The Psychophysiology of Driver Fatigue/Drowsiness: Electroencephalography, Electro-oculogram, Electrocardiogram and Psychological Effects

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Preface

The research reported in this thesis was conducted at the University of Technology (UTS), Sydney, in the Department of Health Science. The author was granted an Australian Postgraduate Award Scholarship to complete the degree of Doctor of Philosophy in Science. The author was a part-time lecturer/tutor at UTS and also completed an internship program in education during the course of the doctoral research and was awarded the Graduate Certificate of Higher Education in 2000. During the period of the doctorate, the author was also an active member of the Academic Board and was also a member of the review panel of the Academic Board at UTS. Towards the end of the PhD, the author attracted a National Health and Medical Research Council (NHMRC) fellowship, 2001 (Australian Clinical Research Fellowship) for further research in fatigue with Professor Ashley Craig as co-investigator. Some of the reviews and research presented in this thesis have been published, accepted for publication or submitted for publication in the following journals.

Manuscripts

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Lal SKL, Craig A. Psychophysiological effects associated with drowsiness: driver fatigue and electroencephalography. International J Psychophysiology 35: 39 (2000).

Lal SKL, Craig A, (2000). Physiological indicators of driver fatigue. Road Safety Research, Policing and Education Conference (2000), Queensland, 489-494.

Craig, A and Lal SKL. Brain Signals and behaviour: applications of encephalography research in humans. XVIth Annual Scientific Research meeting, RNSH and UTS, 19 (1999).

Manuals

Lal SKL (2000) A fatigue questionnaire for assessing physical and mental fatigue (Modified from Wessely and Powell, 1989). Sydney, UTS.

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Abstract

Driver fatigue is a major cause of road accidents and has implications for road safety. Investigating the psychophysiological links to fatigue can enhance our understanding and management of fatigue in the transport industry. A variety of psychophysiological parameters have been identified as indicators of fatigue, with electroencephalography (EEG) perhaps being the most promising. Therefore, monitoring EEG during driver fatigue may be a promising variable for use in fatigue countermeasure devices. However, most previous fatigue-based studies have suffered from methodological shortcomings such as insufficient sample numbers, lack of a controlled testing environment, inadequate study design and statistical analysis. Furthermore, a thorough psychophysiological assessment of fatigue was found to be lacking in the literature. Therefore, the aims of the present doctoral research were to: 1) Assess the EEG and electro-occulogram (EOG) changes during driver fatigue in a 'state of the art' experimentally controlled study. 2) Identify psychological associations with fatigue. 3) Assess the changes in autonomic nervous system activity during fatigue. 4) Investigate the differences in the physiological changes that occur during fatigue in professional versus non-professional drivers. 5) Identify the reproducibility of physiological changes that occur during fatigue. 6) Examine the changes in EEG coherence during fatigue. 7) Utilise the physiological findings in this research for the development of EEG based software to detect fatigue.

The results showed significant increases in delta and theta during driver fatigue. The conventional high amplitude blinks during alertness was replaced with slow, low amplitude blinks during fatigue. Reduced Fatigue-Inertia and decreased Vigour-Activity (which are mood sub-scales) and increased anxiety levels were associated with fatigue. There was an increase in parasympathetic activity during fatigue. Non-professional drivers showed greater increases in the EEG of fatigue compared to professional drivers. The EEG changes associated with fatigue were shown to be reproducible. The changes in EEG coherence were not found to be significant during fatigue. The EEG changes during fatigue were used for the development of an algorithm for a fatigue-countermeasure device and was shown to reliably detect fatigue.

In summary, this research has provided important information on the psychophysiology of driver fatigue clarifying some of the findings of prior research.

Significant changes were found to occur in EEG, EOG and parasympathetic activity during fatigue. From this research it may also be suggested that psychological status of the driver may influence fatigue status. Furthermore, the EEG changes during fatigue are consistent and reliable, which can be utilised to detect fatigue in a EEG-based fatigue countermeasure device. The results are discussed in the light of direction for future driver fatigue studies and fatigue management.

Definition of Technical Terms

Coherence analysis (spectral correlation): The coherence function measures the correlation between two signals as a function of the frequency components which they contain. Thus, the coherence function is a correlation spectrum and also known as spectral correlation. The coherence function is a statistical measure used to determine the likelihood of two stochastic signals arising from some common generator process, and the frequency band in which this occurs. Therefore, the coherence measure is conducted on sample epochs of the signals of interest and is therefore a statistical estimate of the true relationship between the signals.

Electrocardiogram (ECG): The ECG is the measure of the electrical activity of the heart.

Electroencephalography (EEG): The EEG or 'brain wave' is a measure of the electrical activity present in the brain. There are four major types of brain waves which are delta, theta, alpha and beta (refer to 'Electroencephalography frequency bands). The changes in EEG amplitude and magnitude are two common descriptors of EEG activity.

> ***Amplitude:*** The amplitude of EEG waves is measured in microvolts (μV, millionths of a volt). It is determined by measuring the total vertical distance of a wave. Amplitude is the maximum or peak spectral amplitude within a band's frequency range.
>
> ***Magnitude:*** The magnitude of EEG waves is measured in microvolts (μV). Magnitude is the sum of all the amplitude in a band's frequency range.

Electroencephalography frequency bands:

> ***Delta***: These are slow waves between 0.5 and 4 Hz in a range of 20-200 μV. Delta waves are present during the deep sleep stage of normal EEG, that is, synchronised sleep indented by faster spindle waves. Delta activity is also present during various stages of drowsiness.
>
> ***Theta:*** The theta rhythm is an activity within the frequency range of 4-8 Hz, at an amplitude ranging from 20-100 μV. Theta occurs during drowsiness.

Theta has been associated with conditions of low levels of alertness and sleep deprivation and has such been associated with decreased information processing.

Alpha: The alpha rhythm has a frequency range of 8-12 Hz at a magnitude of about 20-60 μV, occurs during wakefulness particularly over the occipital cortex, appears at eye closure and disappears at eyes opening. The classical view of alpha has been that it represents a relaxed state and will be disrupted with any kind of mental work.

Beta: Beta is an irregular wave that occurs at a frequency of 13-50 Hz with an amplitude of approximately 2-20 μV. It is common during increased alertness such as during mental or physical activity.

Electro-occulogram (EOG): The EOG is the measure of changes in electrical potential that occurs when the eyes move.

Heart rate variability: is a spectral measure of changes in ECG and has the potential value of being a non-invasive measure of autonomic nervous system activity. The two main spectral regions of interest are (1) a low frequency (LF) component and (2) a high frequency (HF) component. The higher frequencies are believed to reflect parasympathetic activity, and lower frequencies are believed to be sympathetic activity (Baharav, et al. 1995). The parasympathetic origins of high frequency fluctuations are generally accepted. The interpretation of changes in lower frequencies is controversial. Some believe that LF activity is a composite of parasympathetic and sympathetic influence (Baharav, et al. 1995). Since the neuroautonomic influence at the low end of the spectrum is complex, a useful way to study the autonomic activity by means of spectral analysis is to define a sympathovagal balance or a sympathetic index. The sympathovagal balance or sympathetic index is derived by dividing the LF activity by either the HF activity or total spectral activity, that is, LF:HF or LF: total spectrum (Baharav, et al. 1995; Jaffe et al. 1993).

LF: The lower frequencies are believed to be sympathetic activity.

HF: The higher frequencies are believed to reflect parasympathetic activity.

LF:HF or LF: total spectral activity: The sympathovagal balance or sympathetic index is derived by dividing the LF activity by either the HF activity or total spectral activity, that is, LF:HF or LF: total spectrum.

Fatigue Phases: Fatigue may be divided into transitional, transitional to post-transitional and post-transitional periods as defined below, and the EEG features of each can be presented separately.

Transitional: The transitional phase occurs between awake alpha and absence of alpha, that is, a few to 10 seconds preceding alpha disappearance, during which the EEG changes in frequency, distribution, or amplitude of the dominant activity.

Transitional-post transitional: The transitional and post-transitional phase refers to both or either of the transitional or post-transitional periods.

Post-transitional: The post-transitional phase consists of the first EEG section after alpha disappearance comprising early Stage 1 of sleep.

Chapter One

Introduction and Review of the Concepts and Psychophysiology of Fatigue

1. Introduction

The modern technological society relies upon 24-hour operations or shiftwork in many different occupations and industries such as health care, transportation, manufacturing industries, the military and many public services. People exposed to shiftwork have major disruptions in sleep and circadian rhythms (Åkerstedt, Torsvall, & Gillberg, 1987; Rosekind, et al., 1994). Disruption to 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). Circadian disruption and sleep deprivation can also lead to reduced waking alertness, impaired performance and worsened mood (Bonnet, 1985). Sleepiness or fatigue is also a phenomenon associated with night work (Gillberg, Kecklund, & Åkerstedt, 1996; Kecklund & Åkerstedt, 1993; Torsvall & Åkerstedt, 1987), and is thought to play a major role in night-time accidents (Maycock, 1996; Torsvall & Åkerstedt, 1987), especially accidents in road transport (Kecklund & Åkerstedt, 1993; Lauber & Kayten, 1988). Gander, Nguyen, Rosekind, & Connell (1993) emphasised the association of fatigue, sleepiness, sleep disorders and circadian factors with impaired transportation system safety. While it is recognised that many factors influence fatigue such as workload, stress and environmental factors, the principal physiological sources are circadian disruption and sleep deprivation (Gander et al., 1993; Rosekind, et al. 1994; Vidacek, Radosevic-Vidacek, Kaliterna, & Prizmic, 1993). 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 so as to maximise performance and maintain an adequate margin of safety.

Fatigue has major implications for road fatalities in Australia. An inquiry into managing fatigue in transport by the Committee on Communication, Transport and the Arts (Federal Parliament, 2000) stated that fatigue-related road accidents alone cost around $3 billion per year, with fatigue related heavy vehicle accidents costing approximately $300 million (Standing Committee on Communication, Transport and the Arts, The Parliament of the Commonwealth of Australia, 2000). Others have also identified that the financial cost of accidents due to sleepiness is considerable (Leger, 1994). Accordingly, injury prevention was identified as a national priority by the National Better Health Program (Health for All Committee, 1988) the National Health and Medical Research Council in 1995. Reports indicate that fatigue is responsible for up to 20-30% of road fatalities in NSW (Camkin, 1990; Standing Committee on Communication, Transport and the Arts, The Parliament of the Commonwealth of Australia, 2000), and community-based initiatives have been developed and implemented (Implementation Task Force, 1994).

Horne and Reyner (1995c) found that sleep was a likely contributory factor in about 16-23% of all accidents in the UK and were also higher during the night and mid-afternoon. Driver fatigue is related to arousal levels, and leads to decrements in sensori-motor performance and in some cases is related to sleep apnoea (Bearpark, 1990; George, Nickerson, Hanly, Millar, & Kryger, 1987). Drowsiness related accidents are probably more common than accident statistics indicate, due to the difficulties of attributing drowsiness as a cause. Because drowsiness presents in transportation system hazards, methods need to be developed for operationally assessing and counteracting its effects. In-vehicle technological countermeasures to fatigue have been identified as important strategies needing research and the Federal Government has a responsibility for promoting this area according to the Second International Conference on Fatigue in Transportation, Western Australia in 1996.

Fatigue affects various work environments such as the mining industry, transportation industry, factory workers, executives, managers and industrial engineers (Brisley & Fielder, 1983). A major problem is the phenomenon of mental fatigue. Working for a sustained period of time can increase fatigue, reduce productivity, and alter cardiovascular and neurophysiological functioning (Okogbaa, Shell, & Filipusic, 1994; Schliefer & Okogbaa, 1990; Smith, 1981). Factors associated with work-induced fatigue include low job challenge and control, poor job performance and low physical and information-processing demands (Finkelman, 1994). Furthermore, fatigue changes are also associated with task automation (Harris, Hancock, Arthur, & Caird, 1995). However, research concerning the temporal patterns of fatigue and associated physiological effects are sparse. There has been little attempt to examine the variability in task performance and neurophysiological and cardiovascular activity over a continuous period of time (e.g. minute by minute). However, current technology can reliably measure the neurophysiology of the brain and neural processes during mental activities associated with fatigue. These measurement approaches include recording and processing physiological parameters such as the electroencephalogram (EEG), electro-oculogram (EOG) and electrocardiogram (ECG). The EEG is a measure of the electrical activity present in the brain. Fast Fourier transforms and correlation can be used to quantify the relationship between brain waves and mental fatigue (Okogbaa et al., 1994) (refer to section 1.8). The EOG is the measure of changes in electrical potential that occur when the eyes move (Andreassi, 2000a) (refer to section 1.5.1}. The ECG is the measure of the electrical activity of the heart and in the frequency domain, analysis of heart rate variability can provide information about the autonomic nervous system (Furlan, et al., 1990; Jaffe, Fung, & Behrman, 1993; Malliani, Pagani, Lombardi, & Cerutti, 1991) (refer to section 1.5.3).

The following review will assess and evaluate the psychophysiological relationship of fatigue with emphasis on the impact of fatigue in the transport environment, especially driver fatigue. The development of fatigue countermeasure devices will also be discussed for their potential in fatigue management.

1.1 Definition of Fatigue

The literature is not particularly helpful in defining the term fatigue due to the 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 an impairment of human efficiency when work continued after the person had become aware of their fatigue state. It is important to note that fatigue is the transitory period between awake and sleep and continued fatigue can lead to sleep. Fatigue is also associated with many psychophysiological factors, which will be discussed later in this chapter. Recently, a thorough review arising during the course of this PhD research has been published summarising the psychophysiological associations with driver fatigue (Lal & Craig, 2000a). Fatigue may 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. In the literature, the terms fatigue, drowsiness and sleepiness are used interchangeably and the following review conforms to this tradition.

1.1.1 Physical fatigue

Physical fatigue has been considered synonymous with muscle fatigue, given that muscle contraction is the primary requirement for performing physical work. However, general fatigue is believed to be more psychological in nature and is characterised by an aversion to work. Both physical and mental fatigue can lead to a reduction in alertness and hence affect attention capabilities.

1.1.2 Mental fatigue

Mental fatigue is a gradual and cumulative process and is associated with a reduction in efficiency, a disinclination for any effort, reduced alertness and reduced mental performance. Cameron in 1971 and 1973 described mental fatigue as a generalised response to stress over a period of time, which can also affect task performance. Many factors can affect mental task performance such as cardiac rhythm (Corlett & Mahadeva, 1970; Luczak & Laurig, 1973), nutrition, physical health (Wisner, 1981), environment, physical activity (Sjoberg, 1980) and recuperation period (Okogbaa et al., 1994).

The major symptom of mental fatigue is a general sensation of weariness. We feel ourselves inhibited, and our activities are impaired. There is no desire for physical or mental effort; there is a heavy and drowsy feeling. A feeling of weariness is not unpleasant if we are able to rest, but it is distressing if we cannot allow ourselves to relax. It has long been realised, by simple observations, that weariness is one of nature's protective devices and discourages us from overstraining ourselves, and allows time for recuperation.

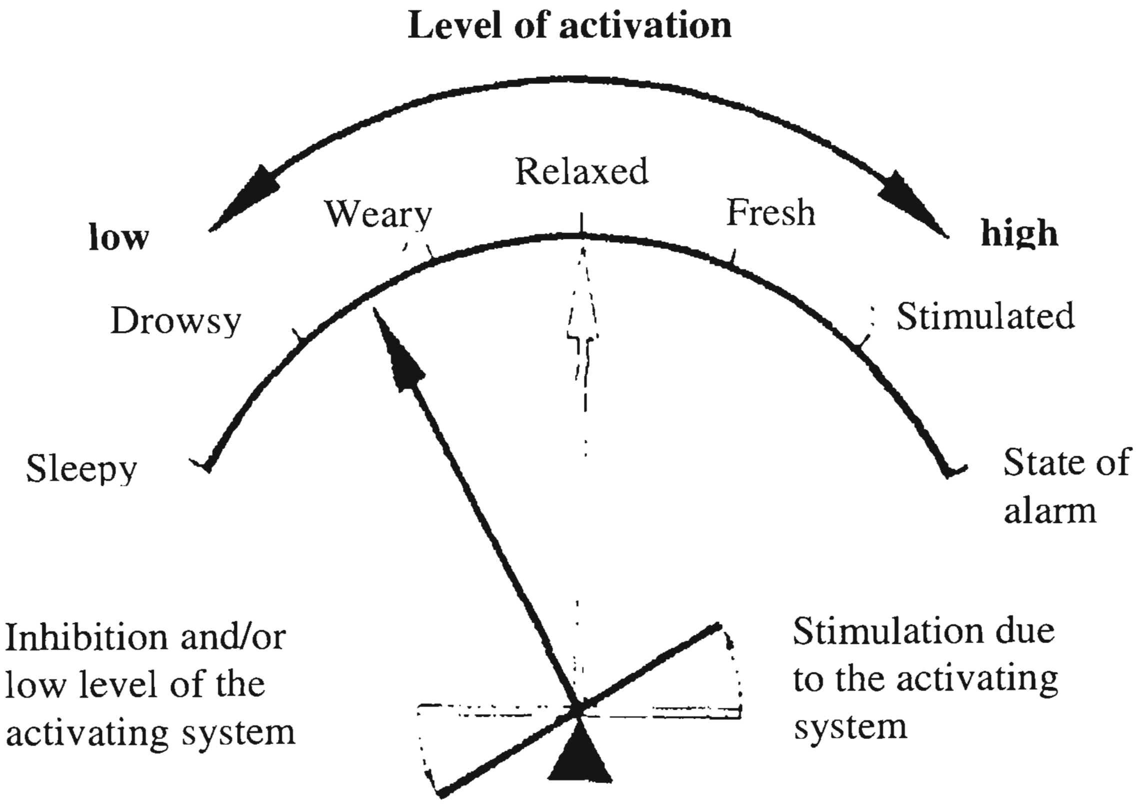
At any moment the human is in one particular functional state, somewhere between the extremes of sleep and of a state of alarm. Within this range there are a number of stages: deep sleep, light sleep, drowsy, weary, hardly awake, relaxed, resting, fresh, alert, very alert, stimulated, in a state of alarm. In this context, mental fatigue is a functional state which grades in one direction into sleep, and in the opposite direction into a relaxed, restful condition; both of which reduces attention and alertness. Indicators of these functional states are seen in the EEG (discussed under section 1.8).

1.1.3 Mental fatigue and boredom

It is important to discuss fatigue and the concept of boredom since one may affect or instigate the other. Some authors have considered boredom to be a special type of fatigue because, in fact, boredom is certainly also caused by a reduction of the activation level of the brain (Grandjean, 1979). For instance, 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, and that by this means the reactivity of the central nervous system is maintained in a high state of readiness. When stimuli are few, the stream of sensory impulses reduces, bringing about a reduction in the level of activation of the cerebrum, and thereby the functional state (see Figure 1.1) (Grandjean, 1979).

The physiological aspects of boredom may therefore be summarised as follows: situations that are characterised by (a) a low level of stimulation and (b) a regular repetition of identical stimuli, or (c) by a few mental or physical demands made upon the operator. This leads to a functional state of the central nervous system characterised by a reduction in the level of cerebral activation, accompanied by feelings of weariness and sleepiness, decreased vigilance, disinclination for the task and decline in alertness. It is obvious that these symptoms of boredom are much the same as those for 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, the rise in alpha waves in the brain and the tired feeling in truck drivers can be signs of a fatigue state or boredom. There are many examples of this kind, which show that situations often arise, both in industrial practice and in traffic conditions, which can be simultaneously boring and fatiguing. In such cases the distinction between these two states is purely arbitrary, and currently the most credible research is that which makes no attempt to draw any distinction (Grandjean, 1979).

Figure 1.1 A theoretical model to illustrate the neuro-physiological mechanism that regulates the functional state of the organism. The level of activation of the cerebral cortex, the degree of readiness for action, and the level of alertness all increase from left to right (adapted from Grandjean, 1979).



1.1.4 Fatigue and vigilance

Since fatigue affects attention and performance it is important to consider 'vigilance' with which fatigue overlaps. In neurobiological research the terms vigilance and arousal are used interchangeably (Benson, Beary, & Carol, 1974). As discussed in Parasuraman (1998), vigilance may refer to a general state of wakefulness that is characterised as arousal or alertness. Both physical and mental fatigue can produce impairments in vigilance and task performance (Davies & Parasuraman, 1982). 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 is termed 'cognitive fatigue' and may result from situations in which high attention demands are imposed in the presence of such stressors (Davies & Parasuraman, 1982). This indicates that environmental factors such as noise during driving can lead to driver fatigue.

1.1.5 Fatigue and circadian rhythms

Circadian rhythms play a crucial role in human arousal and performance as well as in the assessment of fatigue. Circadian rhythms are biological clocks and normally have a period of about 24 hours. Disruption to 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). In humans, if sleep is delayed from the normal bedtime to the morning hours, sleep duration decreases overall (Åkerstedt & Gillberg, 1981). This suggests that sleep onset and sleep maintenance is favoured during the portion of the 24-hour cycle corresponding to the habitual sleep period for the individual. The minima of the 24 hour rhythms of body temperature and plasma cortisol levels vary typically with the habitual sleep period (Moore-Ede, Sulzman, & Fuller, 1982; Weitzman & Hellman, 1974). This relationship is present also when subjects live without time cues, and hence their circadian rhythms are no longer synchronised to the environmental 24-hour cycle. Thus, the onset of major sleep episodes coincides with the descending limb of the circadian temperature rhythm (Zulley, Wever, & Aschoff, 1981), and the highest amount of sleep occurs around the trough of the temperature cycle (Czeisler, Zimmerman, Ronda, Moore-Ede, & Weitzman, 1980; Weitzman, Czeisler, Zimmerman, & Ronda, 1980; Zulley & Campbell, 1985). Because body temperature and cortisol secretion are reliable indicators of the human circadian pace maker (Åkerstedt, 1984; Moore-Ede et al., 1982), the specific phase relation of sleep to these parameters indicates the involvement of circadian factors in sleep regulation. Sleeping at the "wrong circadian time" is considered as a main cause of sleep disturbance, especially during shift work (Åkerstedt, 1988).

