. Associated psychopathology and psychosocial consequences. J. Chron. Dis. 38 (5), 427–434.

Kecklund, G., Åkerstedt, T., 1993. Sleepiness in long distance truck driving: an ambulatory EEG study of night driving. Ergonomics 36 (9), 1007–1017.

Khardi, S., Vallet, M., 1994. Drivers vigilance, analysis of differences in vigilance states assessments by physiological and mechanical indicators. Conference Proceedings 'Telematics for transport', Paris, pp. 1991–1998.

Kogi, K., Ohta, T., 1975. Incidence of near accidental drowsing in locomotive driving during a period of rotation. J. Hum. Ergol. 4, 65–76.

Lal S.K.L., Craig A. (2000a). Driver Fatigue: psychophysiological effects. The Fourth International Conference on Fatigue and Transportation, Australia.

Lal, S.K.L., Craig, A., 2000b. Psychophysiological effects associated with drowsiness: driver fatigue and electroencephalography. Int. J. Psychophysiol. 35, 39(abstract.

Lal, S.K.L., Henderson, R.J., Carter, N., Bath, A., Hart, M.G., Langeluddecke, P., Hunyor, S.N., 1998. Effect of feedback signal and psychological characteristics on blood pressure self-manipulation capability. Psychophysiol. 35 (4), 405–412.

Landström, U., Englund, K., Nordstrom, B., Astrom, A., 1999. Sound exposure as a measure against driver drowsiness. Ergonomics 42 (7), 927–937.

Lehmann, D., Grass, P., Meier, B., 1995. Spontaneous conscious covert cognition states and brain electric spectral states in canonical correlations. Int. J. Psychophysiol. 19, 41–52.

Lemke, M., 1982. Correlation between EEG and driver's actions during prolonged driving under monotonous conditions. Accid. Analy. Prev. 14, 7–17.

Loomis, A., Harvey, E., Hobart, G., 1937. Cerebral states during sleep as studied by human brain potentials. J. Exp. Psychol. 21, 27–144.

Lorist, M.M., Snell, J., Kok, A., Mulder, G., 1994. Influence of caffeine on selective attention in well-rested and fatigued subjects. Psychophysiol. 31, 525–534.

Lumley, M., Roehrs, T., Asker, D., Zorick, F., Roth, T., 1987. Ethanol and caffeine effects on daytime sleepiness/alertness. Sleep 10, 306–312.

Mackie, R.R., Miller, J.C., (1978). Effects of hours of service, regularity of schedules and cargo loading on truck and bus driving fatigue. Human Factors Research Inc. CA, Technical report 1765-F.

Makeig, S., Inlow, M., 1993. Lapses in alertness: coherence of fluctuations in performance and EEG spectrum. Electroencephalogr. Clin. Neurophysiol. 86, 23–35.

Makeig, S., Jung, T., 1995. Changes in alertness are a principal component of variance in the EEG spectrum. Neuroreport 7, 213–216.

Markand, O.N., 1990. Alpha rhythms. J. Clin. Neurophysiol. 7 (2), 163–189.

Mascord, D.J., Heath, R.A., 1992. Behavioral and physiological indices of fatigue in a visual tracking task. J. Safety Res. 23, 19–25.

Matousek, M., Petersen, I.A., 1983. A method for assessing alertness fluctuations from EEG spectra. Electroencephalogr. Clin. Neurophysiol. 55, 108–113.

McDonald, N., 1984. Fatigue, Safety and the Truck Driver. Taylor and Francis, London.

Miller, J.C., Mackie, R.R., 1980. Effects of irregular schedules and physical work on commercial driver fatigue and performance. In: Oborne, D.J., Levis, J.A. (Eds.), Human Factors in Transport Research. Academic Press, New York, pp. 127–133.

Milosevic, S., 1997. Driver's fatigue studies. Ergonomics 40 (3), 381–389.

Morrel, L.K., 1966. EEG frequency and reaction time — a sequential analysis. Neuropsychol. 4, 41–48.

Nilsson, T., Nelson, T.M., Carlson, D, 1997. Development of fatigue symptoms during simulated driving. Accid. Anal. Prev. 29 (4), 479–488.

O'Hanlon, J.F., (1971). Heart rate variability; a new index of drivers' alertness/fatigue. Human Factors Research Inc. California, Report No. 1812-1.

O'Hanlon, J.F., Kelley, G.R., 1977. Comparison of performance and physiological changes between drivers who perform well and poorly during prolonged vehicular operation. In: Mackie, R.R. (Ed.), Vigilance. Plenum Press, New York, pp. 189–202.

Okogbaa, O., Shell, R., Filipusic, D., 1994. On the investigation of the neurophysiological correlates of knowledge worker mental fatigue using the EEG signal. Appl. Ergonomics 25, 355–365.

Parasuraman, R., Warm, J.S., See, J.E., 1998. Brain systems of vigilance. In: Parasuraman, R. (Ed.), The Attentive Brain. The MIT Press, London, pp. 221–256.

Regina, E.G., 1974. Effects of caffeine on alertness and simulated automobile driving. J. Appl. Psychol. 59, 483–489.

Reyner, L.A., Horne, J.A., 1998a. Evaluation 'in-car' countermeasures to sleepiness: cold air and radio. Sleep 21 (1), 46–50.