The effects of circadian rhythm on human performance have been researched for more than 30 years, developing into the independent science of chronobiology. Coverage of the practical implications of circadian rhythms for irregular and abnormal hours of working is provided by many studies (Åkerstedt, 1988; Colquhoun & Rutenfranz, 1980; Folkard, 1987; Folkard, et al., 1993; Rutenfranz, Knauth, & Colquhoun, 1976). Different types of performance seem to adjust to irregular or abnormal working hours in different ways (Craig, Davies, & Matthews, 1987). Acceptance of compliance of human performance to irregular working hours is difficult to achieve. The extent to which performance is impaired is a function of several interacting factors, such as individual characteristics, lifestyle and environmental conditions. For instance, circadian effects on human activity indicate that duty hours, rest, sleep and shiftwork arrangements are important factors that should be considered in order to reduce fatigue effects in work, especially in road safety.

1.2 Fatigue in Different Workplace Situations

Fatigue is prevalent in the workplace (Åkerstedt, Torsvall, & Fröberg, 1983; Åkerstedt et al., 1987; Kogi & Ohta, 1975; Poulton, Hunt, Carpenter, & Edwards, 1978) and is associated with errors and accidents in many industries and transport systems such as aviation and road transport, military, medical and in various workplaces. The effect of fatigue in different workplaces will now be discussed.

1.2.1 Shift/night work and fatigue

A number of surveys have shown that shift workers report more fatigue than day workers ((Åkerstedt et al., 1987). In some studies reported sleepiness was so severe that there were incidents of falling asleep during the night shift (Åkerstedt et al., 1983; Kogi & Ohta, 1975). Medical personnel appear to function less reliably during night work (Poulton et al., 1978; Wilkinson, Tyler, & Varey, 1975), and the task of writing down meter readings also deteriorates during the night (Bjerner, Holm, & Swensson, 1955), as does the response of telephone operators (Browne, 1949). Overall, night-shift fatigue or sleepiness seems indisputable and the obvious sources are sleep loss and circadian trough (Åkerstedt et al., 1987). Another negative effect of night work is the increase in perceived sleepiness, particularly during work. This sleepiness is at its maximum during the last half of the night shift (Åkerstedt, Torsvall, & Gillberg, 1982) and invariably leads to deterioration in performance (Harris, 1977; Mitler, et al., 1988), and increases the risk of falling asleep during work (Åkerstedt et al., 1983). Torsvall and colleagues (1989) concluded that sleep and wakefulness patterns of shift workers are disturbed due to irregular working hours and this led to sleepiness levels during night work where wakefulness could not be maintained (Torsvall, Åkerstedt, Gillander, & Knutsson, 1989).

1.2.2 Fatigue in aviation

Analysis of confidential reports to the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System indicates that about 21% of reported incidents are fatigue related (Graeber, 1988). Monitoring in-flight EEG activity could avert these problems by detecting changes in alertness in real time. The NASA Fatigue Countermeasures Program (Rosekind, et al., 1994) addressed various factors associated with fatigue management. These are:

* analysis and writing of scientific and operational publications on fatigue to transfer information to the community
* the study of onboard rest facilities for the crew on long-haul aircraft
* the development and implementation of an educational training for alertness management in flight operations which provide physiological sources of fatigue
* addressing flight operations which affect the above factors
* making recommendations for fatigue countermeasures

1.2.3 Driver fatigue

Driver fatigue has been specifically defined as a state of reduced mental alertness, which impairs performance of a range of cognitive and psychomotor tasks including driving (Williamson, Feyer, & Friswell, 1996). Many studies have shown that the fatigued driver can cause traffic accidents and the financial cost of these accidents is considerable (Leger, 1994). Nilsson, Nelson, & Carlson (1997)) believe that fatigue is a major reason for road accidents. Fatigue includes changes in physiology, in sensory processing, cognition, and in performance of unrelated tasks (Daniel, 1967; Wierwille, Rahimi, & Casali, 1985) and occurs if a task is performed for a long time (Vivoli, Bergomi, Rovesti, Carrozzi, & Vezzosi, 1993). Statistical analysis of accident data suggest that fatigue is implicated in road accidents, particularly at night (Haworth, Heffernan, & Horne, 1989; Mackie & Miller, 1978) and in situations in which driving hours are very long (Hamelin, 1987; McDonald, 1984). A recent study of truck drivers reported cortical deactivation (EEG) and increased subjective sleepiness during the end hours of an all night driving shift (Kecklund & Åkerstedt, 1993). Ambulatory studies with non-professional drivers have also demonstrated cortical deactivation in response to continuous driving over monotonous and repetitive environments (Brookhius & De Waard, 1993; De Waard & Brookhius, 1991). Any activity, if pursued long enough, will render a person unable to maintain skilled performance and this is true for driving as for any other skill. Experienced drivers know that they endanger themselves and others when they ignore the feelings of fatigue where the natural end result is falling asleep. Researchers studying the influence of truck crew members of several week long trips to the north west of Western Australia found that solo drivers experienced more fatigue than when two crew were present (Hartley & Arnold, 1994). However, due to the small numbers studied, the validity of the results may be questionable.

Based on a literature review, a survey 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. A report for the American Automobile Association (Falls Church, 1985) concluded that 41% of heavy truck accidents were directly related to fatigue. Under controlled laboratory conditions, one can observe marked indications of fatigue in some subjects after only 60 minutes of driving or vigilance tasks (Galinsky, Rosa, Warm, & Dember, 1993; Skipper & Wierwille, 1986). There is a close relationship between driving and vigilance. Wiener (1984) suggested that performance decrement in on-road studies may be attributed to reduction in vigilance or driver fatigue. The literature on vigilance shows a relation to driver fatigue, and as Harris (1977) suggested, decrements in vigilance have a substantial role in vehicle accidents.

It is important to consider the variability of the relation between driving time and accident rates, which has two implications according to Nilsson et al. (1997):

1) Even with reasonable limits placed on driving time, some persons will still have accidents due to fatigue.

2) Time is not the only factor producing fatigue. Other factors have been identified (Brown, 1994; Gaillard, 1993; Hoyos, 1988; Ugajin, Ikeda, & Yoneyama, 1989) and include the following points:

- Hard work before driving leads to physical tiredness and hence fatigue during driving.
- Extra demands while driving, such as poor traffic conditions, traffic and other traffic rules lead to stress.
- Stress leads to fatigue.
- Alcohol and use of drugs not only lead to drowsiness but also reduce reaction time.
- Environmental factors such as heat and noise all contribute to fatigue.
- Monotony and repetition of a task are known to lead to reduction of attention and also increase fatigue.
- Sleep deprivation will cause the subject to be drowsy during the wake period and hence reduce performance.
- Time of day or late nights and sleep disorders can lead to fatigue.

The above factors not only lead to fatigue but also increase the potential of road related accidents and decrease performance and reaction time during driving.

1.2.3.1 Driver fatigue and arousal

The concept of arousal is an important area in driver fatigue. For regulation of cortical arousal, there are multiple ascending pathways from subcortical nuclei, each associated with varying neurotransmitters and neuromodulators (Parasuraman, Warm, & See, 1998). The basal forebrain cholinergic and the locus coerulus noradrenergic systems may be important for vigilance and phasic alertness to stimuli (Parasuraman et al., 1998), which are important during driving. Parasuraman et al. (1998) reported that sleep deprivation reduces detection rates on vigilance tasks. This has major implications for drivers performing shift-work who consequently have disturbed circadian rhythms. Parasuraman et al. further suggest that vigilance decrement can be due to neural habituation which has been linked to general arousal. Such habituation is generally observed under passive conditions which mimic a monotonous task such as driving similar routes. Similarly, Adkins (1964) showed that the changing levels of arousal produced by circadian rhythms are affected by the corresponding variations in performance

Fatigue incurred by driving during the part of the day when physiological activity is increasing would be associated with improvement in performance. The increase in perceptual effectiveness and better performance observed in previous studies during approximately nine hours of driving can probably also be attributed to the arousal phase of the circadian rhythms (Brown, Simmonds, & Tickner, 1967b; Potts, 1951). Furthermore, any fatigue incurred by driving during times of the day when physiological activity is diminishing will act synergistically with the deterioration in performance which this decrease produces. Others have also found that sleepiness, drowsiness and boredom were also associated with fatigue during monotonous simulated driving (Dureman & Bodén, 1972).

1.2.3.2 Driver fatigue and psychological determinants

It has also been suggested that fatigue could be experienced differently by drivers having different personality and temperament (Brown & Eng, 1967a). In a previous study, Lal et al. (1998) showed that environmental stimuli and psychological factors such as anxiety affect cognitive task performance. Mood type and expectation were also related to task outcome. Recently, in pilot studies, Lal and Craig (2000b and 2000c) have found strong associations between driver fatigue and negative mood states such as increased fatigue-inertia and decreased vigor-activity and increased anxiety. Further investigation into the psychological associations during driver fatigue is reported in Chapter 4. Other studies have also indicated associations between brain activity and psychological factors such as anxiety (Heller, Nitschke, Etienne, & Miller, 1997). However, research on the psychological links to driver fatigue is still exploratory and is an important area that needs further investigation.

1.2.3.3 Fatigue and the professional driver

Drivers of heavy-goods vehicles and public service vehicles regularly deliver freight and passengers, respectively, over long distances. These drivers may be seriously at risk from fatigue effects because they are not free to determine their own work schedules and because their job-demands often involve irregular hours of work. Their irregular shifts will force them to continue driving during troughs in their circadian rhythm, so that performance may decline to sub-optimal levels. Irregular work schedules will also curtail the periods available for continuous rest and sleep. Also, they are likely to be exposed to other stressors that interact with fatigue, such as heat, noise and vibration. The importance of factors such as these was demonstrated by Storie's (1984) study of motorway accidents. This author believed that fatigue was implicated in 11% of accidents, even though 62% of the accidents occurred with vehicles driven less than 100 miles that day.

Growing evidence suggests that professional drivers working irregular shifts present an increasing problem for road safety (Fuller, 1980; McDonald, 1980; Miller & Mackie, 1980). It was noted that accidents attributed to fatigued drivers are second only to alcohol related accidents in California (Fuller, 1980; McDonald, 1980; Miller & Mackie, 1980). A review on truck and bus driver fatigue suggested that irregular driving schedules produced greater subjective fatigue, physiological stress, and performance degradation than did regular hours of work (Mackie & Miller, 1978). Fatigue effects became evident after about eight hours on regular schedules and considerably earlier when work was irregular. "Sleeper" driver operations (involving a two-man crew, one taking rest in the cab) showed earlier and greater signs of subjective fatigue and performance degradation than did "relay" driving (individual drivers handing over their freight to others) (Mackie & Miller, 1978). Sleeper driver performance was strongly affected by the time of day. Harris (1977) reported that twice as many truck accidents happened in the second half of the trip. The number of single-vehicle accidents was nearly 2.5 times greater than expected between midnight and 8 am, with accidents attributed to drivers dozing at the wheel, occurring almost 3.5 times more frequently than expected.

Hamelin (1987) reported similar accident patterns in French drivers. Accident risk increased throughout the day; that is, the risk was low till noon, showed a small and transient peak between noon and 2 p.m., and then increased linearly to a high peak between midnight and 2 a.m. The risk rate of this peak was around 2.5 times the daily average. Also the risk rate was greater among drivers over the age of 30 years. This was attributed to lower strength resources of drivers over 30, which limit their ability to compensate for fatigue effects once they have accumulated a certain number of duty hours or during the more difficult night driving hours.

When discussing the effect of fatigue, it is also important to discuss the effect of irregular schedules and physical work on the performance and fatigue in commercial drivers with emphasis on bus and truck drivers. Studies in this area have been summarised previously (Miller & Mackie, 1980):

* Long-haul truck drivers operating on an irregular schedule suffered greater subjective fatigue, physiological stress, and performance degradation than drivers who worked a similar number of hours on a regular schedule.
* For drivers operating alone, fatigue became evident after about eight hours of driving with a regular schedule and considerably earlier than when the schedule was irregular.
* Some cumulative fatigue occurred during six consecutive days of driving, but the time of the day strongly affected the magnitude of this effect.
* Pairs of truck drivers engaging in round-the-clock sleeper operations showed earlier and/or greater signs of subjective fatigue and performance degradation than single, long haul drivers.
* Two-crew driver fatigue, physiological state, and performance were strongly affected by time of day.
* Bus drivers operating on irregular schedules suffered greater subjective fatigue and physiological stress than drivers on a regular schedule. Fatigue effects were evident after about 7 hour of bus driving when the schedule was regular, and considerably earlier when the schedule was irregular.
* Participation of truck drivers in moderately heavy cargo handling, generally increased fatigue when a single driver engaged in relatively long driving stints.
* The major problem posed by irregular operations appears to be that the driver must at some time drive during those hours of the night when circadian reduction in physiological arousal is substantial. The ability to get adequate sleep just prior to these trips also appears to be reduced by circadian influences.
* For all classes of drivers, significant increases in subjective fatigue, changes in physiological state, and degradation in driving performance occur after considerably less driving time than current regulations allow (10 hours).
* Results from field experiments were in agreement with data on accidents in which driver fatigue, sleepiness, or inattentiveness were considered to be major factors.
* Drivers do not always obtain 8 hours of sleep each night in the irregular, uncertain schedules faced by many professional drivers.

1.3 Fatigue, Driving and Sleep Disorders

A special case of fatigue causation among drivers may be associated with sleep disorders. Aldrich (1989) showed evidence of higher accident rates among narcoleptics (those who have chronic difficulty remaining awake) and apneics (in whom breathing is impaired during sleep). While the incidence of sleep related accidents among apneics was found to be lower than among narcoleptics, apneics represent a potentially more serious problem for road safety because of their greater numbers. An additional problem is that apneics may not be fully aware of their problem. They may not recognise that they are becoming sleepy, and they may get no warning of acute sleep "attacks". Horne (1992) showed that truck drivers seemed particularly vulnerable to obesity, which is known to exacerbate the problem of sleep apnoea. Therefore, a significant fatigue problem may exist among heavy goods vehicle drivers who become apneic as a result of occupation and at a stage in their career when they are reluctant to sacrifice professional driving.

Drivers who suffer from the sleep disorder categorised as hypersomnia have increased risks of being involved in car accidents. Patients with diurnal hypersomnia due to sleep apnoea perform poorly on cognitive testing in terms of thinking, perception, communication and ability to perceive new information. They are potentially more distractible, confused and hostile. They also show psychomotor impairment, especially while undergoing tests that require a high level of attention and concentration (Bonnet, 1985; Findley, Barth, & Powers, 1986; Kales, Caldwell, & Cadieux, 1985).

Studies have used various methods and techniques to investigate driver fatigue, usually measuring fatigue by psychophysiological and biochemical tests before and after driving as well as continual recording of physiological and behavioural variables during driving. However, methodological limitations such as small sample numbers and inadequate sampling and poor statistical design are present in most of these studies making the results questionable. For example, many studies only use 10-15 subjects in the experimental and control groups (Haraldsson, Carenfelt, Laurell, & Törnros, 1990). A similar study of drivers in a truck simulator had nine professional drivers in a repeated measures design (Gillberg et al., 1996). Other sleepiness and vigilance studies using EEG have also had small subject numbers such as 10 (Torsvall & Åkerstedt, 1988) and 9 (Wierwille & Ellsworth, 1994). Such small numbers limits the generalisability of the data and opens the conclusions to higher risks of Type I or Type II errors.

1.4 Measurement of Fatigue

There are various psychophysiological measurements of fatigue that have been described in the literature. Some of the these measures of fatigue according to Okagbaa et al. (1994) will now be described in detail.

1.4.1 Primary task measure

Primary task measure is a method of mental workload assessment. Since driving is affected by differing task demands (such as traffic congestion, fatigue or lane width) one should be able to use driving performance as a criterion for an indicator of fatigue. Performance changes over time can be observed with different degrees of task demands.

1.4.2 Secondary task measure

A secondary task measure is assessed in addition to a primary task. If the subject is able to perform well on both the primary and secondary task then it indicates that the primary task is relatively easy. However, if the subject is unable to perform the secondary task and at the same time maintain a reasonable level of performance on the primary task, then this indicates that the primary task is more demanding (Knowles, 1963). The difference between the performance obtained from the two conditions, with and without inclusion of the primary tasks, is then taken as an index of the workload imposed by the primary task.

1.4.3 Objective indicators of fatigue

The literature is abundant with studies which have sought to measure variables associated with fatigue, and these includes, performance, perceptual, electrophysiological and biochemical measurements. The critical flicker fusion frequency has been used to define the central nervous system's ability to process information and has been shown to be related to fatigue (Kishida, 1973; Kumashiro, 1995). Other indicators involve cardiovascular measurements such as heart rate and heart rate variability however, more investigation is needed to identify the autonomic changes that occur during fatigue (Costa, 1993; Nelson, Carlson, & Nilsson, 1982; Hartley & Arnold, 1994, O'Hanlon, 1971). Increases in eye blink rates have been related to fatigue (Stern, Boyer, & Schroeder, 1994). Others have linked EEG changes to deteriorated driving (Kecklund & Åkerstedt, 1993; Lemke, 1982). The P300 component of the cortical evoked response has been used to determine task difficulty (Polich, 1987). It is however difficult to envisage how this complex technology could be applied even to professional drivers for either monitoring or alerting fatigue. Findings of sleep related changes in hormone or peptide levels have been reported, but a review found no consistent evidence for a chemical indicator of a need to sleep (Borbely & Tobler, 1989). The development of sensitive microspectrometers that could analyse blood components with an ear-lobe sensor may lead to a physio-chemical indicator (Nilsson et al., 1997) during driving. However, it would be disadvantageous to have such a device on the ears while driving (Nilsson et al., 1997) since it could be distracting and hinder the use of earphone-based devices. The search for a reliable indicator of fatigue is still elusive even though the technology has greatly improved over the past twenty years.

1.4.4 Subjective measures of fatigue

These include direct (overlaps with objective task measures) or indirect assessment of the subject and their opinion of the workload involved in a task. The easiest way to estimate the mental workload of a person who performs a certain task is to ask the subject how they feel about the mental load level of the task. Bartley (1970) likens fatigue to a perceptual system that informs the person when it is important to stop a given activity and do something else. Fatigue can be viewed as experience of tiredness, dislike of the current activity and unwillingness to continue (Bartley, 1970). This arises from a person's physiological state such as metabolic activity of the muscle, heart rate and respiration, which can be monitored as possible indicators. If it were as simple as this, than to prevent accidents it might simply be a matter of being told to stop when tired. The Road Traffic Authority in NSW has conducted many public campaigns and advertisements to promote this issue. Unfortunately, human adaptation extends beyond the psychology. We may all recall deliberately continuing to drive when tired, over-estimating our endurance and ignoring sensations that should otherwise have been heeded to as a signal to take a break. Nilsson et al. (1997) suggested that certain subjective experiences of the individual are good predictors of critical levels of fatigue, the most salient changes being development of sore feet, tired eyes and feelings of drowsiness. These authors suggest that teaching drivers to recognise these symptoms may be a more effective and practical method than telling them to stop every so often. Once again, daily demands and responsibility while driving do not always allow drivers to stop and they drive on regardless of the fatigue symptoms. There are many cases where drivers appear unaware of these physical and physiological symptoms that accompany fatigue. Many doze off and reach a state where an accident cannot be avoided. This is where a fatigue alerting device may play an important role (see Chapter 9). Such a device could alert the driver during early signs of fatigue, prevent dozing, and hence avoid road mishaps that may occur.

1.5 The Physiological Indicators of Fatigue

Individuals subjected to mental workload exhibit changes in a variety of physiological functions. One of the most prominently used measurements is the EEG, the electrical activity of the brain. There are also other physiological measures that have been used extensively. These include the electrocardiogram (ECG) and the electro-oculogram (EOG). These will now be discussed in some detail.

1.5.1 Eye movement as a measure of fatigue

A promising measure of drowsiness is eye movement, assessed by electro-oculogram (EOG). Since there are rich sensory and motor connections between the eye and the brain, eye movement can provide valuable warning signs of drowsiness. Eye movements enable the visual system to acquire information by scanning relevant aspects of the environment, crucial when driving. Object recognition, discrimination, and other information intake by the visual system is accomplished mostly through scanning eye movement (Andreassi, 2000a). The EOG has been useful in a wide range of applications such as rapid eye movements measured in sleep studies and studies of eye movements during real and simulated car driving (Andreassi, 2000a). Its predictive ability of arousal status is becoming accepted.

1.5.2 Eye blinks to monitor fatigue

Studies are concerned with psychological or behavioural variables that may affect blink rate. Eye blinks are also easily recorded with the EOG and are particularly useful in studies of eyelid conditioning as a control for possible eye blink contamination in EEG research, and as a measure of fatigue, lapses in attention, and stress (Andreassi, 2000a). Some authors have suggested that mental fatigue is physiologically measurable and single out the eye blink as a major indicator of mental fatigue (Stern et al., 1994). Other studies have used eyelid movement i.e. blinking frequency and duration of closed eyes as a parameter of fatigue in human operators (Simonov & Frolov, 1985). Eyelid movement was found to be a sensitive parameter of fatigue and corresponded to decreased quality in performance. These authors gave an auditory warning during symptoms of fatigue identified by eyelid movement and found that operator performance increased by 15-20%.

In an early study disappearance of blink artifacts was found to be associated with drowsiness (Erwin, Somerville, & Radtke, 1984). Others found deterioration of mental task performance with decreasing blink frequency (Simonov & Frolov, 1985). Research has suggested that the disappearance of blinks and mini-blinks and relative quiescence in eye movement are the earliest reliable signs of drowsiness, preceding slow eye movement and alpha frequency and amplitude changes (Santamaria & Chiappa, 1987a). The blink rate transition from wakefulness (0.4 Hz) to drowsiness (0 Hz) remains a valuable area of investigation into fatigue monitoring (refer to Chapter 3). The detection of blinking either using a movement transducer or a differential amplifier is feasible because it is distinct and the signal magnitude is relatively high.

1.5.3 Heart rate and heart rate variability as an indicator of fatigue

Heart rate measured using electrocardiogram (ECG) has been employed as a physiological measure of workload especially during driving conditions. There is a general decrease in heart rate during these situations. In a small study, the heart rate of seven city bus drivers was measured by an ECG recorder during daytime driving (Milosevic, 1997). Heart rate generally decreased from the beginning to the end of city driving by about 10 beats per minute as has been found during prolonged night driving (Riemersma, Sanders, Hildervanck, & Gaillard, 1977).

Some researchers reported that, after a few hours at the wheel, the performance of drivers of buses and of heavy lorries became distinctly poorer, especially their judgement of the edge of the road, and the necessary number of corrective movements of the steering wheel (Harris, et al., 1972). Simultaneously, the variability of heart rate and a feeling of fatigue both increased, which the authors interpreted as signs of a fall in the level of cerebral activation. This confirms the results of others (O'Hanlon, 1971), who found distinctly higher heart rate variability among drivers of motor vehicles after long test-drives. The observed rise in variability was interpreted as a sign of diminished alertness.

Some studies have confirmed that cardiac sinus arrhythmia is highly correlated with mental workload (Vincent, Thornton, & Moray, 1987). These authors showed that the mid-frequency band of the spectrum of heart rate variability, between 0.06-0.14 Hz, decreases substantially in response to increasing demands of a mental task. It has been proposed that sinus arrhythmia decreases as controlled mental effort is increased in response to a demanding mental task (Vincent et al., 1987). Furthermore, the mid-frequency component of the spectrum has been shown to be free from the influence of respiration rate, motor activity and thermoregulation (Hartley & Arnold, 1994). Accordingly, heart rate variability has been suggested to be one of the best, independent, physiological measures of the mental demands of tasks. It is therefore a good candidate for measuring fatigue arising from the demands of driving (Hartley & Arnold, 1994).

Since there is a link between heart rate and fatigue, it is important to discuss the concept of heart rate variability and its importance in the frequency domain. Spectral analysis techniques have been used to link beat-to-beat changes in heart rate to nervous system activity. Spectral analysis of heart rate variability has suggested that power in specific frequency bands can be related to parasympathetic and sympathetic nervous system activity. Specifically, relative power in high frequency areas, usually from 0.15-0.5 Hz, has been used to infer parasympathetic nervous system activity. Evidence has been published showing that the peak in the lower frequency component is in the range of 0.09-0.11 with a standard deviation of 0.02 (Furlan, et al., 1990). To include both the peak and the surrounding area, a range of lower frequencies from 0.05 to 0.15 Hz has been related to a combination of parasympathetic and sympathetic influences (Jaffe et al., 1993; Malliani et al., 1991; Yeragani, Srinivasan, Vempati, Pohl, & Balon, 1993). Because the lower frequency power is a combination of sympathetic and parasympathetic effects, investigators frequently infer sympathetic nervous system activity from the ratio of low frequency (LF) (which influenced by both parasympathetic and sympathetic components) to high frequency (HF) (which is predominantly parasympathetic) activity, that is LF: HF. In this case parasympathetic activity in the LF band to some extent cancels out of the ratio (Rizzoni, et al., 1991; Yeragani et al., 1993) leaving a better indicator of sympathetic activity. This will then provide a more adequate representation of sympathetic activity changes in the LF band while the HF band indicates the parasympathetic activity during driver fatigue. Refer to Chapter 5 for further details on deriving autonomic activity from heart rate variability.

1.6 Other Methods to Assess Fatigue

1.6.1 Psychomotor tests to measure fatigue

Psychomotor test measures functions that involve perception, interpretation and motor reactions. The following tests are often used (Grandjean, 1979):

* simple and selective reaction times
* tests involving tapping squares in a grid
* tests of skill
* driving tests under simulated conditions
* typing
* tachistoscopic tests to measure performance involving perception

Several examples of such test methods have been described (Welford, 1968). In tests like these it is assumed that a reduction in performance can be taken as a sign of a state of fatigue. A disadvantage of psychomotor tests is that often the test itself makes heavy demands on the subject, thereby raising the level of cerebral activity which can temporarily mask any possible signs of fatigue (Grandjean, 1979).

1.6.2 Mental tests to assess fatigue

Performance of mental tests often involves arithmetic sums, tests of concentration (such as crossing-out tests), estimation tests (such as estimation of time intervals), and memory tests. These tests usually alert the subject and raise the cerebral activity.

1.6.3 Questionnaire studies of fatigue

Given that the subjective component of fatigue is very important, then questionnaire investigations are relevant in the study of driver fatigue. Questionnaires provide information about signs of fatigue, time of fatigue appearance and other factors contributing to driver fatigue. However, it should be noted here that questionnaires alone cannot be the sole indicator/identifier of fatigue symptoms and that physiological measures need to accompany them for verification of fatigue. In a study of truck drivers, questionnaires were administered and the questions mostly related to the signs and time of fatigue appearance (Milosevic, 1997). The results revealed that frequent physical signs associated with fatigue were back pain and pain in the legs. Other frequent psychophysiological signs were drowsiness, sleepiness, bad mood and irritability and eye pain (see Table 1.1, adapted from (Milosevic, 1997)). It should be noted that these answers were derived at the end of driving, where these symptoms of fatigue are most prominent.

Most of the information about sleepiness in shift work has been based on self-rating techniques, which can have limitations. It is a subjective measure, and self-report cannot provide data on moment-to-moment fluctuations of sleepiness. Also, self-report techniques could hardly be considered to measure sleepiness *per se*.

1.6.4 Video indication of fatigue

The level of drowsiness and fatigue can be assessed using a video image of the vehicle operator's face (Belyavin & Wright, 1987). Observers can estimate the level of drowsiness of the driver based on characteristics such as facial tone, slow eyelid closure, and mannerisms (rubbing, yawning and nodding) (Belyavin & Wright, 1987). It is important in fatigue studies or even for the development of any drowsiness detection device that the level of drowsiness be independently validated. Facial expression is an objective and reliable measure of fatigue yet very few studies have applied "facial expression" to drowsiness research (Belyavin & Wright, 1987; Yabuta, Iizuka, Yanagishima, Kataoka, & Seno, 1985). In a previous study, a three-level ordinal scale of facial expression was used in assessing alertness (Yabuta et al. 1985). The other components were brain-wave evaluation and amount of blinking. The combined assessment was called an alertness index and was used as an independent variable in simulator tests directed at devising a drowsiness detection system. For obvious reasons, drowsiness studies should have an independent variable to assess the onset and different levels of fatigue. A video recording of the face can serve as an independent variable for the validation of fatigue.

1.6.5 Electroencephalography as an indicator of fatigue, alertness and sleep

The electrical activity of the brain is classified according to rhythms which are defined in terms of the frequency bands alpha, theta, beta and delta (described in section 1.8.3). It is postulated that changes in the EEG signal would be associated with the appearance of fatigue and changes in performance due to mental fatigue. In order to investigate fatigue symptoms using EEG it is important to have a basic insight into the neuroscience of the brain and an understanding of electroencephalography and the features of sleep. These will now be briefly discussed in sections 1.7 and 1.8.

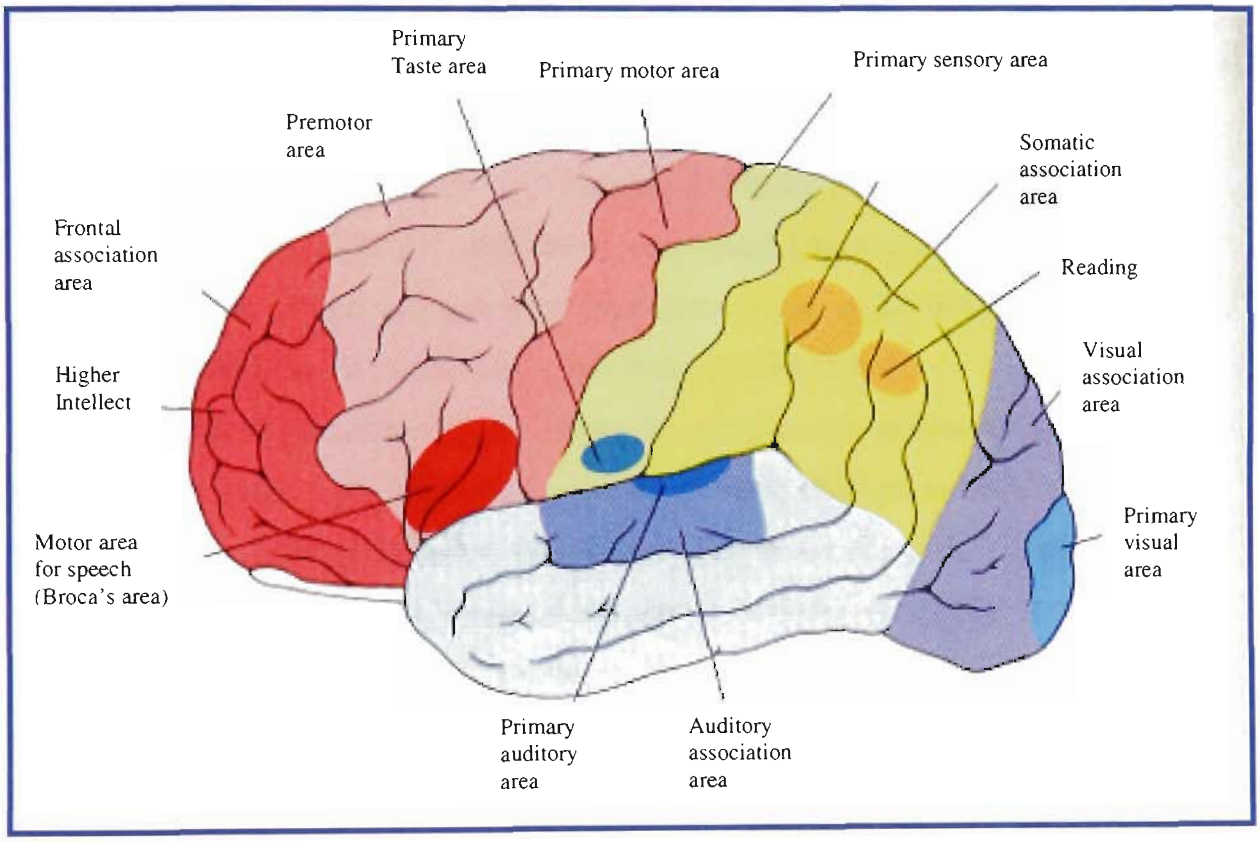
Table 1.1 Ranks and numbers of most frequent signs of fatigue in long-distance and dump-truck drivers (three possible answers per driver) (adapted from Milosevic, 1997)

	Long-distance drivers		Truck drivers	
Fatigue signs	Rank	Number of answers	Rank	Number of answers
Back pain and pains in the legs	1	118	1	83
Drowsiness and sleepiness	2	107	4	44
Bad mood and irritability	3	52	5	30
Slowed-down activity	4	49	9	8
Pain and other eye problems	5	42	3	48
Intense excitability	6	21	7.5	9
Headache	7	19	2	56
Distraction and attention switch	8	18	7.5	9
Poor observation of signals and signs	9	15	10	2
Hesitation in difficult situations	10	13	11.5	1
Errors in the sequence of driving operations	11	12	11.5	1
Trembling of hands and legs	12	7	6	14
Something else		6		0
No responses		121		16

1.7 Fundamentals of Neuroscience

The brain may be divided into three main portions: the cerebrum, the cerebellum, and the brain stem. The cerebrum occupies much of the external surface of the brain and has two hemispheres, the left and the right. The cerebellum overlies the posterior aspect of the brain while the brain stem is the structure on which the cerebellum is positioned. The surface of the cerebrum has many convolutions. The cerebral cortex is divided into four lobes: the frontal, parietal, occipital, and temporal. The cortical surface controls basic sensory and motor functions (Figure 1.2) and will now be briefly described (Andreassi, 2000b). The primary motor area is concerned with control of movement in the lower limbs, head and neck. The somatosensory cortex receives input from sensations such as touch, temperature and pressure. The primary visual cortex is located in the occipital lobe. The primary auditory area for processing sounds is located in the temporal lobe. An area concerned with understanding of spoken language is located posterior to the primary auditory cortex. The frontal lobe is involved with 'biological intelligence' or the ability to plan, make decisions, and solve problems. Areas of the cortex that are not involved with specific sensory and motor functions are called the association cortex. The association cortex is believed to serve the functions of learning, planning and perceiving (Andreassi, 2000b).

Figure 1.2 General functional areas of the cerebral cortex (adapted from Spence & Mason, 1987)



1.8 The Electroencephalography (EEG)

The electrical activity in the brain or 'brain wave' (EEG) was first described by Caton in 1875 (quoted in Fuller, 1980). Caton showed that when a flash of light was presented to an animal's eye, a change in electrical activity occurred in the occipital area. In 1929, Hans Berger published the first work on the human EEG. He identified two basic brain wave patterns and termed the larger and slower waves as alpha and the smaller, faster ones as beta. Later, investigators defined other types of brain waves and called them gamma, delta, theta, kappa, lamda and mu waves (Fuller, 1980). The most reliable of these later-defined waves, in terms of consistency and occurrence, have been delta and theta. The delta wave is characterised by very low frequency and high amplitude and was given its name by Walter in 1937 (quoted in (Fuller, 1980)). The term theta was first used by Walter in 1953 to describe a wave with a frequency between 3 and 7 cycles per second. The characteristics of the main waves, which are delta, theta alpha and beta are described in more detail later under Section 1.8.4.

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. By comparison, neuronal action potentials, which have much smaller potential fields and are shorter in duration (1 msec or less compared to postsynaptic potentials, which have a duration of 15 to more than 200 msec), do not contribute significantly to either routine scalp recordings or to EEG recordings from the cortical surface (Fisch, 1991a). The rhythmical activity in a routine scalp recorded EEG represents postsynaptic cortical neuronal potentials, which are synchronised 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 organising impulses from subcortical pacemakers.

1.8.1 EEG recording

Scalp electrodes mainly record the summated postsynaptic potential changes of neurons in the underlying cortex, favouring slow potential changes generated in large areas near the recording electrode. Scalp electrodes rarely record potentials produced in distant parts of the brain. However, subcortical structures may send synchronising impulses to cortical neurons and induce widespread synchronous cortical potential changes. Scalp electrode recordings may also show extracerebral potential changes produced either by biological activity such as eye movements, heartbeat and scalp muscle activity, or by interference or defects of the recording equipment. Recording electrodes transfer electrical potentials at the recording site to the input of the recording machine. The electrode type most commonly used in non-invasive EEG recordings is metal discs or cups attached to the scalp and other recording sites. Electrode surfaces are usually made of gold, silver chloride or other materials, which have minimum interaction with the scalp. Electrical contact impedance of the electrode should be between 100-5000 ohms. Placement of electrodes should cover the entire head depending on the investigation and the recordings should be reproducible (refer to Chapter 7). This is accomplished with the International 10-20 System of electrode placement, which provides for uniform coverage of the entire scalp (Fisch, 1991b). Most psychophysiological research is directed towards a description of normal EEG activity and somewhat by tradition has been performed in relation to an inactive reference site. Recordings in which one electrode is seen to be inactive are referred to as monopolar or common reference recording (Cacioppo & Tassinary, 1990).

After assessing the literature, it seems likely that the EEG may be the only brain imaging modality suitable for use in operational environments and ambulatory subjects. To increase the resolution of the EEG it is necessary to have adequate spatial sampling of brain electrical fields on the scalp. The 19-channel 10/20 montage (Jasper, 1958) is commonly used in clinical and research recordings and has an inter-electrode distance of about 6 cm on a typical adult head.

1.8.2 Descriptors of EEG activity

Several methods are used to quantify EEG signals; including amplitude analysis, power spectrum analysis and wave indices (Bechtereva, 1981; Gogolitsin & Kropotov, 1981; Grandjean, 1988; Ivanitsky, 1980). To analyse the EEG, the reader needs to distinguish: 1) Wave form 2) Repetition 3) Frequency 4) Amplitude 5) Distribution 6) Phase relation 7) Timing 8) Persistence and 9) Reactivity. These features allow recognition of different patterns. These descriptors of EEG activity will now be described (Fisch, 1991b):

Wave Form

Waveform or shape are simple terms used to describe the configuration or morphology of a wave. Any change in the difference of the electrical potential between two recording electrodes is called a wave. Any wave or sequence of waves is called activity.

Repetition

Repetition of waves may be called rhythmic or arrhythmic. Rhythmic repetitive waves have similar intervals between individual waves. They are usually regular and often sinusoidal in shape. Arrhythmic repetitive waves are characterised by variable, irregular intervals between individual waves. They can be considered to be a sequence of waves of different frequency and have irregular shapes.

Frequency

Frequency refers to the number of times a repetitive wave recurs in one second. The frequency of single or repetitive waves can be determined by measuring the duration of an individual wave, the wavelength and calculating the reciprocal. The frequencies of the EEG waves are often divided into four groups or frequency bands: delta, theta, alpha and beta (described in section 1.8.3).

Amplitude

The amplitude of EEG waves is measured in microvolts (μV). It is determined by measuring the total vertical distance of a wave.

Distribution

Distribution refers to the occurrence of electrical activity recorded by electrodes positioned over different parts of the head. EEG patterns may appear over large areas on both sides of the head, over one side only, or in a restricted, small area.

Phase Relation

Phase refers to the timing and polarity of components of waves in one or more channels. Waves of different frequency may occur in different channels so that the troughs and peaks occur at the same time; these waves are in phase and if they do not coincide in this manner, the waves are out of phase.

Timing

Timing of waves in different areas of the head may be similar or different. The terms 'simultaneous' and 'synchronous' are used to indicate that two events occurred at the same time.

Persistence

Persistence describes how often a wave or pattern occurs during a recording. Some waves occur only occasionally or intermittently; other waves are present in most of the recording. The persistence of waves can be measured from the proportion of time during which these waves appear. This is called the index.

Reactivity

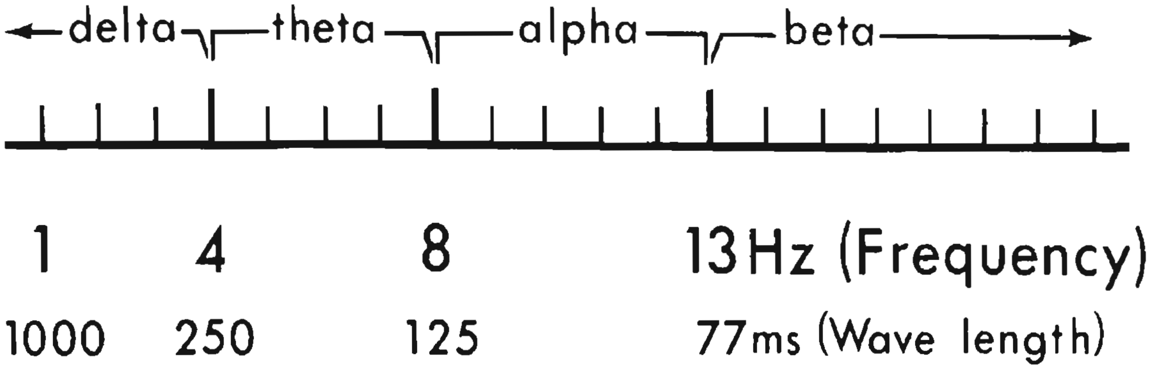
Reactivity refers to normal and abnormal changes which can be produced by various manoeuvres e.g. opening or closing eyes, hyperventilation, photic or sensory stimuli, changes in levels of alertness, and motor movements or other manoeuvres.

1.8.3 Description of the EEG frequency

The frequency of EEG waves are often divided into four groups or frequency bands: Delta: <4 Hz, theta: 4-<8 Hz, alpha: 8-13 Hz and beta: >13 Hz (see Figure 1.3 adapted from (Fisch, 1991b)). These divisions are somewhat arbitrary, and the literature is variable in defining the bands. An example is Wada, Nanbu, Koshino, Shimada, & Hashimoto (1996) who report the following bands: delta (2-3.5 Hz), theta-1 (4-4.5 Hz), theta-2 (6-7.5 Hz), alpha-1 (8-9 Hz), alpha 2 (9.5-10.5 Hz), alpha-3 (11-12.5 Hz), beta-1 (13-19.5 Hz) and beta-2 (20-25 Hz). Although waves less than 8 Hz are commonly called slow waves and waves over 13 Hz are commonly called fast waves, it is more accurate to state the frequency when reporting electroencephalographic activity.

Some researchers also define an extra band called sigma and hence have different divisions of the frequency bands such as beta (0.2-3.8 Hz), theta (4.0-7.8 Hz), alpha (8.0-12.8 Hz), sigma (13.2-14.8 Hz) and beta (15.0-20.0 Hz) (Lubin, Johnson, & Austin, 1969). The above bands are described in more detail in Section 1.8.4. In this doctoral study the frequency bands have been defined according to (Cacioppo & Tassinary, 1990) which is: delta: 0- 4 Hz, theta: 4- 8 Hz, alpha: 8-13 Hz and beta: 13-30 Hz. The literature specifies that the slightly different bands used by investigators do not influence or alter the results significantly (Cacioppo & Tassinary, 1990).

Figure 1.3 Frequency bands. Delta, theta, alpha and beta frequency bands, defined by wave frequency (Hz) and length (ms)



The association between EEG and some psychological states which will be discussed further in this review and is summarised briefly in Table 1.2 (adapted from Cacioppo & Tassinary, 1990). Table 1.2 describes a continuum in which lower levels of consciousness such as deep sleep are associated with large-amplitude low-frequency activity, whereas more alert activity and excitement are associated with high-frequency low-amplitude waves. Middle levels of alertness such as drowsiness and relaxed wakefulness are indexed by middle-range frequencies of EEG activity.

Table 1.2 Levels of consciousness in terms of psychological states and EEG (adapted from Cacioppo & Tassinary, 1990)

Behavioural state	**EEG**
Excited emotion	Fast, mixed frequencies with low to moderate amplitude
Alert	Mainly fast, low amplitude wave
Relaxed Wakefulness	Optimal alpha rhythm
Drowsiness	Reduced alpha and occasional low-amplitude slow waves
Light sleep	Sleep spindles and slow waves; loss of alpha waves
Deep sleep	Large and very slow waves; random; irregular patterns

1.8.4 The effects of the EEG Rhythms

Since the frequency bands are referred to frequently in this review, it is important to describe the mechanisms and behavioural connotations of EEG rhythms.

1.8.4.1 Delta activity

These are slow waves between 0.5 and 4 Hz in a range of 20-200 μV. Delta waves are present during the deep sleep stage of normal EEG, that is, synchronised sleep indented by faster spindle waves. Delta activity is also present during various stages of drowsiness (Santamaria & Chiappa, 1987a). Delta waves are generated by vertically arranged dipolar generators which are parallel to each other such as the pyramidal neurons of the cerebral cortex.

1.8.4.2 Theta frequency

The theta rhythm is an activity within the frequency range of 4-8 Hz, with amplitude ranging from 20-100 μV. Walter (1953) found theta to occur during drowsiness. Three major types of theta waves can be distinguished.

(a) A first type of theta rhythm represents a slowing down of the alpha activity.

(b) A second type of theta activity, particularly that which occurs intermittently and with fronto-temporal predominance, is often attributed to disturbances in midline structures (Gloor, 1976).