Reyner, L.A., Horne, J.A., 1998b. Falling asleep whilst driving: are drivers aware of prior sleepiness? Int. J. Legal Med. 111 (3), 120–123.

Riemersma, J.B.J., Sanders, A.F., Hildervanck, C., Gaillard, A.W., 1977. Performance decrement during prolonged night driving. In: Mackie, R. (Ed.), Vigilance: Theory, Operational Performance and Physiological Correlates. Plenum Press, New York, pp. 41–58.

Rosekind, M.R., Gander, P.H., Miller, D.L., Gregory, K.B., Smith, R.M., Weldon, K.J., Co, E.L., McNally, K.L., Lebacqz, J.V., 1994. Fatigue in operational settings: examples from the aviation environment. Hum. Factors 36 (2), 327–338.

Roth, B., 1961. The clinical and theoretical importance of EEG rhythms corresponding to states of lowered vigilance. Electroencephalogr. Clin. Neurophysiol. 13, 395–399.

Santamaria, J., Chiappa, K.H., 1987a. The EEG of Drowsiness. Demos Publications, New York.

Santamaria, J., Chiappa, K.H., 1987b. The EEG of drowsiness in normal adults. J. Clin. Neurophysiol. 4, 327–382.

Schliefer, L.M., Okogbaa, O.G., 1990. System response time and method of pay: cardiovascular stress effects in computer-based tasks. Ergonomics 33 (12), 1495–1509.

Schubert, M., Johannes, S., Koch, M., Wieringa, B.M., Dengler, R., Munte, T.F., 1998. Differential effects of two motor tasks on ERPs in an auditory clasification task — evidence of shared cognitive resources. Neurosci. Res. 30 (2), 125–134.

Sheer, D.E., 1988. A Working Cognitive Model of Attention to Fit in the Brain and in the Clinic. Academic Press, New York.

Sjoberg, H., 1980. Physical fitness and mental performance during and after mental work. Ergonomics 23 (10), 977–985.

Skipper, J.M., Wierwille, W.W., 1986. Drowsy driver detection using discriminant analysis. Hum. Factors 28, 527–540.

Smith, M., 1981. Occupational stress: an overview of psychosocial factors. In: Salvendy, G., Smith, M. (Eds.), Machine Pacing and Occupational Stress. Taylor and Francis, London, pp. 13–19.

Steriade, M., Dossi, R.C., Paré, D., 1988. Mesopontine cholinergic systems supress slow rhythms and induce fast oscillations in thalamocortical circuits. In: Basar, E., Bullock, T.H. (Eds.), Induced Rhythms in the Brain. Elsevier, Amsterdam, pp. 251–268.

Stern, J.A., Boyer, D., Schroeder, D., 1994. Blink rate: a possible measure of fatigue. Hum. Factors 36 (2), 285–297.

Storie, V.J. Involvement of goods vehicles and public service vehicles in motorway accidents. 1984; U.K.: Department of the Environment/ Department of Transport, Transport and Road Research Laboratory.

Time, 1995. Time Magazine article. Time, 71.

Torsvall, L., Åkerstedt, T., 1983. Sleepiness and irregular work hours. Sleep Research 12, 376.

Torsvall, L., Åkerstedt, T., 1987. Sleepiness on the job: continuously measured EEG changes in train drivers. Electroencephalogr. Clin. Neurophysiol. 66, 502–511.

Townsend, R.E., Johnson, L.C., 1979. Relation of frequency-analyzed EEG to monitoring behavior. Neurophysiol. 47, 272–279.

Trachsel, L., Schreiber, W., Holsboer, F., Pollmächer, T., 1994. Endotoxin enhances EEG alpha and beta power in human sleep. Sleep 17 (2), 132–139.

Volow, M.R., C.W. Erwin. The heart rate variability correlates of spontaneous drowsiness onset. 1973; Detroit, Mich: International Automotive Engineering Congress.

Welford, A.T., 1968. Fundamentals of Skill. Methuen, London.

Wiener, E.L., 1984. Vigilance and inspection. In: Warm, J.S. (Ed.), Sustained Attention in Human Performance. John Wiley, New York, pp. 207–246.

Wierwille, W.W., Ellsworth, L.A., 1994. Evaluation of driver drowsiness by trained raters. Accid. Anal. Prev. 26 (5), 571–581.

Williamson, A.M., Feyer, A., Friswell, R., 1996. The impact of work practices on fatigue in long distance truck drivers. Accid. Anal. Prev. 28 (6), 709–719.

Wisner, A., 1981. Organizational stress, cognitive load, and mental suffering. In: Salvendy, G., Smith, M. (Eds.), Machine Pacing and Occupational Stress. Taylor and Francis, London, pp. 37–44.

Wright, K., Badia, P., Wauquier, A., 1995. EEG analysis and transition from wake: topographical and temporal patterns of brain activity during the transition from wakefulness to sleep. Sleep 18 (10), 880–889.

Yabuta, K., Iizuka, H., Yanagishima T., Kataoka, Y., & Seno, T.K. Yabuta, H. Iizuka, T. Yanagishima, Y. Kataoka, & T. Seno. The development of drowsiness warning devices. US Department of Transportation. (1985). Section 4, 282 p.

Yamamoto, S., Matsuoka, S., 1990. Topographic EEG study of visual display terminal (VDT) performance with special reference to frontal midline theta waves. Brain Topogr. 2 (4), 257–267.