(c) Localised theta activity may represent the mildest form of polymorphic delta activity.

Theta activity has been associated with a variety of psychological processes including hypnagogic imagery, REM (rapid eye movement) sleep, problem solving, hypnosis and meditation (Schacter, 1977). Theta has been associated with conditions of low levels of alertness and sleep deprivation and has such been associated with decreased information processing. One interpretation of this association is that of inhibition of attention. On the other hand, it has been associated with active and efficient processing of various types of problem solving and perceptual tasks (Schacter, 1977).

1.8.4.3 Alpha waves

The alpha rhythm has a frequency range of 8-12 Hz at a magnitude of about 20-60 μV (millionths of a volt), occurs during wakefulness particularly over the occipital cortex, appears at eye closure and disappears at eyes opening. The general conclusion from animal studies is that there are thalamocortical and cortico-cortical systems which interact in the generation of cortical alpha rhythms (Steriade, Gloor, Llinas, Lopes da Silva, & Mesulam, 1990). Alpha waves can be produced by almost anyone sitting quietly in a relaxed position, with eyes closed. As soon as the individual becomes involved in mental or physical activity, the alpha waves generally become reduced and disappear and are replaced by beta waves. The classical view of alpha activity has been that it represents a relaxed state and will be disrupted with any kind of mental work.

1.8.4.4 Beta waves

Beta is an irregular wave that occurs at a frequency of 13-50 Hz with an amplitude of approximately 2-20 μV. This band can be divided into an 18-30 Hz component called beta waves and a 30-50 Hz component referred to as gamma waves, a term that is infrequently seen in the literature. It is common during increased alertness such as during mental or physical activity. Beta activity has been reported to occur in humans while performing a reaction-time motor task (Sheer, 1988). It was hypothesised that the 40 Hz activity is an index of the focused arousal in motor programming and that it represents an optimal periodicity for maximal synaptic transmission in cortical circuits. Walter (1953) associated beta activity with tension as would be seen in states of anxiety.

1.8.5 EEG coherence analysis

EEG coherence is a non-invasive measure of functional relationships between brain regions (refer to Chapter 8). Coherence of two EEG signals recorded from spatially separated scalp electrodes estimate the similarity of waveform components generated by the mass action of neurons in underlying cortical regions (French & Beaumont, 1984; Shaw, 1981). Very few studies have examined EEG coherence during light drowsiness. In a study by Boldyreva and Zhavoronkova (1991) a change of coherence asymmetry was reported during transition from wakefulness to drowsiness. Wada et al. (1996) conducted a study in 14 volunteers to examine both inter- and intrahemispheric EEG coherence during wakefulness and light drowsiness. They measured interhemispheric coherence between three homologous electrode pairs: in the frontal (F3-F4), central (C3-C4) and occipital (O1-O2) sites. Intrahemispheric coherence was measured at the centro-occipital region in the left (C3-O1) and right hemispheres (C4-02). These authors found that interhemispheric coherence was significantly lower during light drowsiness than during wakefulness for 01-02 in the alpha-1 band and for F3-F4 in the beta-1 band. Intrahemispheric EEG coherence was significantly greater during light drowsiness for C4-02 in the theta-1 and beta-1 bands. These results indicate that light drowsiness alters both inter- and intrahemispheric EEG coherence, suggesting cerebral function organization changes during drowsiness.

1.8.6 EEG signal processing and artifact detection

One of the most common reasons for misinterpreting the EEG is the failure to identify correctly the non-cerebral potentials. EEG signal contamination due to artifact is a major concern when processing EEG data (Barlow, 1986; Duffy, 1986; Kahn, Weiner, Brenner, & Coppola, 1988; Torello, 1989). Muscle artifact, movement, eye blinks and saccades and heart beat can contaminate the signal of primary interest for making inferences about mental status (Skelly, Purvis, & Wilson, 1988; Sterman, Schummer, Dushenko, & Smith, 1988). For successful application of real-time physiological methods to assess operator alertness, the development of reliable means of identifying and correcting recording artifact is important. The patient and the EEG record must be closely observed throughout the recording and notations made whenever artifacts occur. The following describes different types of artifacts.

Blinking and other eye movements

Eye movements and blinking cause potential changes which are detected mainly by frontal electrodes, although they may extend into central and temporal areas. Rapid eye movements may cause jagged artifacts. Muscle artifact may appear along with eye movements. A single sharp muscle potential may precede lateral eye movements.

Muscle artifact

Muscle activity causes very short potentials which usually recur. Muscle artifacts from the head and face muscles occur mainly in the frontal and temporal regions.

Movement artifact

Movement of the head or body or of the electrode wires can cause artifacts. Movement artifacts are often erratic and not repetitive unless the movement is rhythmical such as breathing or head movement with each heartbeat.

Electrocardiogram artifact

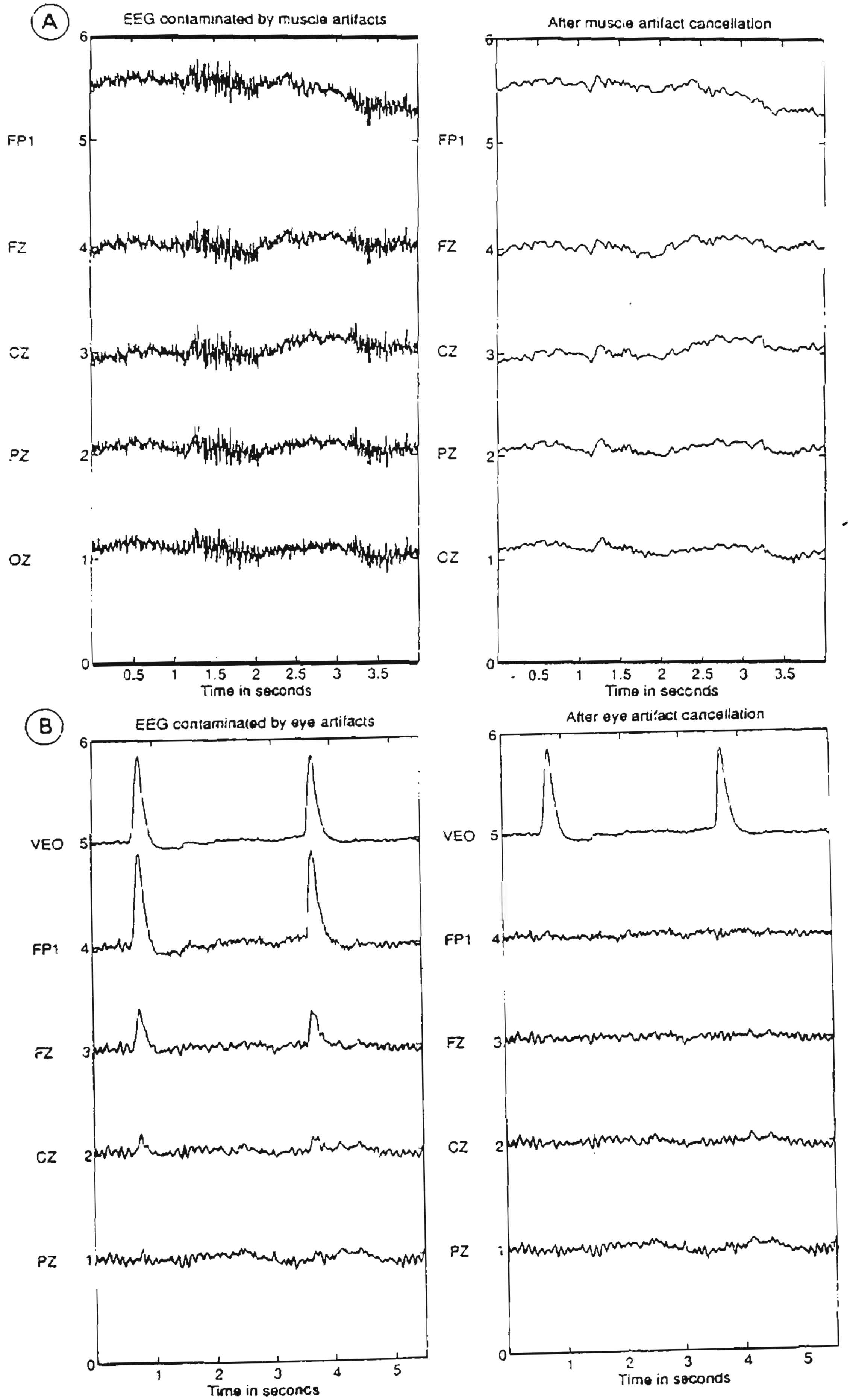
Potential changes generated by the heart are detected in the EEG mainly in recordings with wide inter-electrode distances, especially in links across the head and to the left ear. The artifact may appear in all channels using a common reference.

Filtering is used to separate the frequencies into the appropriate bands (Okogbaa et al., 1994). Low-pass filters are used to eliminate noise from the trace, while high-pass filtering allows elimination of bandwidth below 4 Hz. The 60 Hz contamination from the mains is generally biologically isolated and removed from the recorded signals. Previously, many artifact removal systems have been developed (Gevins & Morgan, 1988) such as comparison of each digitised EEG time series with a maximum voltage threshold which when exceeded allows a data segment to be removed. Tuned threshold detectors (Gevins, Zeitlin, Ancoli, & Yeager, 1977b) and adaptive filtering and neural network analysis have also been described (Du, Leong, & Gevins, 1994; Gevins & Morgan, 1988). Gevins et al. (1995) discussed advances in on-line reduction of muscle and eye movement artifacts based on low pass filtering with variable cut-off frequencies using the estimated signal-noise ratio (see Figures 1.4a and 1.4b). These authors have also been developing an improved adaptive eye artifact reduction filter, which adjusts filter coefficients to achieve maximum artifact reduction (Du, Leong, & Gevins, 1994). Others have also described the minimisation of EOG artifacts from EEG signals using a neural network approach (Sadasivan & Dutt, 1994).

1.9 The Electroencephalographic Features of Normal Sleep

Since fatigue and drowsiness are related to sleepiness patterns, it is relevant to review the EEG changes during sleep. The EEG of sleep has been intensively studied during daytime naps, overnight sleep recordings, following sleep deprivation and under a wide variety of environmental conditions. This review will now concentrate on the recording of sleep using conventional EEG techniques. Much remains to be known regarding the function of sleep. The basic concepts of sleep staging will now be discussed.

Figure 1.4a and 1.4b EEG after on-line reduction of muscle and eye artifact contamination



1.9.1 Sleep stages

The attempt to correlate EEG changes with behavioural depth of sleep led to sleep staging. The widely accepted system was that of Loomis, Harvey, & Hobart, (1937) who described five levels of sleep designated A-E. The currently accepted system is based on the scheme proposed by previous researchers (Dement & Kleitman, 1957). These investigators did not designate a separate Stage REM (rapid eye movement), but rather referred to Stage 1 EEG with REM. The scheme was refined and a Stage REM added by the Association for the Psychophysiological Study of Sleep. Rechtschaffen and Kales (1968) published a manual for recording and scoring sleep stages. Their system was based on a single EEG derivation (C3 or C4 to contralateral ear), two electro-oculographic (EOG) channels, and the submental electromyogram (EMG).

1.9.2 Sequential changes and sleep

The earliest signs of drowsiness in adults usually consist of reduction in muscle activity, the disappearance of blinking and the REM potentials of wakefulness, and a slowing and increase in the amplitude of the alpha rhythm. As drowsiness deepens, low voltage activity begins to interrupt the alpha rhythm. The low voltage activities which are composed of 2-7 Hz activities gradually, lengthen until the alpha rhythm is completely replaced. Also at this time slow eye movements (SEM) of sleep occur. With deepening drowsiness, vertex waves, and positive occipital sharp transients of sleep (POSTS) appear. Next, the sleep spindles and K-complexes appear (combined vertex wave and sleep spindles). As sleep deepens, high voltage delta waves appear in increasing amounts. Meanwhile, vertex waves, K-complexes, sleep spindles, and POSTS continue. This is followed by REM sleep, in which the EEG background resembles early drowsiness (sawtooth waves may appear), rapid irregular eye movements occur, and myogenic potentials are markedly attenuated. The major criteria described by Rechtschaffen and Kales (1968) is as follows:

Stage 1 (drowsiness/light sleep):

Greater than 50% abundance of low voltage 2-7 Hz activity. Vertex waves may occur. K-complexes and sleep spindles are absent. SEM is usually in early Stage 1.

Stage 2 (light sleep):

Spindles and/or K-complexes of a duration greater than 0.5s. Eye movements do not occur.

Stage 3 (slow wave sleep/deep sleep):

Between 20 and 50% of the epoch in question consists of delta activity of 2 Hz or slower, with amplitudes greater than 75 μV.

Stage 4 (slow wave sleep/very deep sleep):

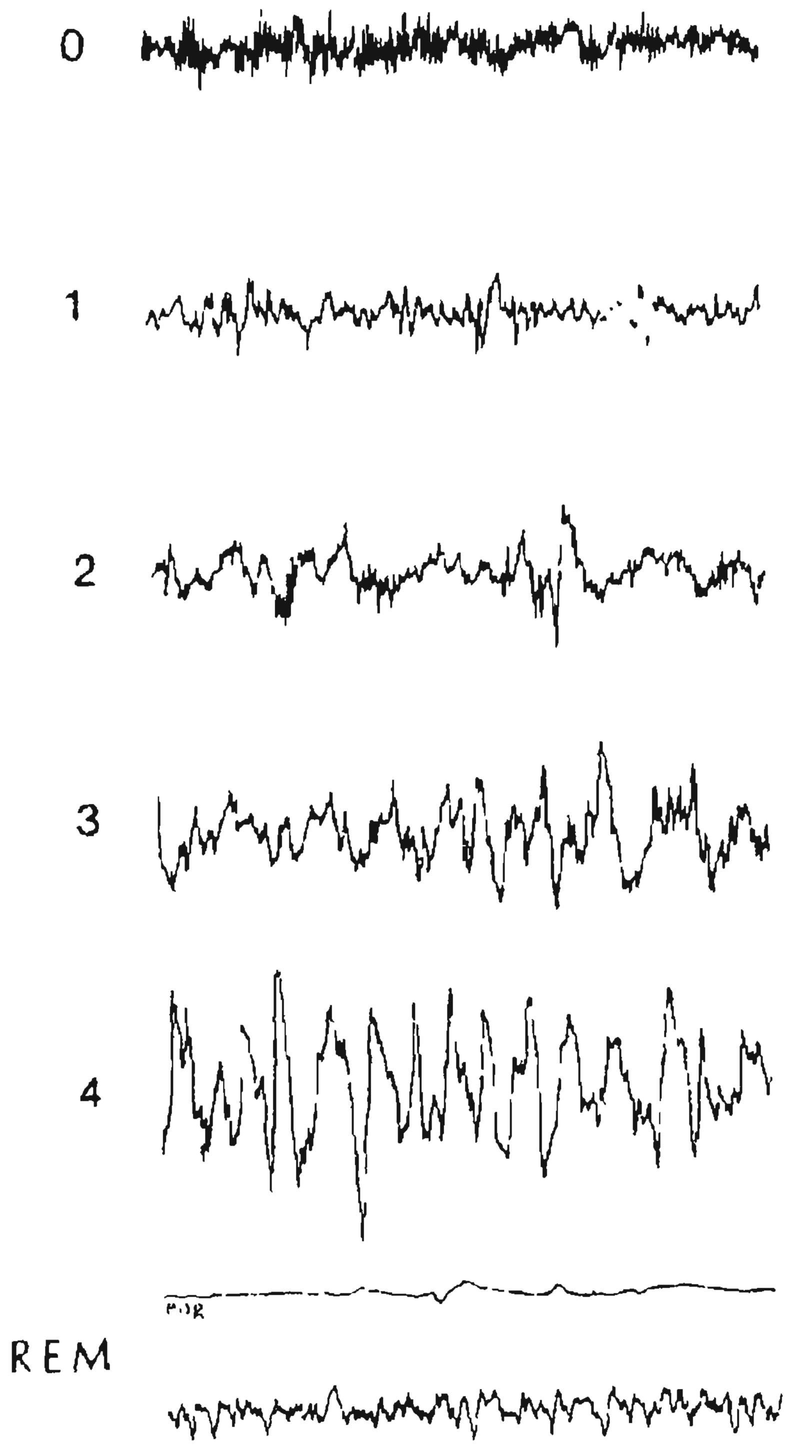
More than 50% of an epoch consists of delta activity ≤ 2 Hz and greater than 75 μV.
Note: Stages 1-4 are also known as non-REM sleep.

Stage REM (paradoxical sleep):

Low voltage, mixed frequency EEG activity, and episodic REM. Sleep spindles and K-complexes are absent. EMG markedly reduced with regard to tonic features although phasic events are common.

Others have used the frequency bands for practical purposes during the traditional analysis of sleep/wakefulness (Åkerstedt et al., 1987). Figure 1.5 (adapted from Åkerstedt et al., 1987) illustrates EEG activity during 0= active wakefulness (beta), 1= relaxed wakefulness (alpha), 2= stage 1 of sleep i.e. fatigue/drowsiness (theta). As sleep deepens, 3 and 4= sleep stages 2,3 and 4 occur distinguished by decreasing frequency and increasing amplitude.

Figure 1.5 EEG stages 0-4 and REM. The EOG pattern during REM sleep is the second trace from the bottom (adapted from Åkerstedt et al., 1987).



At this stage it is important to briefly discuss the effects of sleep deprivation and how it influences fatigue.

1.9.3 Sleep deprivation

In 1975, Naitoh distinguished among three types of sleep deprivation studies using human subjects. 1) Total sleep deprivation, in which a person is kept awake throughout one or more entire sleep periods. 2) Partial sleep deprivation, which involves loss of a portion of the regular sleep period. 3) Differential sleep deprivation, where certain sleep stages are selectively prevented from occurring based on observing the EEG and then arousing the person (Naitoh, 1975).

The types of activities most likely to suffer impairment due to sleep loss are quick reactions, reasoning, decision-making and attention (Andreassi, 2000c), all of which have implications during a driving task. Other sleep deprivation effects are slowing of reaction time, decrease in vigilance performance, increased irritability, and micro sleeps (short lapses in attention). It has been reported that sleep deprivation results in REM and stage 2 sleep and that sleep onset is much quicker for sleep-deprived subjects (Horne & Wilkinson, 1985). It has also been suggested that total sleep loss can be disruptive and detrimentally affects mood and performance (Andreassi, 2000c).

1.10 Electroencephalography of Fatigue and Drowsiness

Before the EEG effects in different workplace and environments are discussed, it is important to classify the EEG changes that occur in various stages of fatigue and drowsiness. The classification of fatigue/drowsiness will now be described briefly according to Santamaria and Chiappa (1987a). Fatigue may be divided into four periods as defined below, and the EEG features of each will be presented separately. The transitional phase occurs between awake alpha and absence of alpha, that is, a few to 10 seconds preceding alpha disappearance, during which the EEG changes in frequency, distribution, or amplitude of the dominant activity. The transitional and post-transitional phase refers to both or either of the transitional or post-transitional periods. The post-transitional phase consists of the first EEG section after alpha disappearance comprising of early Stage 1 of sleep. The arousal phase is characterised by the emergence from fatigue/drowsiness. Although there is a great deal of variability in the EEG of fatigue among different subjects, it is possible to classify most of the fatigue

EEG patterns (Santamaria & Chiappa, 1987a). According to Santamaria and Chiappa (1987a) not all fatigue EEG patterns fit neatly into the phases described. However, the classification system provides a useful means for organising phases of fatigue and allows comparison of EEG data assessed during a fatigue state. Table 1.3 describes the major EEG changes that occur in each phase according to Santamaria and Chiappa (1987a).

Table 1.3 Classification of fatigue/drowsiness EEG and arousal EEG

Phase	Phase continued
1) Transitional	***2) Transitional and post-transitional***
1. Change in alpha distribution	1. Frontocentral beta (33.3%)
Increase in amplitude of:	2. Generalized 3-5 Hz slowing (20%)
a) Centrofrontal alpha	3. Midtemporal theta (few)
b) Temporal alpha	
2. Change in alpha amplitude	***3) Post-transitional***
a) Decrease (33.3%)	1. Posterior slowing (20%)
b) Increase (25%)	2. Frontocentral slowing (67%)
3. Increase in slow activities	
a) Posterior delta/theta + alpha	***4) Arousal from drowsiness***
b) Centrofrontal delta/theta + alpha	1. Centrofrontal beta (50%)
c) Alpha slowing (<5%)	2. Centrofrontal alpha (10%)
d) Temporal delta/theta	3. Posterior alpha (10%)

Note: The percentage values represent the proportion of subjects in which the EEG pattern can occur during fatigue (from Santamaria and Chiappa, 1987a).

1.10.1 Electroencephalography of Fatigue and Drowsiness in Different Environments and Situations

It has been known for some time that changes in brain arousal involve specific changes in oscillatory brain activity (Chrousos, et al., 1995; Jung & Makeig, 1994; Lehmann, Grass, & Meier, 1995; Makeig & Inlow, 1993; Santamaria & Chiappa, 1987b; Steriade, Dossi, & Paré, 1988) and can be recorded by EEG. Even though numerous physiological indicators are available to describe the level of alertness, the EEG signal is considered to be the most predictive and most reliable (Erwin & Al., 1973; Volow & Erwin, 1973). Recently, Artaud et al., (1994) also concluded that although numerous physical indicators are available to describe an individuals' level of alertness, the EEG signal remains the most reliable". There is an abundance of literature describing the EEG effects of drowsiness and fatigue but the conclusions are quite variable. There have been previous observations of changes in the EEG spectrum during the transition to sleep (Chrousos, et al., 1995). The EEG spectrum was found to shift towards lower frequencies such as delta and theta. Amplitude changes in theta, alpha, sigma, and beta frequencies have been long associated with drowsiness and sleep onset (Chrousos, et al., 1995). EEG has also been found to be sensitive to fluctuations in vigilance and can predict performance degradation (Gevins, Bressler, Cutillo, Illes, & Fowler-White, 1990; Gevins et al., 1977b; Matousek & Petersen, 1983; Wierwille & Ellsworth, 1994).

Associations between decreasing alertness and reduction in vigilance have been known to occur in the ongoing EEG (Lubin, Johnson, & Austin, 1969; Roth, 1961; Walter, Rhodes, & Adey, 1967). Others have also indicated that fluctuations in the spectral component and coherence of the ongoing EEG are sensitive indicators of momentary lapses in alertness as indicated by performance decrements in target detection, vigilance tasks (Makeig & Inlow, 1993). Some early EEG studies of drowsiness showed associated lapses in auditory detection with increased EEG amplitude in the theta range (Beatty, Greenberg, Deibler, & O'Hanlon, 1974; Davis, Davis, Loomis et al., 1938; Schacter, 1976). Levels of alertness have been classified according to appearance of theta waves as well as quantity of alpha bursts, characteristic of severe hypoalertness (Torsvall & Åkerstedt, 1987). Other authors have also shown the importance of the alpha rhythm in the EEG signal to describe lapses in alertness (Cabon & Al., 1993; Kecklund & Åkerstedt, 1993).

1.10.2 The electroencephalogram changes and aviation

Studies have shown that in-flight EEG's are sensitive to changes in workload and fatigue. Blanc, LaFontaine, & Medvedeff (1966) collected EEG data from commercial aviators using an airborne recording system and documented different levels of alpha activity during takeoff, flight and landing. Howitt, Hay, Shergold, & Ferres (1978) found workload related changes in the EEG recorded from a pilot flying instrument-referenced manoeuvres, and also showed that in-flight EEG's after sleep deprivation were not the same as those observed when the subject had slept well. This indicates that there is a change in EEG activity during fatigue and drowsiness.

1.10.3 The electroencephalogram changes and driver fatigue

Drivers cannot maintain a high level of consciousness when they are mentally fatigued and this may be reflected in the EEG. Research has suggested that EEG is associated with driver fatigue. A study of truck drivers reported cortical deactivation and increased sleepiness during the end hours of an all night driving shift (Kecklund & Åkerstedt, 1993). Ambulatory studies with non-professional drivers have also demonstrated cortical deactivation in response to continuous driving over monotonous and repetitive environments (Brookhius & De Waard, 1993; De Waard & Brookhius, 1991). Work done by Lemke (1982) showed that monitoring EEG signals in both 'on road' and simulator situations were a promising method for monitoring fatigue in drivers.

In a study of drivers subjected to monotonous tasks, mean EEG activity in the theta and alpha bands increased and higher theta activity accompanied performance impairment (Horváth, Frantik, Kopriva, & Meissner, 1976). Others have also reported increased delta and theta activity in drivers showing extremely degraded performance in vehicle operation (O'Hanlon & Kelley, 1977). These authors described the appearance of delta and theta as the end stages of arousal preceding sleep. Another study recorded the EEG of 11 train drivers and found that rated sleepiness increased sharply during the night journey (Torsvall & Åkerstedt, 1987). Alpha activity was shown to be the most sensitive to sleepiness with delta and theta activity increasing by a lesser extent. The same group of investigators compared day and night-time driving in nine professional drivers on a simulated truck driving task and found the EEG changes of sleepiness were higher during night driving (Gillberg et al., 1996). Furthermore, in a field study the same group of 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.

In another study of night driving, EEG was recorded from a parieto-occipital derivation with amplification close to the electrodes (O'Hanlon & Kelley, 1977). The results showed that unskilled drivers had increased power in the alpha band over the duration of the drive compared to skilled drivers. Sleep intruded while the drivers still had their eyes open, and was indicative in the EEG i.e. sleep was accompanied by theta waves, sleep spindles (frequency of 11-15 Hz, duration of >0.5 sec (Fisch, 1991b)) and k-complexes (a transient EEG pattern of sharp positive wave followed by a negative wave, duration of >0.5 s described by (Bankman, Sigillito, Wise, & Smith, 1992)). Interestingly, the drivers had not been aware that they had been driving the car while asleep. The researchers concluded that the alpha band was sensitive to changes in alertness while the theta and delta bands were necessary for distinguishing lower levels of arousal. Others recorded EEG from four subjects during night driving (Caille & Bassano, 1977). The EEG was recorded telemetrically via fronto-parietal and parieto-occipital derivations together with electro-oculogram (EOG). Towards the end of the driving, alpha bursts frequently appeared followed by theta and sometimes sigma waves.

Other studies obtained 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. Fruhstorfer, Langanke, Meinzer, Peter, & Pfaff (1977) also studied EEG derived from 3 subjects during night driving. The preliminary results showed a clear increase in alpha during monotonous segments, as well as occasional theta bursts. Blink duration increased and EOG velocity decreased in connection with the increase of alpha. Other research recorded EEG and EOG of 11 train drivers during a 4.5 hour night or day trip, always along the same route (Torsvall & Åkerstedt, 1983). During night driving alpha power increased significantly above daytime levels for the sleepy group. This group also exhibited higher night trip alpha power than the alert group. The results were very similar for theta power and the self-rated fatigue paralleled the EEG data. The authors concluded that night work causes increased sleepiness, and that the degree of sleepiness is reflected in the EEG spectral content mainly in the alpha and theta bands (Torsvall & Åkerstedt, 1983).

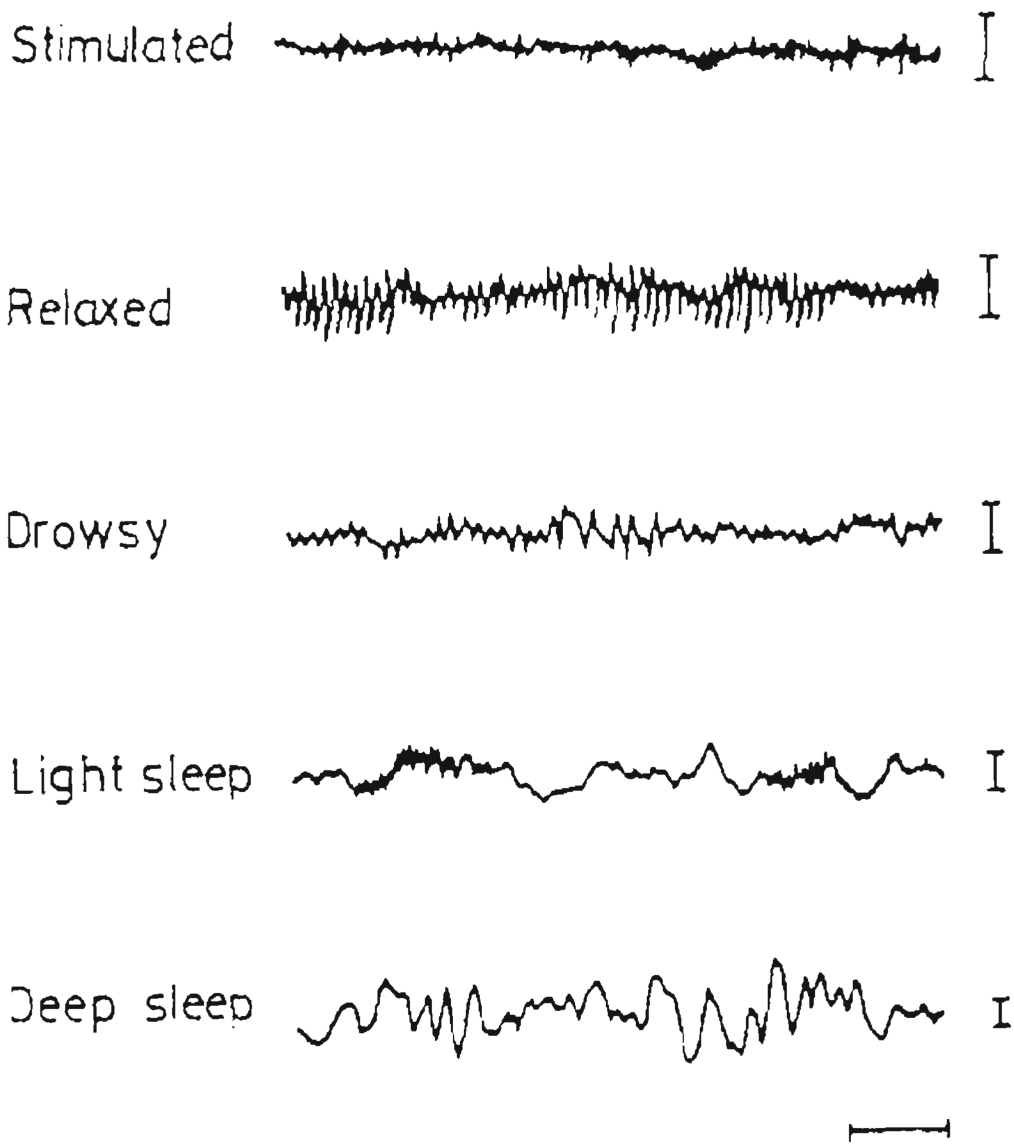
1.11 Specific Effects of Different Functional States of the Brain on the EEG Activity

Some specific changes of the brain-state during fatigue/drowsiness and its effects on the EEG activity in the delta, theta, alpha and beta bands will now be discussed briefly.

1.11.1 Effects of attention and drowsiness on EEG rhythms

The EEG is particularly suitable for standardised research in the laboratory. Figure 1.6 shows five records from electroencephalograms, each characteristic of a different functional state of the body (adapted from Grandjean, 1979). Variations in the trace in the sense of increasing synchronisation (increase of alpha and theta rhythms, reduction of beta waves) are interpreted as indicating states of weariness and sleepiness. As stated previously, studies which relate changes in the EEG with vigilance, have generally shown that deterioration in performance is associated with increased theta and changes in alpha intensity (Davies, 1965; Gale, Davies, & Smallbone, 1977; Morrel, 1966). Makeig and Jung (1995) also found EEG trends in alpha and theta waves related to reduced performance and fatigue. In another study over a night of continuous activity in ambulatory subjects, alpha and theta activity increased significantly across the night (Åkerstedt, Torsvall, & Gillberg, 1984). Ratings of sleepiness also correlated with alpha and theta power. Haslam (1982) also demonstrated an increase in alpha index in sleep-deprived soldiers. These changes perhaps reflect decreased cortical arousal which is likely to occur during long monotonous tasks requiring sustained attention. Furthermore, during drowsiness, there is a change in alpha distribution i.e. occipitoparietal alpha spreads to anterior areas and becomes more centrofrontal and temporal alpha (Santamaria & Chiappa, 1987b).

Figure 1.6 Five sections from electroencephalograms, characteristic of various functional states. The vertical lines indicate the scale for 1 mV (adapted from Grandjean, 1979).



EEG theta activity is found to occur in a variety of mental states including hypnagogic state 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. Others reviewed studies showing changes in the EEG with vigilance deteriorated performance and is associated with increased theta and changes in alpha intensity with others indicating that beta activity is also altered (Townsend & Johnson, 1979; Wierwille & Ellsworth, 1994). Similarly, the authors also found the most useful indicator of reduced vigilance was beta activity (14-21 Hz).

Drowsiness also has a profound effect on the alpha rhythm (Markand, 1990). With the onset of drowsiness, the alpha rhythm may attenuate or 'drop out' 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. Other changes in the distribution, amplitude and frequency of the alpha rhythm have also been emphasised (Santamaria & Chiappa, 1987b). There is an increase in the amplitude of the centrofrontal alpha (alpha wave activity spreading to the anterior regions) lasting 1-10 seconds, and often occurring concurrently with a decrease in the amplitude of the occipital alpha rhythm (Santamaria & Chiappa, 1987b). Another change during drowsiness is the appearance or persistence of mid- or posterior-temporal alpha, lasting several seconds after occipital alpha has already disappeared. Both centrofrontal and temporal alpha rhythms of drowsiness are usually 1-2 Hz slower than the occipital alpha (Markand, 1990).

It is interesting that there are few reports on changes in delta activity with drowsiness/fatigue, even though there is a strong emphasis in the literature that fatigue influences slow wave activities such as delta and theta (Santamaria & Chiappa, 1987b; Stein, 1995). One possible reason is the susceptibility of delta waves to artifacts. However, the current technology allows removal of noise and movement artifacts from EEG signals (Gevins et al., 1995; Gevins, Yeager, Zeitlin, Ancoli, & Dedon, 1977a) and changes in variables such as delta during fatigue can be reported with confidence.

1.12 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 provide appropriate warnings, or intervene directly (Brown, 1994). It is important to note that the detector of fatigue impairment must provide high detection capability with a low risk of false alarm and the device should not be a nuisance for the driver. In other words, the device should not be too large and uncomfortable to wear and should not hinder driving. Current opinion believes that driving (a task which does not need full conscious attention) most likely encourages lowered performance through boredom (under arousal) and tiredness (over arousal). The ability of the brain to operate without conscious input on tasks has been called dissociation (Birrell, 1990). Others have stated that "the experienced and expert driver is very easily seduced into thinking the he/she is competent when they are not.....all that is needed is a move further along the dissociative path." (Birrell, 1990, p.18).

Possible countermeasures include (a) preventing fatigue by maintaining alertness and (b) preventing fatigued drivers losing control of their vehicles by providing a physiological warning of their vigilance status. Fatigue monitors that have been developed include devices that sense eye closures. Feedback is provided (in the form of a buzzer) to the driver (Haworth, 1990) but this 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. Hence head nodding monitors based on sensing of loss of neck muscle tone may not be useful for road safety application. This area is discussed in more detail in Chapter 9.

1.12.1 Countermeasures using eye activity

Many car manufacturers are attempting to develop in-car monitors of driver sleepiness. Eye activity has attracted interest for monitoring driver sleepiness, especially with respect to developing in-car, remote devices. For example, eye blink rate has attracted much attention, as there is a general tendency for the rate to rise with increasing sleepiness (Stern et al., 1994). Problems exist with monitors detecting eye activity. For example, the extent of eye activity changes depends on the demand level of the task undertaken, there being a negative correlation between blink rate and task difficulty. Recently, Nissan reported a five-year plan to produce a device using video images on the driver's face, the purpose being to extract eye blink rate and blink duration to detect drowsiness (Time, 1995). The Nissan strategy employs a video camera and a powerful computer for imaging processing. However, its high costs coupled with the possibility that the motorist cannot wear sunglasses while using the system, disadvantage this system. Furthermore, the video frame rate of 50 to 75 per second would place a time resolution limit to between 13 to 20 ms at best, which may not be optimal to detect the fine eye movements. The advantage of the Nissan system is that no device is attached to the driver.

1.12.2 Countermeasures using neural networks

Research has also focussed upon a 'driving assisting system' comprising of different components based on the use of artificial neural networks (Onken & Feraric, 1997). For example, the current traffic situation is analysed by classifying it from the driver's viewpoint based on the environmental data. This information is used to predict the average behaviour of other vehicles in terms of driver behaviour. This methodology allows different aspects of the traffic to be monitored such as car following and lane keeping/overtaking. A model is then created for the driver's normal driving style.

The warning system then combines the output of the above two components in order to issue a danger warning/alert in the case of a dangerous deviation from normal driving behaviour. Warning signals are given through vibration signals on the steering wheel, steering wheel torque in the direction to be adapted by the driver and vibration through the cabin floor near the accelerator foot. These researchers (Onken & Feraric, 1997) present the positive aspects of this computer based behavioural driver model and do not discuss limitations such as the deviation in the 'normal' driving behaviour even when the driver is alert, which is inevitable in various driving situations. Drivers behave differently on different days, and the vibration may or may not be adequate to alert the driver in all situations. The reliability and the adequacy of this system is questionable.

1.12.3 Countermeasures using EEG

Horne and Reyner (1995a) believe the EEG measure can be useful in adaptive automated systems designed to predict and compensate for performance errors that tend to occur in fatigued individuals. Others also believe that the use of EEG could be useful for vigilance detection on the road (Khardi & Vallet, 1994). EEG has been used in fatigue monitors and is related to the driver's state of awareness, which is an advantage over indirect strategies of monitoring. Haworth, Triggs and Grey (1988) state in their report that: "EEG enables one to tell if the driver is...on the verge (of falling off to sleep) and has been shown to validly measure fatigue".

An automated drowsiness detector was developed almost 20 years ago by Gevins et al. (1977b). This detector classified EEG from four bipolar channels utilising decision heuristics based on increased ratios of both delta-band to alpha-band and theta-band to alpha-band spectra intensity as compared to thresholds automatically determined for each subject from a waking calibration period. In 1995, Gevins et al. reviewed advances in the engineering of EEG recording systems that are small and easy to use and suitable for a number of environments (Gevins, et al. 1995). The development of signal processing algorithms and progress in increasing the amount of information useful in derivation of neurophysiological indices of mental load and fatigue was also reviewed (Gevins, et al., 1995).

When driving for a long period of time or long distances on limited access highways, it is difficult for the driver to maintain attentiveness as the driving conditions become monotonous. It is thought that grouped alpha waves occur in the EEGs when brain activity decreases due to drowsiness (Idogawa, 1991). These authors suggest that a fatal accident can be predicted by observing an increase in the generation of grouped alpha waves. According to Idogawa (1991) drowsiness can be detected by noting the appearance of grouped alpha waves and informing the driver automatically with an electrical or sound stimulus. Fukuda et al. (1994) have described a system that automatically detects grouped alpha waves of EEGs using moving average methods. These researchers claim to utilise the decrease in arousal associated with the appearance of grouped alpha waves to detect driver sleepiness and prevent traffic accidents. However, the operation and evaluation of this device was not described.

A recent account by others claims that steering wheel reversals are a good indicator of sleepiness, with both the number and amplitude of these increasing with sleepiness (Khardi & Vallet, 1994). These investigators showed that the number of reversals correlated significantly with the amount of theta and alpha activity appearing in the EEG.

These studies do seem to provide convincing examples of the basic feasibility of using neurophysiological measures to create an automated system that monitors lapses in the alertness of human operators. However, the above authors do not mention any further progress in the development or evaluation of such a device.

1.12.4 Other types of countermeasure methods

Renault's *Départment Biomédical de l'Automobile* developed a test system for detecting lapses in alertness based on driving behaviour and used it to estimate the level of alertness as well as warn drivers of any lapse (Artaud, et al., 1994). From their studies, the transition between waking, hypoalertness and sleep were found to be associated with steering wheel movements. Further studies by the same group analysed the driver's breathing regularity as a predictor of deteriorated alertness. However, the researchers have not confirmed this device in a real life driving situation nor do they elaborate on the technical difficulties of the two methods. Others have developed a microcomputer-based drowsiness warning system, which also detects changes in driver's alertness through steering behaviour (Yabuta et al., 1985). Alertness was quantified according to brain activity and blinking. This system is based upon the assumption that the drowsy driver has unique steering patterns that are not seen during normal driving (Yabuta et al., 1985). The drowsiness warning device detects the corrective steering pattern that appears following non-steering and emits a warning to the driver. The system needs further development but has already been incorporated into the Nissan's Bluebird model. Even though a variety of countermeasures of fatigue have been developed, the effectiveness of these devices in preventing deterioration in driving performance is disappointing and none have been critically evaluated for their efficacy.

1.12.5 'Break periods' and practical countermeasures

Public health campaigns suggest that long distance drivers should take a break every two hours and exercise. However, there is no substantive evidence on the effectiveness of this method. 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. For example, these warnings are not sudden and may not gain the attention of the driver. Furthermore, Horne and Reyner (1995b) report from preliminary findings that a car radio in these circumstances does not improve deteriorating driving but may in fact distract sleepy drivers. This indicates that the continuous, monotonous environment may need to be changed by a sudden warning signal, preferably audible if the driver is going to 'alerted' out of the drowsy state. Another approach of alleviating sleepiness involves the driver taking pharmacological stimulants, caffeine being the most acceptable. Low doses of caffeine have been found to improve alertness in sleepy subjects (Griffiths, et al., 1990; Lorist, Snell, Kok, & Mulder, 1994; Lumley, Roehrs, Asker, Zorick, & Roth, 1987), but only marginally in alert subjects (Lorist, Snell, Kok, & Mulder, 1994). Again 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). Others have shown that caffeine and napping significantly reduced driving incidents, subjective sleepiness, and associated EEG activity indicative of drowsiness (Horne & Reyner, 1995b). However, encouraging the use of stimulants on a regular basis may also be detrimental to health. While taking a break from driving and exercising would be preferable to taking stimulants, it may not be always effective. For example, Horne and Reyner (1995a and 1995c) reported that doing light exercise makes subjects alert, but only for 10-15 minutes after cessation of exercise. Heavy exercise was shown to result in marked improvement in performance, but was too strenuous to be of any practical benefit. Furthermore it was thought that few drivers would complete such an exercise routine (Horne & Reyner, 1995a; Horne & Reyner, 1995c).

1.12.6 Criteria for effective countermeasures

According to Desmond and Matthews (1997), a fatigue countermeasure device should meet two criteria:

1) It must provide a valid indication of fatigue, rather than some type of performance impairment.
2) The stimulus delivered when the performance impairment is detected must assist in successfully restoring normal performance of the task that may have deteriorated due to fatigue.

For countermeasures that aim to restore alertness, the assumption made is that the driver can voluntarily increase attention efficiency when the warning signal is delivered. This can only be feasible if the fatigue countermeasure device does not cause a hindrance, which can increase task load. Matthews and Desmond (1995) have also noted that stress and fatigue can influence the use of in-car systems with potentially hazardous consequence. In a laboratory-based research, Fisher, Goodhall, & Wark, (1994) showed that information displayed in cars might divert attention away from the traffic environment. Since driving is primarily a visual-motor task, the implication is that in-vehicle countermeasures should make use of different input and output modalities. For example, the system could provide auditory information, in response to voice commands. Others demonstrated that discrete route guidance during simulated driving is better presented in auditory mode rather than visual (Parkes & Coleman, 1990).

It should be noted that detection of alertness or drowsiness with a device would need to take into account inter- and intra-individual differences as well as a broad range of driving situations (Matousek & Petersen, 1983). For instance, there is little research on the reproducibility of fatigue effects in individuals. It should also be recognised that short periods of drowsiness often remain undetected (Åkerstedt, 1988). The fact that vigilance fluctuates between wakefulness and sleep complicates the design of a drowsiness-monitoring device. Most researchers today agree that EEG and EOG monitoring is feasible for detection of drowsiness, the EEG being thought to be the most promising. However, differences in the signals can be small during wakefulness and drowsiness periods, allowing artifacts to mislead the analysis system. Additional difficulties for the analysis can be caused by the inter- and even intra-individual variance in the EEG patterns of drowsiness (Santamaria & Chiappa, 1987a), hence it is important to have sufficient sample power in such fatigue-based investigations. So far, the EEG of drowsiness has been quantified with frequency analysis, mostly spectral analysis by fast Fourier transform (Matousek & Petersen, 1983; Torsvall & Åkerstedt, 1988). However, not many previous studies have automatically detected the stages leading to drowsiness and this is an area that needs further research. Furthermore, a drowsiness detection system needs to fulfil certain requirements before it can be applied for detecting fatigue in real working conditions.

1.13 On the Methodology of Fatigue Studies

While a number of studies have been have been conducted on fatigue including driver fatigue, the results have been equivocal. Methodological limitations occur in most studies and include the following: (a) The variable use of referential and bipolar EEG montages, a problem previously discussed by Broughton and Hasan (1995). (b) The use of heterogeneous samples with clinical problems and EEG abnormalities (Janati, Kidawi, & Nowack, 1986). (c) 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 generalise results to the broader population. Furthermore, difficulties during analysis can be caused by the inter- and intra-individual variance in the EEG patterns of drowsiness. Hence, it is important to have sufficient sample power to ensure valid statistical outcomes. (d) Omitting to report the sample size. (e) Testing limited scalp sites, i.e. measuring fatigue from only one to three sites on the brain. Since not all brain regions exhibit the same changes, it is important to have electrodes which span most of the cerebral cortex (Wright, Badia, & Wauquier, 1995). (f) Only reporting activity in some EEG bands which may not be an adequate representation of the brain function deactivation that occurs in a fatigue state. In order to assist understanding in this area, refer to Tables 1.4 and 1.5 for details on previous fatigue studies undertaken. Table 1.4 highlights the methodology and limitations while Table 1.5 summarises the findings of the fatigue studies.

A further problem originating from these studies involves lack of true replications, resulting in different findings. The main EEG activity reported in the fatigue studies were increases in delta, theta and alpha (Lal & Craig, 2000b; Torsvall & Åkerstedt, 1988), theta wave persistence (Yamamoto & Matsuoka, 1990) and appearance of grouped alpha waves (Ninomija, Funada, Yazu, Ide, & Daimon, 1993). However, others found increases in delta, theta and beta activities (Kiroy, Warsawskaya, & Voynov, 1996) while others reported increases in only delta and theta (Makeig & Jung, 1996). This does not allow firm conclusions to be made about the changes in EEG associated with fatigue and therefore limits the use of EEG as a basis for a fatigue countermeasure. As a result it was believed a state of the art study was required to clarify the psychophysiological changes that occur during fatigue, with emphasis upon EEG effects. Such a study formed the basis of this doctoral research.

1.14 Aims

1.14.1 General Aim

The broad aim of this research was to investigate psychophysiological associations in the transition from alertness to fatigue/drowsiness in drivers during a simulated sensory motor driving task. A further purpose was to conduct the study in an experimentally controlled environment in randomly selected subjects, taking the methodological limitations of previous fatigue studies into account.

1.14.2 Specific Aims

The specific aims of this doctoral research are briefly summarised here and will be addressed in the following chapters accordingly:

Chapter 3: To assess the physiological changes associated with driver fatigue/drowsiness.

Chapter 4: To identify psychological associations with driver fatigue.

Chapter 5: To assess the potential of heart rate and heart rate variability as an indicator of driver fatigue.

Chapter 6: To compare physiological changes in professional versus non-professional drivers.

Chapter 7: To assess the reproducibility of the physiological changes during driver fatigue.

Chapter 8: To assess inter- and intra-hemispheric EEG coherence during driver fatigue.

Chapter 9: To utilise EEG activity observed during fatigue for the development of an EEG based fatigue countermeasure software and to test its reliability in detecting fatigue.

Chapter 10: To summarise and suggest directions for future research in the area of driver fatigue.

The chapter that follows will describe the general methodology used to assess the psychophysiology of driver fatigue.

Table 1.4 Summary of major published fatigue, drowsiness and related studies

Study/Event	Subject type	Study Condition	Measures	EEG position/analysis	Number, sex, age	Year/Reference
Anterior drowsy theta	patients	hospital	EEG	16 of 10/20 system	n=1300, - , <20	(Janati, Kidawi, & Nowack, 1986)
Sleepiness EEG	train drivers	train journey	EEG, EOG, ECG	O2-P4, delta, theta, alpha	n=11, -, 27-58	(Torsvall & Åkerstedt, 1987)
EEG & vigilance	-	booth, vigilance task	EEG, EOG, EMG	P3-O1 & P4-O2, DTAB	n=9, 4m/5f, 18-49	(Wierwille & Ellsworth, 1994)
EOG & EEG of sleep	employees	chair front of display	EEG, EOG, vigilance test	Cz-Oz	n= 10, 5m/5f, 25-50	(Torsvall & Åkerstedt, 1988)
VDT & EEG	office volunteers	-	EEG	16 of 10/20 system	n=5 &6, -, 18->58	(Yamamoto & Matsuoka, 1990)
Sleep simulated driving	patients/controls	monotonous driving	RT & road episodes	-	n=25, all m, 30-69	(Haraldsson et al., 1990)
Assess driver status	volunteers	alcohol/road vigilance	car moves, EEG, ECG	Pz-Oz /theta, alpha, beta	n=20, all m, 25-40	(De Waard & Brookhius, 1991)
Fatigue & visual tracking	-	chair front of screen	HR, HRV, RT, task	-	n=17, -, 19-40	(Mascord & Heath, 1992)
Fatigue and eye moves	-	visual target on CRT	critical flicker frequency	-	n=6, all m, 20.8± 1.2	(Saito, 1992)
ECG and sleep	students	driving test course	EEG, ECG, eye blink	C3-O1	-, all m, 20-22	(Ninomija et al., 1993)
Fatigue in solo and two crew	truck drivers	truck driving on road	endocrine, cardiac, performance	-	n=3 (1 solo, 2 crew)	(Hartley & Arnold, 1994)
Observer drowsiness rating	students	vehicle simulation lab	videotape of face, rating	-	-	(Belyavin & Wright, 1987)
Alertness lapse in driving	volunteers	Renault 25 vehicle	quests, EEG, EOG, video, resp.	O1-O2, F3-F3 of 10/20	n=21, 8m, 13f, 20-60	(Artaud, et al., 1994)
Database of work fatigue	offices	job	performance	-	n=3705 (10000 controls)	(Finkelman, 1994)
Drowsiness EEG	patients	sound attenuated labs	EEG, EOG, EMG	19 EEG, DTAB	n=19, -, -	(Broughton & Hasan, 1995)
Day/night driver	drivers	truck simulator	moves, rate, RT, EEG, EOG	C3-A2 and O2-P4	n=9, -, 28-55	(Gillberg et al., 1996)
Hemispheric coherence	students	sound proof, dark room	EEG (8 bands), EOG	F3-F4, C3-C4, 01-02, C3-01, C4-02	n=14, 7m/7f, 20-25	(Wada et al., 1996)
EEG & mental activity	healthy subjects	dimly lit chamber	psych, tasks, EEG	F3, F4, P3, P4, 01, 02, DTAB1&B2	n= 13, all m, 19-45	(Kiroy et al., 1996)
Auditory awareness	adult volunteers	-	EEG, EOG, alert index	Cz & Pz/Oz, D, T, gamma	n=15, -, -	(Makeig & Jung, 1996)
EOG of fatigue	pilots	flight simulator	quests, EOG, tasks	-	n=10, 9m/1f, 25-42	(Morris & Miller, 1996)
Fatigue & conditions	drivers/passengers	four wheel drive	EMG	-	n=4/4, all m, 18-42	(Moglia, et al., 1997)
Wake sleep transition	volunteers	sound proof room	EEG, EOG	12 EEG sites, alpha	n=6, 1m/5f, 19-35	(Hiroshige & Dorokhov, 1997)
Truck driver fatigue	truck drivers	different locations	record, interview, survey	-	n=1249, -, -	(Arnold et al., 1997)

Table 1.4 continued

Study/Event	Subject type	Study Condition	Measures	EEG position/analysis	Number, sex, age	Year/Reference
Simulated driving	hired	drive till cannot	fatigue/physical checklist	-	n=80, all m	(Nilsson, Nelson, & Carlson, 1997)
Fatigue & countermeasures	young drivers	driving simulator	fatigue, mood, attention, workload	-	n=80, 40m/40f, 18-30	(Desmond & Matthews, 1997)
Fatigue & driving	volunteer drivers	bus shifts	HR, BP, endocrine, self-report	-	n=10, all m, 31-54	(Raggat & Morrissey, 1997)
Fatigue & long flights	pilots	two-crew operation	quests, ECG, EEG, EOG	C4-A1, C3-A2, O2-A1	n=22, all m, 25-55	(Samel, et al., 1997)

Key to Table 1.4:

'-' means that information was not supplied in the publication

m-male; f-female

EEG: electroencephalography	BP: blood pressure
EOG: electro-oculogram	RT: reaction time
ECG: electrocardiogram	DTAB: delta, theta, alpha, beta
EMG: electromyogram	quests: questionnaires
HR: heart rate	psych: psychological
HRV: heart rate variability	resp: respiration

Table 1.5 Psychophysiological findings and relevant conclusions of the above studies

Findings	Reference
* There was a frontal-central burst of theta activity over both hemispheres in drowsiness.	(Janati, Kidawi, & Nowack, 1986)
* Rated sleepiness increases during night journey as well as spectral power in the alpha, theta and delta bands. EEG and EOG reflect sleepiness.	(Torsvall & Åkerstedt, 1987)
* The most powerful association was seen between worsening vigilance and beta activity.	(Wierwille & Ellsworth, 1994)
* Greatest power density was in alpha, theta & delta bands & most SEM before dozing. Prior ultimate sleepiness, delta & theta & alpha increased	(Torsvall & Åkerstedt, 1988)
* Work speed was associated with theta changes, a break should be considered when theta waves persist, before complaints of fatigue.	(Yamamoto & Matsuoka, 1990)
* The break reaction time and deviations from road-line increased in patients with sleep apnoea syndrome.	(Haraldsson, Carenfelt, Laurell, & Törnros, 1990)
* ECG and EEG changes reflected driving impairment.	(De Waard & Brookhius, 1991)
* HR, HR variability and RT were indicators of fatigue (or boredom) during a lengthy tracking task. HR decreased & HR variability increased.	(Mascord & Heath. 1992)
* No significant change found in eye movement during and /or after 5 hours of rapid eye tracking task.	(Saito, 1992)
* Grouped alpha waves appear in sleepy states of drivers and a system was developed; and ECG is used to improve the reliability of this system.	(Ninomija, Funada, Yazu, Ide, & Daimon, 1993)
* Solo drivers show greater changes in endocrine catecholamine, cardiac sinus arrhythmia and reaction performance than two-up crew & control.	(Hartley & Arnold, 1994)
* Videotape of driver's face can be rated for drowsiness and is reliable.	(Belyavin & Wright, 1987)
* The development of an on-board system for detecting lapses of alertness when driving requires validation in a real life driving condition.	(Artaud, et al., 1994)
* Low job challenge, poor supervision, low control, poor performance, low pay, low physical and processing demand leads to fatigue.	(Finkelman, 1994)
* Theta activity of drowsiness was maximum at Cz and Fz.	(Broughton & Hasan, 1995)
* Night driving is slower and more variability of speed and lane position. EEG/EOG sleepiness higher during the night.	(Gillberg, Kecklund, & Åkerstedt, 1996)
* Interhemispheric coherence was lower during light drowsiness than during wakefulness for 01-02 in the alpha-1 band and for F3-F4 in the beta-1 band. Intrahemispheric EEG coherence was significantly higher during light drowsiness for C4-02 in the theta-1 and beta-1 bands.	(Wada, Nanbu, Koshino, Shimada, & Hashimoto, 1996)
* Delta, theta and beta activities increased at the end of the prolonged mental activity, reflecting deterioration of general brain state activity.	(Kiroy, Warsawskaya, & Voynov, 1996)
* Delta and theta is higher at the sleep spindle frequency.	(Makeig & Jung, 1996)
* Flying performance decrements occur due to changes in fatigue.	(Morris & Miller, 1996)
* EMG fatigue of masseter muscles seems to be more related to psychic stress.	(Moglia, et al., 1997)

Table 1.5 continued

Findings	Reference
* Drowsiness was considered to be heterogeneous showing spatial changes in alpha activity.	(Hiroshige & Dorokhov, 1997)
* 20% of drivers had less than 6 hours of sleep, and 40% of dangerous events that occurred were reported by these drivers.	(Arnold, Hartley, Corry, Hochstadt, & Penna, 1997)
* No matter how long a subject drove, they still developed the same level of subjective fatigue.	(Nilsson, Nelson, & Carlson, 1997)
* Fatigue impairs adaptation to conditions of underload and task-specific fatigue effects have implications for in-vehicle fatigue countermeasures.	(Desmond & Matthews, 1997)
* Cardiovascular and catecholamine data elevated during a driving workday. Anxiety higher pre-shift. HR & arousal lower at end, onset of fatigue.	(Raggat & Morrissey, 1997)
* Motor activity, brainwave activity and heart rate indicated drowsiness and a low state of vigilance and alertness during night flights.	(Samel, et al., 1997)

Chapter Two

Procedures Involved in Psychophysiological Assessment of Driver Fatigue

2. Methods

The method reported in this chapter is that used for studies reported in this thesis. However, some details of methodology may vary between chapters and will be reported accordingly.

2.1 Justification of Psychophysiological Procedures Used

Conflicting results continue to be obtained from previous studies as most have poor experimental designs and insufficient subjects to achieve adequate statistical power (see Chapter 1). Controlled experimental designs have been lacking in most previous studies in the area of fatigue monitoring. Therefore, the variability in the results reported in the literature may well be due to the experimentally uncontrolled studies that have been conducted and a well-designed study is required to identify any definite EEG changes that may occur during fatigue.

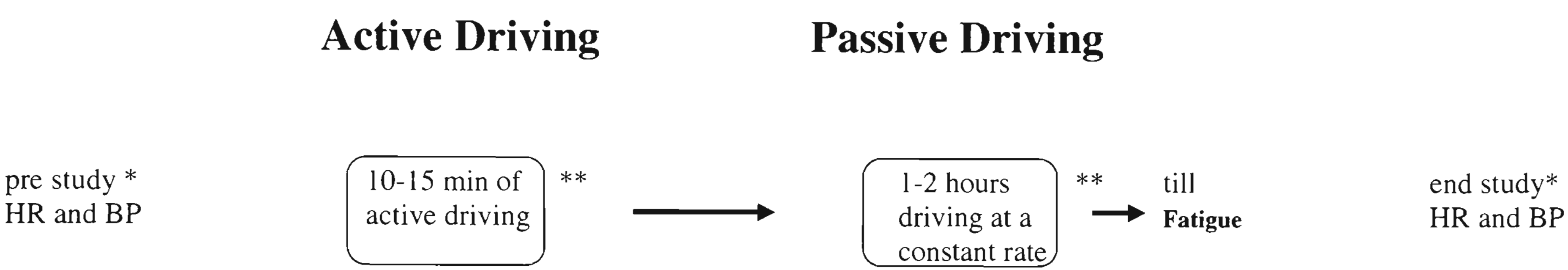
To overcome some of the above experimental limitations, in this doctoral research the experiments conducted were considered to be 'state of the art' study, to assess the psychophysiology of driver fatigue. This research aimed to produce results from a study design with sufficient statistical power in an experimentally controlled environment. Furthermore, this research attempted to identify psychophysiological indicators of fatigue using electroencephalography (EEG), electro-cardiogram (ECG), electro-oculogram (EOG), blood pressure (BP) and psychological predictors such as state and trait anxiety, mood, perceived control and self-reported physical and mental fatigue measures. A scientifically controlled driver simulator study was conducted in randomised samples with strict inclusion/exclusion criteria and adequate sample size based on appropriate power and statistical analysis. An appropriate validation criteria for fatigue was used whereby all subjects were video monitored to provide an objective indicator of fatigue. Electroencephalography measures included testing the entire surface of the brain surface using the 19-channel 10/20 montage EEG system (Jasper, 1958). The following sections will describe the procedures used in detail.

2.2 Experimental Procedure

2.2.1 Study protocol

The subjects were randomly selected into the study with every subject having an equal chance of being selected. Randomisation ensured homogeneity of the sample. All the volunteers that responded to advertisements on the study were batched and the random selection decided entry into the study proper. The study was conducted in a temperature-controlled laboratory (22-24° C) as the subjects performed a standardised sensory motor driver simulator task. Figure 2.1 shows the study protocol. The total study time, which included completing questionnaires, taking blood pressure, study preparation, electrode attachment and the experimental intervention, that is, the driving task took a total of 4-5 hours per subject. Caffeine, tea and food intake was restricted for four hours and alcohol for 24 hours before the study. Subjects were sleep deprived for approximately two hours the night before. They were verbally requested to sleep approximately two hours less than their normal routine. The study was conducted at approximately the same time of the day, which was close to noon (12 noon ± 1 hour). The driver simulator equipment consisted of a car frame with an in-built steering wheel, brakes, accelerator, gears and speedometer with a video display (Hyper Stimulator, Australia). This was supported by software for simulated driving (Grand prix 2, Micro Prose, UK). The subjects sat in a comfortable car seat in the car frame in front of the video display (Figure 2.2 shows the laboratory setting). They were given instructions on the operation of the driver simulator. All subjects were exposed to the same vehicle conditions and driving track. The driving task consisted of 5-10 min of active driving to familiarise the subject with the driving equipment and track (the screen display with presence of other cars in an alert driving situation is shown in Figure 2.3). This was followed by approximately two hours of driving at a restrained speed in a monotonous condition (< 80 kilometre/hour) until the subjects showed physical signs of fatigue (the lack of environmental stimuli during driving in a fatigue-based situation as displayed on the screen is represented in Figure 2.4). The physical signs that were noted on the video recording to indicate fatigue included changes in blink rate, head nodding, mannerisms etc. (see section 2.2.4 for detail). Experimentally controlling fatigue studies is difficult since a control group that is not subjected to the driving task would show some fatigue effects from doing nothing. Therefore such a study design would not serve as a true control group. In fatigue-based studies subjects act as their own controls, therefore a separate control group is generally not required. Data is assessed in alert and fatigue states in the same individuals, with the alert phase designated as the control baseline. Therefore in the current study, the active driving phase served as the control baseline (fatigue-free) to which the various stages of fatigue incurred from continuous monotonous driving was compared.

Figure 2.1 Fatigue Study Protocol



* Psychological questionnaires

- Mood
- State/Trait Anxiety
- Locus of control of behaviour
- Fatigue

* Life style questionnaire

** Physiological signals monitored

- EEG
- EOG
- ECG
- \- video recording of face

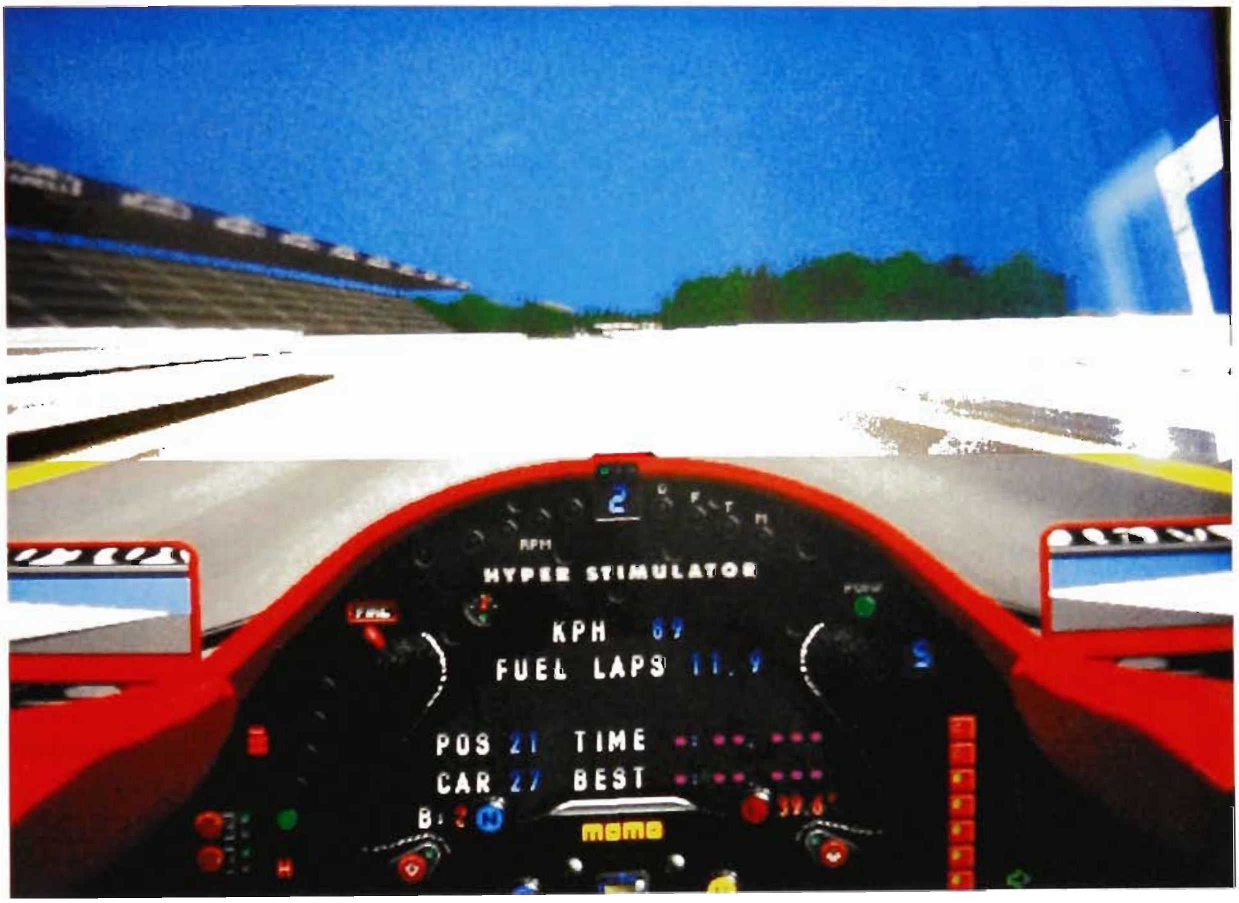
Figure 2.2 Shows fatigue laboratory with car simulator and other equipment

Note: The car simulator, the physiological monitor for recording the 19 channel EEG, EOG and ECG and video equipment are shown.

Figure 2.3 The screen as displayed to the subject during active and alert driving

Note: Shows environmental stimuli such as presence of other cars.

Figure 2.4 The screen as displayed to the subject during passive driving



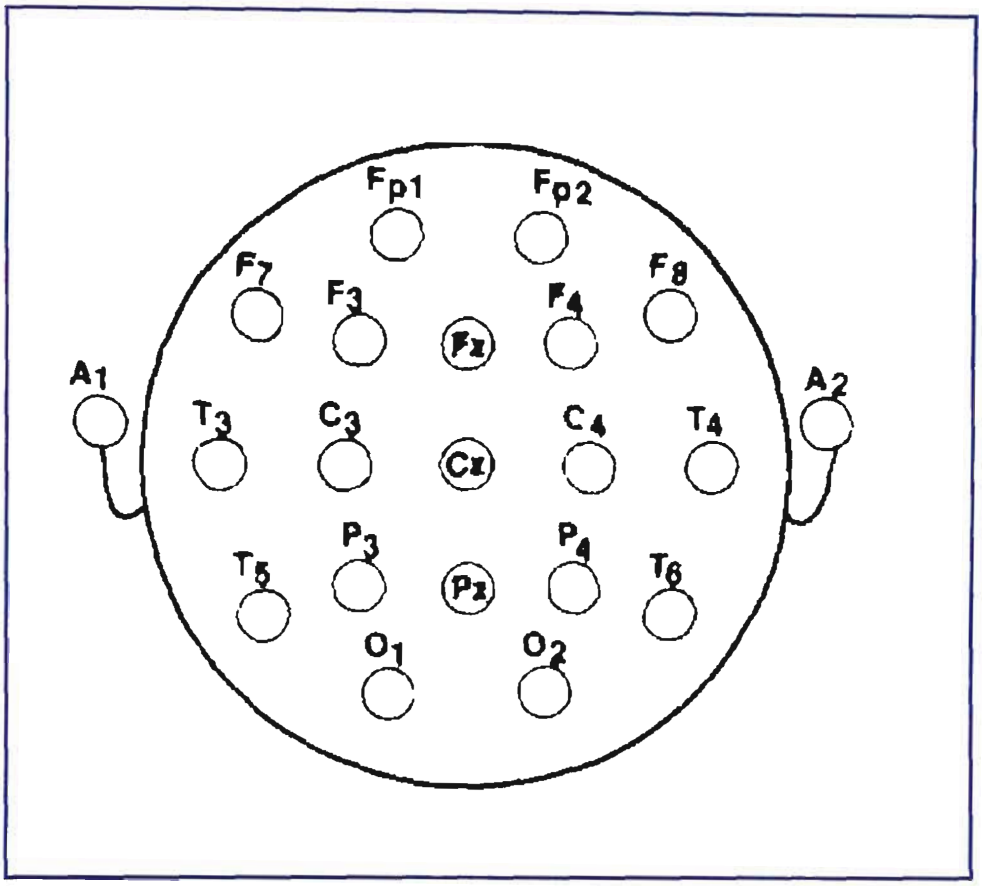
Note: Shows lack of environmental stimuli.

2.2.2 Physiological assessment

Simultaneous physiological measures were obtained during the driving task. These consisted of electroencephalography (EEG) and electro-oculogram (EOG) and three lead ECG. Nineteen channel EEG was recorded according to the International 10-20 system (Fisch, 1991b), which is commonly used in research and clinical recordings. The International 10-20 system of electrode placement provides a uniform coverage of the entire scalp. The use of this system assures symmetrical, reproducible electrode placements and allows a comparison of EEG activity from the same and different subjects. The standard set of electrodes for adults consists of 21 recording electrodes and one ground electrode. The electrode configuration according to the International 10-20 system is shown in Figure 2.5. In a typical adult head the electrode distance is 6 cm.

A monopolar or referential montage was used, that is, EEG activity in each active electrode was recorded in relation to an inactive reference site (electrodes placed on ear lobes). A cap incorporated with the nineteen electrode mounts was placed on the head (Electro-Cap System™, Electro-Cap International, Inc, USA) (see Figure 2.6). Each mount of the electrode was filled with electrode gel (Electro-Gel™, Electro-Cap International Inc, USA). The Electro- Gel™ is formulated for use with the Electro-Cap System™. A blunted needle and syringe was used to fill each mount with simultaneous rocking and rotation to lower the impedance. The impedance for each electrode was tested with an impedance meter (Checktrode® Electrode Tester, Model 1089, Lexicor Medical Technologies Inc, Neurosearch-24, USA) to ensure that conductivity was high and resistance was below 10 kOhms. This ensures that a reliable EEG signal was being acquired. The reference ear-clip electrodes were also covered with Electro- Gel™ before positioning on both ear lobes. Figures 2.7 a and b shows the materials used in this study for the preparation of the Electro-Cap System™.

Figure 2.5 The International 10-20 System of Electrode Configuration



Note: The recording electrodes are named with a letter and a subscript. The letter is an abbreviation of the brain region for example:

Fp= prefrontal

F= frontal

C= central,

T= Temporal,

P= Parietal,

O= Occipital

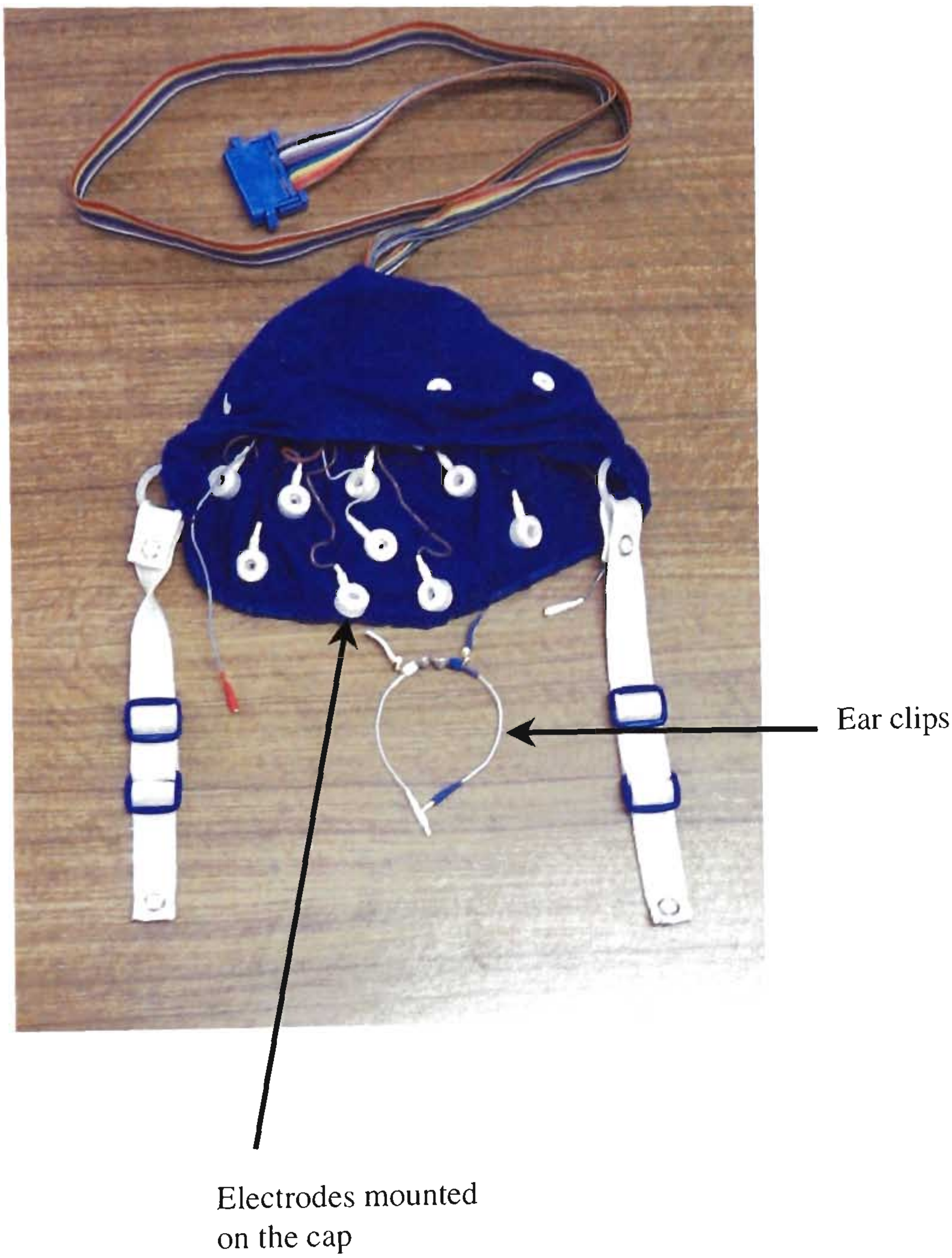
A= Auricular.

The subscript is either a letter z, indicating midline placement, or a number, indicating lateral placement. Odd numbers refer to electrodes on the left; even numbers refer to electrodes on the right side of the head.

Left eye EOG was obtained with disposable electrodes (Red dot, Ag/AgCl, Health Care, Germany, see Figure 2.8) positioned above and below the eye with a reference on the masseter bone. The EOG allowed the measure of eye movements. The EOG was used to measure changes in electrical potential that occur when the eyes move. The EOG also recorded eye blinks. The EOG and EEG data were linked in real time. The EOG signal was used to identify blink artifact in the EEG data as well as changes in blink types such as small and slow blink during fatigue.

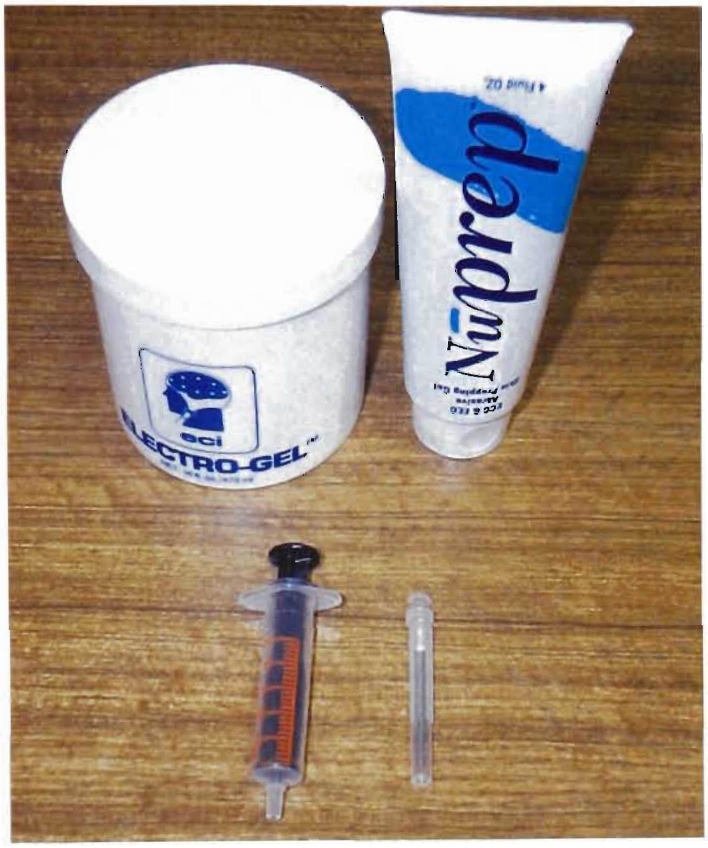
Three lead ECG was recorded via disposable electrodes (Red dot, Ag/AgCl, Health Care, Germany, see Figure 2.8) placed on the chest, one reference and two active electrodes. The ECG provides a measure of the electrical changes occurring during the hearts contraction. The ECG provided a measure of heart rate and autonomic nervous system activity during driver fatigue (refer to Chapter 5). All disposable electrodes were connected with electrode connection clips for recording (refer to Figure 2.8). Sterile techniques were used for all procedures involving the use of disposable electrodes and gel. All interventions were painless with minimum discomfort. Sitting brachial blood pressure (BP) was measured using a standard mercury sphygmomanometer, and pulsated heart rate (HR) was recorded before and after the driving session.

Figure 2.6 Shows the electrodes mounted on the Electro-Cap System™ and reference ear clips



Figures 2.7 a and b Shows the equipment and material used in the study with the Electro-Cap System™.

a) electrode gel, syringe and blunted needle



b) resistance meter and electrode tester

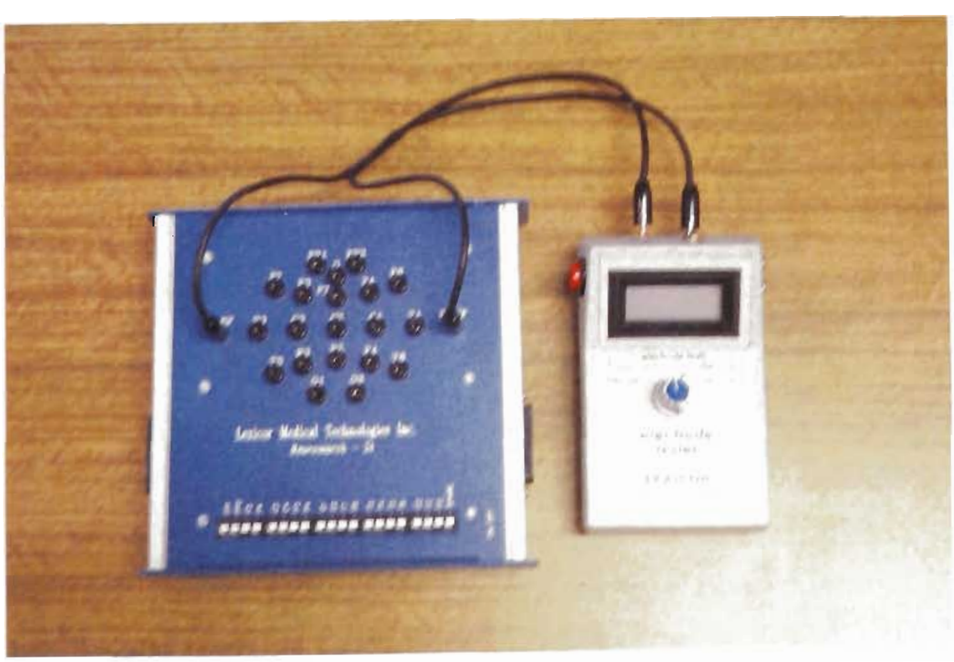
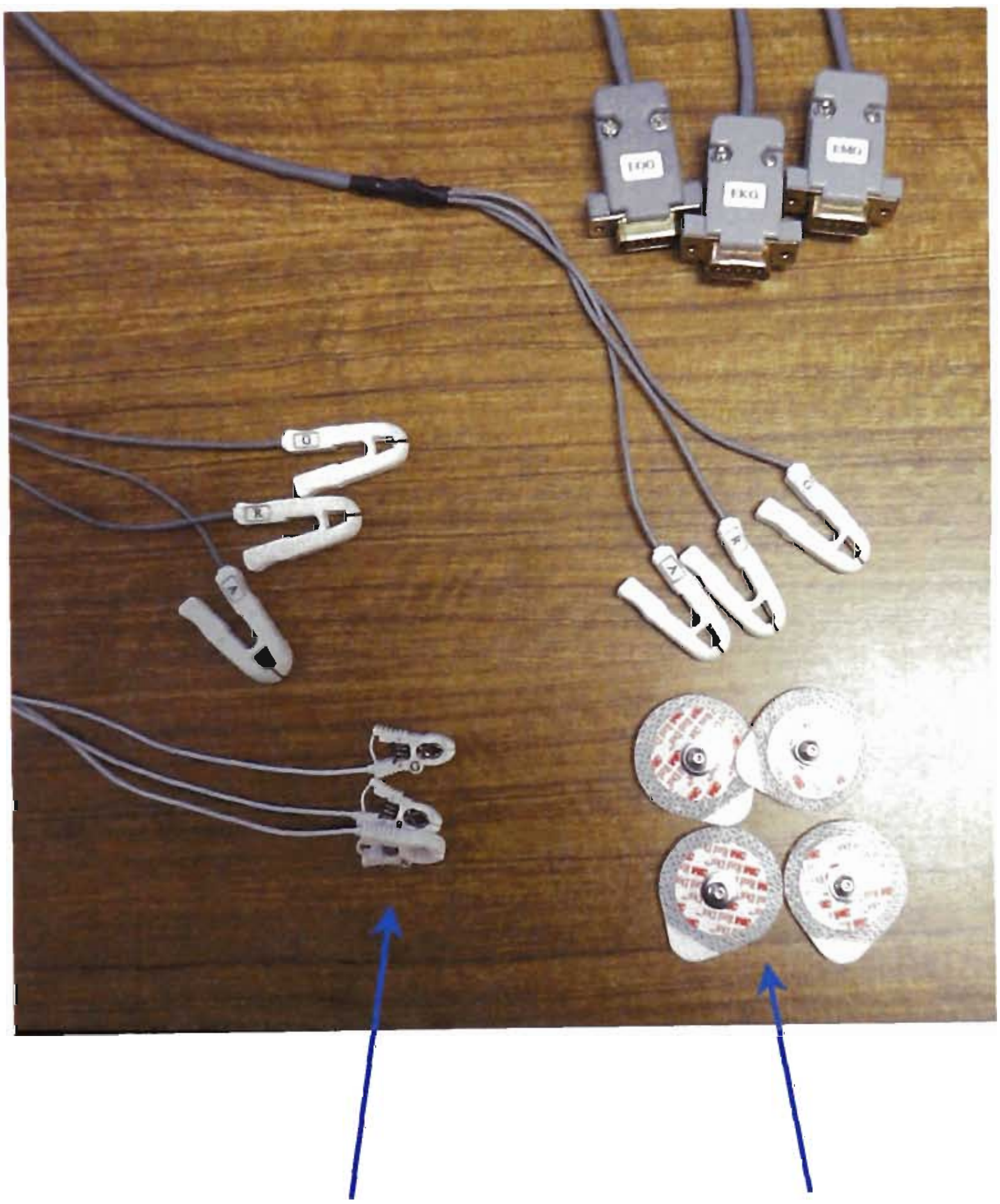


Figure 2.8 The Red dot electrodes and connections 'clips' used for EOG and ECG recordings.



2.2.3 *Validation of fatigue*

A video image of the driver was continuously recorded during the study. 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 validating drowsiness. Specific facial features characteristic of fatigue observed during the driving task included changes in facial tone, blink rate, eye activity and mannerisms such as nodding and yawning. The video image, which showed the physical signs of fatigue and the corresponding EOG changes (according to Santamaria & Chiappa, 1987a) were used to validate the EEG changes, associated with fatigue and drowsiness. Drowsiness has been assessed reliably and consistently based on the video image of a vehicle operator's face (Wierwille & Ellsworth, 1994). These investigators could estimate the level of driver drowsiness based on characteristics such as facial tone, slow eyelid closure and mannerisms such as rubbing, yawning and nodding etc.

2.2.4 *Reliability of the video identification of fatigue*

Two independent observers checked the reliability of identifying fatigue from the video recording. Both observers independently identified physical signs of fatigue from the same video recording. This was done in 10 randomly selected subjects. The identification of physical signs of fatigue from the video for inter- (r=0.88) and intra-observer variability (r=1.00) showed high reliability and agreement in the ten randomly chosen subjects. The corresponding EEG epochs were then selected by two observers to represent the physiological changes during fatigue. The choice of epochs in the ten subjects based on the video recordings and its interpretation for a fatigue state or blink artifact showed high 100% agreement between the two observers.

2.2.5 *Psychological assessment*

Anxiety, mood states and locus of control of behaviour were evaluated prior to the driving task. All questionnaires utilised have been shown to be valid and reliable. Trait (general) anxiety and State (current) anxiety were measured using the Spielberger State-Trait Anxiety Inventory (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983). The Profile of Mood States provided a measure of six mood states: tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia and confusion-bewilderment (McNair, Lorr, & Droppleman, 1971). Locus of control of behaviour (LCB), an outcome efficacy measure, provided a measure of the subject's perception of the relation between events and behaviour (Craig, Franklin, & Andrews, 1984). The State Anxiety Inventory was re-administered at the end of the driving study protocol. A questionnaire recording subjective aspects of fatigue states was modified from Wessely and Powell (1989) (Wessely & Powell, 1989) for this study (refer to Appendix 1). The present fatigue levels before and after the driving task was evaluated by a simple likert type scale created specifically for this research study referred to as the 'fatigue state question' (refer to Chapter 4). The following is a description of all the above psychological questionnaires.

2.2.5.1 The State-Trait Anxiety Inventory

The questionnaire consists of forms Y-1 (State Anxiety) and Y-2 (Trait Anxiety) (Spielberger et al., 1983). Anxiety states are characterised by subjective feelings of tension, apprehension, nervousness and by activation or arousal of the autonomic nervous system. Although personality states are often transitory, they can recur when evoked by appropriate stimuli; and they may endure over time when the evoking conditions persist. In contrast to the transitory nature of personality states, personality traits can be conceptualised as relatively enduring differences among people in specifiable tendencies to perceive the world in a certain way and in dispositions to react or behave in a specified manner with predictable regularity. Trait-anxiety refers to relatively stable individual differences in anxiety-proneness, that is, to differences between people in the tendency to perceive stressful situations as dangerous or threatening and to respond to such situations with elevations in the intensity of their state anxiety reactions. Stability measured by test-retest coefficients is relatively high for the Trait Anxiety scale and low for the State Anxiety scale, as would be expected for a measure assessing changes in anxiety resulting from situational stress (Spielberger et al., 1983). The internal consistency for both the State and Trait Anxiety scales are quite high as measured by alpha coefficients and correlation (Spielberger et al., 1983). The overall median alpha coefficients for the State and Trait Anxiety scales for Form Y in the normative samples are 0.92 and 0.90, respectively.

2.2.5.2 The Profile of Mood States (POMS)

There are six clearly defined POMS factors. Six independent factor analytic studies were conducted in the development and validation of the POMS (McNair et al., 1971). These studies indicated that the six mood factors could be identified, measured reliably and replicated in different samples of subjects. A Total Mood Disturbance score may be obtained from the POMS by summing the scores across all six factors.

Tension-Anxiety

Factor T is defined by adjective scales of heightened muculoskeletal tension. The defining scale includes reports of somatic tension, which may not be overtly observable, as well as observable psychomotor manifestations. Correlations of the scales with the factor are generally consistent across the six replications.

Depression-Dejection

Factor D appears to represent a mood of depression accompanied by a sense of personal inadequacy. It is best defined by feelings of personal worthlessness, futility regarding the struggle to adjust, a sense of emotional isolation from others and guilt. The factor is broadly defined and replicated in the six studies.

Anger-Hostility

Factor A represents a mood of anger and antipathy towards others. The principal defining scales that represent feelings of intense, overt anger have been repeatedly replicated and their factor correlations are consistent across the six studies. Other scales which describe milder feelings of hostility also have factor correlations that are relatively consistent across studies. The more sullen and suspicious components of hostility have been replicated in four or more studies.

Vigor-Activity

Factor V suggests a mood of vigorousness, ebullience and high energy. The factor has consistently appeared in all six studies. It is negatively related to the other POMS factors.

Fatigue-Inertia

Factor F represents a mood of weariness, inertia and low energy level. Its reliability and validity has been confirmed in the six studies.

Confusion-Bewilderment

Factor C appears to be characterised by bewilderment and muddle-headedness and has been confirmed in three studies. This factor may be possibly related to the classical organised-disorganised dimension of emotion. It may represent a self-report of cognitive efficiency, possibly a by-product of anxiety or related states.

2.2.5.3 The Locus of Control of Behaviour

This is an outcome efficacy measure. It provides a measure of the subject's perception of the relation between events and behaviour (Craig et al., 1984). The Locus of Control scale measures the extent to which a person perceives events as being a consequence of his or her own behaviour and therefore potentially under personal control. If a subject attributes the relation to luck then it is labelled as external control. Conversely, if the relationship is attributed to personal effort then the belief is labelled internal control. The Locus of Control of Behaviour scale has satisfactory internal reliability, is test-retest reliable and is independent of age, sex and social desirability (Craig et al., 1984).

2.2.5.4 The Fatigue State Questionnaire

This includes 13 items recording potentially different aspects of fatigue, arbitrarily divided into eight physical and five mental fatigue states (refer to Appendix 1, adapted from Wessely & Powell, 1989). Responses to each item were scored from 0 to 2 for each symptom, with '0' representing same as usual, '1' worse and '2' much worse than usual (Wessely & Powell, 1989).

2.2.5.5 The fatigue state likert question

A Likert scale 'question' was constructed specifically for this study to assess the present level of fatigue (refer to Chapter 4). This questionnaire was administered before and after the driving task.

2.3 Data Acquisition and Statistical analysis

2.3.1 Data acquisition

The EEG and EOG data was acquired using a multi channel physiological monitor (Neurosearch-24, Lexicor, USA). An individual EEG data point was classified as an epoch; a basic unit for stored EEG data. In the Neurosearch-24 data acquisition package, an epoch is defined as many channels each consisting of 256 EEG data points over time. The time for an epoch is proportional to the sampling rate at which the data was collected. Data was sampled at 256 Hz and the total sample time till the subject fatigued was individual dependent. The appearance of physical and physiological signs of fatigue also was different for each subject. Data was collected until the subjects were aroused from their fatigue states by a verbal interaction from the investigator.

2.3.2 Data management, conversion and analysis

Data was entered into various spreadsheets and statistical management software for analysis. Physiological data was managed using a statistical data management and analysis package called Statistica (Statistica for Windows, V 5.5, 1999, StatSoft, USA). The EEG data was converted from time domain data to frequency domain data with a fast Fourier transform using a spectral analysis package (Exporter, Lexicor, USA). The EEG was defined in terms of frequency bands including delta (0-4 Hz), theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) (Fisch, 1991b). For each band the average EEG magnitude (μV) and maximum amplitude (μV) were computed. Amplitude was defined as the maximum or peak spectral amplitude within a band's frequency range. Magnitude was the sum of all the amplitude in a band's frequency range. Drowsiness was classified according to Santamaria and Chiappa (1987a) into transitional (between awake and absence of alpha), transitional-post transitional (which has characteristics of both), post transitional (early Stage 1 of sleep) and arousal phases (emergence from drowsiness). For each of the above stages 10 epochs were averaged and the EEG data in each phase for the four frequency bands was compared to an alert baseline which was also an average of 10 epochs.

Psychological data was analysed using macros written in Epi Info (Version 5.00, Public Domain Software for Epidemiology and Disease Surveillance, World Health Organization, Switzerland, 1990). Refer to Appendix 2 for the macros written to score the psychological data. A questionnaire file ('.qes' file) was created for each of the psychological questionnaires administered before and after the driving task. Subjects entered their response to each questionnaire directly into the computer. Data was stored on the computer as a record file, ('.rec') ready for scoring. The psychological questionnaires were scored using the macros written in Epi-Info and compiled using a statistical analysis package, SPIDA (Statistical Package for Interactive Data Analysis, SPIDA V6.0, Macquarie University, Sydney, Australia).

2.3.3 *Statistical and sample power analysis*

Statistica was used for subsequent data analysis. A sample size calculation using the EEG parameter changes in all frequency bands provided a statistical power (1-β) of >0.9 based upon a moderate to large effect size of >0.9 (there was a large difference in the mean values between groups and a small standard deviation). The statistical power was therefore adequate for all comparisons performed. The differences between 'office' BP and HR measured before and after the driving task was compared using paired Student's *t* test. The fatigue phases were compared to an alert baseline using a repeated measures analysis of variance (ANOVA). A post hoc analysis using a Scheffé test was used to determine where the differences existed in the comparison of the means. The total score for each psychological measure was correlated to the EEG changes during the transition to fatigue using Pearson's correlation. Finally, standard multiple regression was used to identify which of the significant psychological variables contributed most to the EEG variability during fatigue. Since the psychological analysis in this study was exploratory, all significant results are reported. The significance level was set at $p<0.05$ for all analyses performed. The next chapter will discuss the physiological changes that occur during fatigue in non-professional drivers.

Chapter Three

Physiology of Fatigue and Drowsiness in Non-Professional Drivers

3 Fatigue effects in Non-Professional Drivers: electroencephalography and electro-oculogram effects

3.1 Introduction to the Physiology of Driver Fatigue

Fatigue has implications in road fatalities and is a major hazard in transportation systems. The early introduction to the subject by Grandjean (1979 and 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 of a range of cognitive and psychomotor tasks including driving (Williamson et al., 1996). It generally impairs human efficiency when individuals continue working after they have become aware of their fatigue state.

Driver fatigue is an issue that is receiving increasing attention in the road safety field. It is a serious problem in transportation systems and a direct or contributing cause of many accidents and is believed to account for 35-45% of all vehicle accidents (Idogawa, 1991). Drivers may experience fatigue from the length of the journey, monotonous driving situations and the time of the day (Horne & Reyner, 1995c), irregular work schedules (Åkerstedt, Kecklund, Gillberg, & Lowden, 2000) and demands to meet delivery schedules (Hartley & Arnold, 1994). Analysis of accident data suggest that driver-related fatigue is implicated in road accidents, particularly at night (Haworth et al., 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 also impairs 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).

Fatigue can lead to drowsiness and sleepiness. It has been suggested that sleepiness involves the physiological tendency to fall asleep and that it may be measured by the time it takes to go to sleep, assessed by the Multiple Sleep Latency Test (MSLT) (Carskadon & Dement, 1982). The latter refers to the occurrence of stage I of sleep in the electroencephalography (EEG). Recently, investigators have started using the term sleepiness and fatigue interchangeably (Dinges, 1995; Torsvall & Åkerstedt, 1987). The term 'sleepiness' and 'fatigue' are used synonymously to mean sleepiness resulting from the neurobiological processes regulating circadian rhythms and the drive to sleep (Dinges, 1995). This author states that 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 a physiological state associated with long working periods, reduced rest and being unable to sustain a certain level of task performance. Such a state would overlap extensively with sleepiness and its effect on performance and for communication purposes the terms are used interchangeably in this research. However, it should be noted that there are empirical (e.g. MSLT) and conceptual distinctions between the two.

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 and conflicting results continue to be obtained. Despite the literature being variable and numerous physiological indicators found to be linked to fatigue (Riemersma et al., 1977; Stern et al., 1994), the EEG signal may be one of the most predictive and reliable (Artaud, et al., 1994; Erwin & Al., 1973; Volow & Erwin, 1973). Drivers cannot maintain a high level of consciousness when they are mentally fatigued and this is indicative in the EEG, which is believed to show consistent and reliable changes during fatigue (Lal & Craig, 2000c). A study of truck drivers reported cortical deactivation and increased sleepiness during a night driving shift (Kecklund & Åkerstedt, 1993). Studies with non-professional drivers have also demonstrated cortical deactivation in response to continuous driving (Brookhius & De Waard, 1993; De Waard & Brookhius, 1991). Lemke (1982) showed that monitoring the EEG signal in both 'on road' and simulator situations were a promising method for monitoring fatigue in drivers'. Furthermore, researchers have found changes in EEG delta, theta, alpha, beta and sigma waves during continuous driving (Caille & Bassano, 1977; Lal & Craig, 2000c; Torsvall & Åkerstedt, 1983; Torsvall & Åkerstedt, 1987).

The aim of this study was to examine the physiological changes during the transition from alert to drowsiness due to fatigue in a driver simulator task in non-professional drivers. The research also aimed to establish the EEG band most sensitive to drowsiness. The hypotheses generated for this study were:

1) During transition from an alert to a fatigue/drowsy state there will be significant changes in brain wave activity such as increases in slow wave activity, that is, delta and theta.
2) During fatigue different regions of the brain will show varying amounts of EEG activity. For example the frontal and temporal lobes which are involved with 'biological intelligence' or the ability to plan, perceiving, make decisions and solve problems (Andreassi, 2000b) should show greater response to a fatigue state.
3) Slow wave EEG activity will persist into deeper fatigue states.
4) During fatigue there will be physical changes such as rubbing, nodding, yawning etc.

3.2 Methods

3.2.1 Subjects

Thirty-five subjects (9 females and 26 males) who were current non-professional drivers, aged 21-52 (34 ± 9.6) years, were recruited from a large tertiary institution and the local community and randomly assigned to the study (refer to chapter 2 for details on randomisation). Subjects responded to email broadcast and newsletter and advertisement on the research. Thirty-five subjects were required to complete the study. Subjects were randomly selected for the study from a total of eighty that responded to the advertisement. After the randomisation, sex was not evenly distributed. All subjects gave written consent for the study, which was approved by the institutional ethics committee. To qualify for the study subjects had to have no contraindications such as severe concomitant disease, alcoholism, drug abuse and psychological or intellectual problems likely to limit compliance. This was identified using a 'Life Style' questionnaire, which also provided the demographic details of the subjects.

3.2.2 Study protocol

The study was conducted in a temperature-controlled laboratory as the subjects performed a standardised sensory motor driver simulator task. Caffeine, tea and food intake was restricted for four hours and alcohol for 24 hours before the study. Subjects were instructed to sleep at least two hours the night before, so were sleep deprived before the experiment. The study was conducted at approximately the same time of the day, which was close to noon. 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 driving task consisted of 5-10 minutes of active driving to familiarise the subject, followed by approximately two hours of driving (speed < 80 km/hr) till the subjects showed physical signs of fatigue.

Simultaneous physiological measures were obtained during the driving task. These consisted of electroencephalography (EEG) and electro-oculogram (EOG). Nineteen channel EEG was recorded according to the International 10-20 system (Fisch, 1991b), which is commonly used in research and clinical recordings. A monopolar montage was used i.e. EEG activity was recorded in relation to an inactive reference site (electrodes placed on ear lobes). Left eye EOG was obtained with electrodes (Red dot, Ag/AgCl, Health Care, Germany) positioned above and below the eye with a reference on the masseter bone. The EOG and EEG data were linked in time. The EOG signal was used to identify blink artifact in the EEG data as well as changes in blink types such as small and slow blink during fatigue. Sitting brachial blood pressure (BP) was measured using a standard mercury sphygmomanometer, and heart rate (HR) was recorded before and after the driving session.

Physical signs of fatigue were identified using a video image of the driver's face, linked in real time with the physiological measures. The video analysis served as an independent validator of drowsiness assessment. Specific facial features characteristic of fatigue observed during the driving task included changes in facial tone, blink rate, eye activity and mannerisms such as nodding and yawning. The video image, which showed the physical signs of fatigue and the corresponding EOG changes such as changes in eye movement and blink rate (according to (Santamaria & Chiappa, 1987a)) were used to validate the EEG changes, associated with fatigue. The identification of physical signs of fatigue from the video had a high reliability for inter-observer (r=0.88) and intra-observer (r=1.00) variability (between 2 observers) (refer to Chapter 2, section 2.2.4).

3.2.3 Data acquisition and analysis

The data acquisition and analysis is briefly described. Complete details can be found in Chapter 2. The EEG and EOG data were acquired using a 24 channel physiological monitor (Neurosearch-24, Lexicor, America). An individual EEG data point was classified as an epoch; a basic unit for stored EEG data. Data was sampled at 256 Hz and the total sample time was individual dependent, till arousal from fatigue by a verbal interaction from the investigator. A fast Fourier transform was performed on the EEG data using a spectral analysis package (Exporter, Lexicor, USA). The EEG was defined in terms of frequency bands including delta (0-4 Hz), theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) (Fisch, 1991b). For each band the average EEG magnitude (μV) and maximum amplitude (μV) over all 19 channels were computed. Amplitude was defined as the maximum or peak spectral amplitude within a band's frequency range. Magnitude was the sum of all the amplitude in a band's frequency range. The EEG of drowsiness/fatigue was classified into transitional (between awake and absence of alpha), transitional-post transitional (which has characteristics of both), post transitional (early Stage 1 of sleep) and arousal phases (emergence from drowsiness) (Santamaria & Chiappa, 1987a). These EEG fatigue phases were then compared for these phases to an alert baseline.

3.2.4 Statistical analysis

Statistical analysis package Statistica (for Windows, V 5.5, 1999, StatSoft, USA) was used for data analysis. A sample size calculation using the EEG parameter changes in all frequency bands provided a statistical power (1-β) of >0.9 based upon an effect size of >0.9. The statistical power was therefore adequate for all comparisons performed. The differences between 'office' BP and HR measured before and after the driving task were compared using paired Student's *t* test. The average EEG changes in the fatigue phases determined by video analysis of facial expressions were compared to an alert baseline using a repeated measures analysis of variance (ANOVA). A post hoc analysis using the Scheffé test was then used to determine where the differences existed in the comparison of the means. A repeated measures ANOVA was also used to compare the maximum activity in one section of the brain to all the other sections. Scheffé test then identified which section of the brain was significantly different to the section showing maximum activity. The significance level was set at $p<0.05$ for all analyses performed. Results are reported as mean and standard deviation of differences.

3.3 Results

A total of forty-seven subjects were assessed in the study. Data from thirteen subjects were not included in the analysis due to technical problems (in ten) and subjects who did not show any physical signs of fatigue (in three). The subject demographics are summarised in Table 3.1. The following data and results are reported from a total of 35 subjects who were required to complete this study. The subjects had an average pre-study BP of 119 ± 13/74 9 mm Hg (systolic/diastolic). The BP after the study did not change significantly from baseline (pre study BP: 119 ± 13/74 ± 9 and post study BP: 117 ± 10/75 ± 9 mm Hg). Heart rate was significantly different ($t=5.9$, $df=34$, $p<0.01$) from before (68 ± 11 beats/min) to after the driving task (62 ± 10 beats/min). The average time to the transition to fatigue identified from the EEG and video analysis was 26 ± 3 minutes. Table 3.2 shows the amplitude and magnitude of EEG in delta, theta, alpha and beta bands for the five phases tested.

Table 3.1 Shows the demographics of the subjects in the study (n=35 non-professional drivers)

Variable	Mean ± SD	Minimum	Maximum
Age	34 ± 9.6	21	52
Weight (kg)	75 ± 14.5	49	117
Height (cm)	174 ± 6.6	161	187.5
Head circumference (cm)	57 ± 4.0	3.8.5	62
Handedness	32 right handed	3 left handed	
Gender	9 females	26 males	

Table 3.2 The average EEG activity (over all 19 channels) during the alert baseline, transitional phase to fatigue, transitional-post transitional, post transitional and the arousal phase in non-professional drivers (n=35)

EEG Band	Alert	Transition to Fatigue	Transitional-post transitional	Post-Transitional	Arousal
Amplitude (μV)					
Delta	8.5 ± 1.91	10.2 ± 2.75**	10.8 ± 2.20**	13.9 ± 2.53**	10.4 ± 2.56
Theta	2.8 ± 0.71	3.5 ± 1.02**	3.1 ± 0.83**	3.5 ± 1.00**	2.9 ± 0.78
Alpha	2.2 ± 0.19	2.4 ± 0.26**	2.4 ± 0.19**	2.5 ± 0.25**	2.3 ± 0.19**
Beta	1.6 ± 0.08	1.7 ± 0.10	1.8 ± 0.10**	1.8 ± 0.09**	1.6 ± 0.09
Magnitude (μV)					
Delta	24.8 ± 6.13	30.3 ± 9.27**	30.3 ± 7.18**	37.5 ± 8.69**	30.1 ± 8.61**
Theta	8.8 ± 2.20	11.1 ± 3.07**	9.7 ± 2.43**	11.1 ± 2.80**	9.2 ± 2.54*
Alpha	8.3 ± 0.71	9.0 ± 0.86**	8.9 ± 0.68**	9.5 ± 0.81**	8.7 ± 0.72**
Beta	8.0 ± 0.36	8.4 ± 0.52**	9.0 ± 0.40**	8.6 ± 0.39**	8.0 ± 0.41

Note

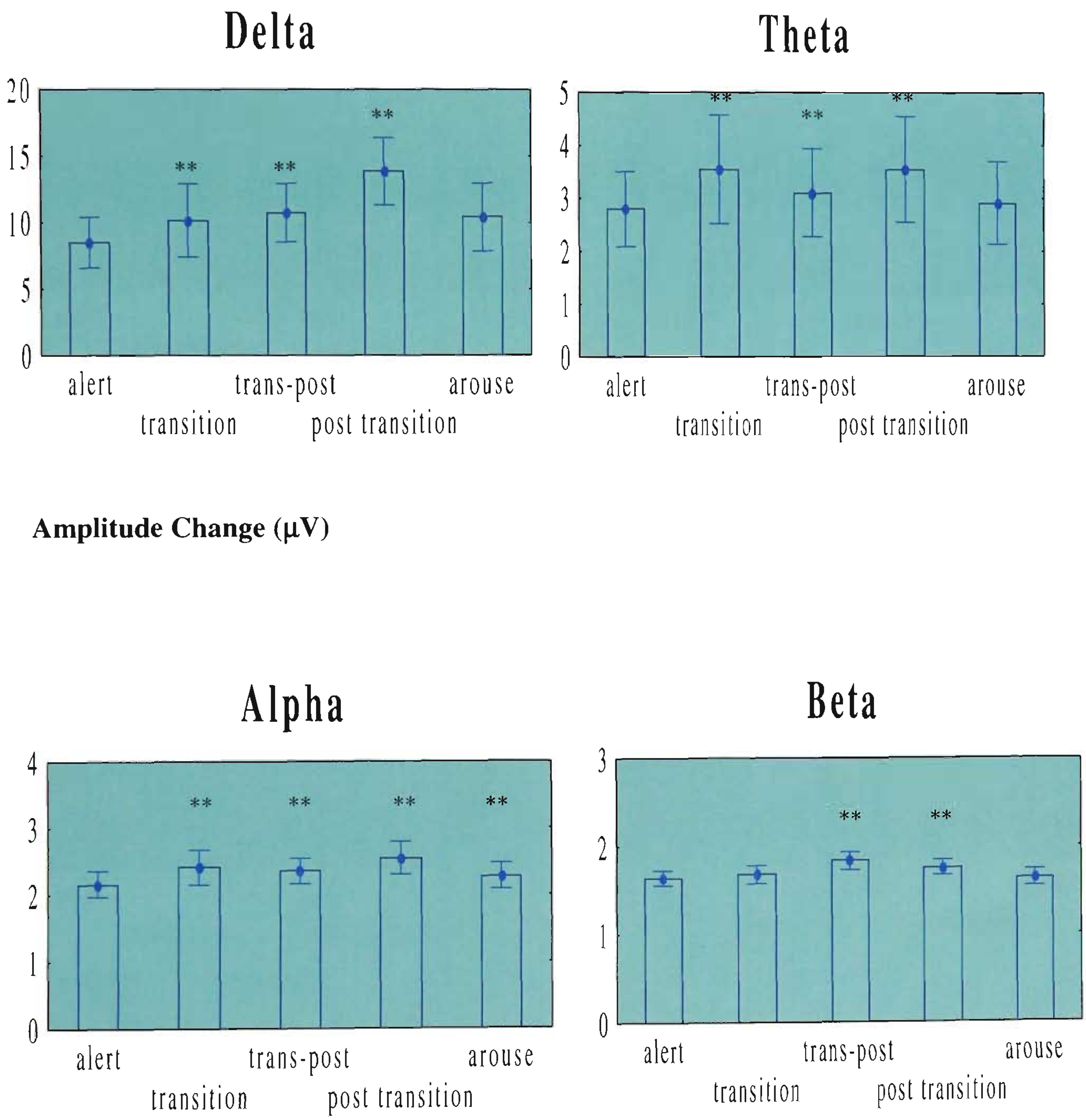
The results are reported as mean ± sd

* $p < 0.05$ ** $p<0.01$

The ANOVA analyses on the amplitude and magnitude data revealed overall differences between the five phases tested (alert baseline, transitional phase, transitional-post transitional, post transitional and an arousal phase). The effects for amplitude were: delta ($F=238$, $df=4, 72$, $p<0.0001$), theta ($F=103$, $df=4,72$, $p<0.0001$), alpha ($F=95$, $df=4,72$, $p<0.0001$) and beta ($F=62$, $df=4,72$, $p<0.0001$). Magnitude results were: delta ($F=157$, $df=4,72$, $p<0.0001$), theta ($F=142$, $df=4,72$, $p<0.0001$), alpha ($F=85$, $df=4,72$, $p<0.0001$), beta ($F=77$, $df=4,72$, $p<0.0001$). Figures 3.1 and 3.2 show the mean EEG amplitude and magnitude for the five phases tested.

In the post hoc analyses all the phases were compared to the alert baseline for the magnitude and amplitude data. The analyses identified that EEG magnitude and amplitude during the transitional phase, transition-post transitional and post-transitional phases were significantly different to the alert baseline ($p<0.01$) except for beta amplitude during transition to fatigue, which was not significantly different to the alert phase. An example of the change in EEG activity from baseline to the transition to fatigue state is shown in Figures 3.3 and 3.4 respectively. An increase in amplitude and appearance of slow wave activity is noticed in most channels during transition to fatigue in Figure 3.4. The raw EEG display in Figures 3.3 and 3.4 shows waveforms in all nineteen channels designated on the left scale by its corresponding International 10-20 montage. The amplitude in microvolts (y-axis) scale is displayed in the upper right corner.

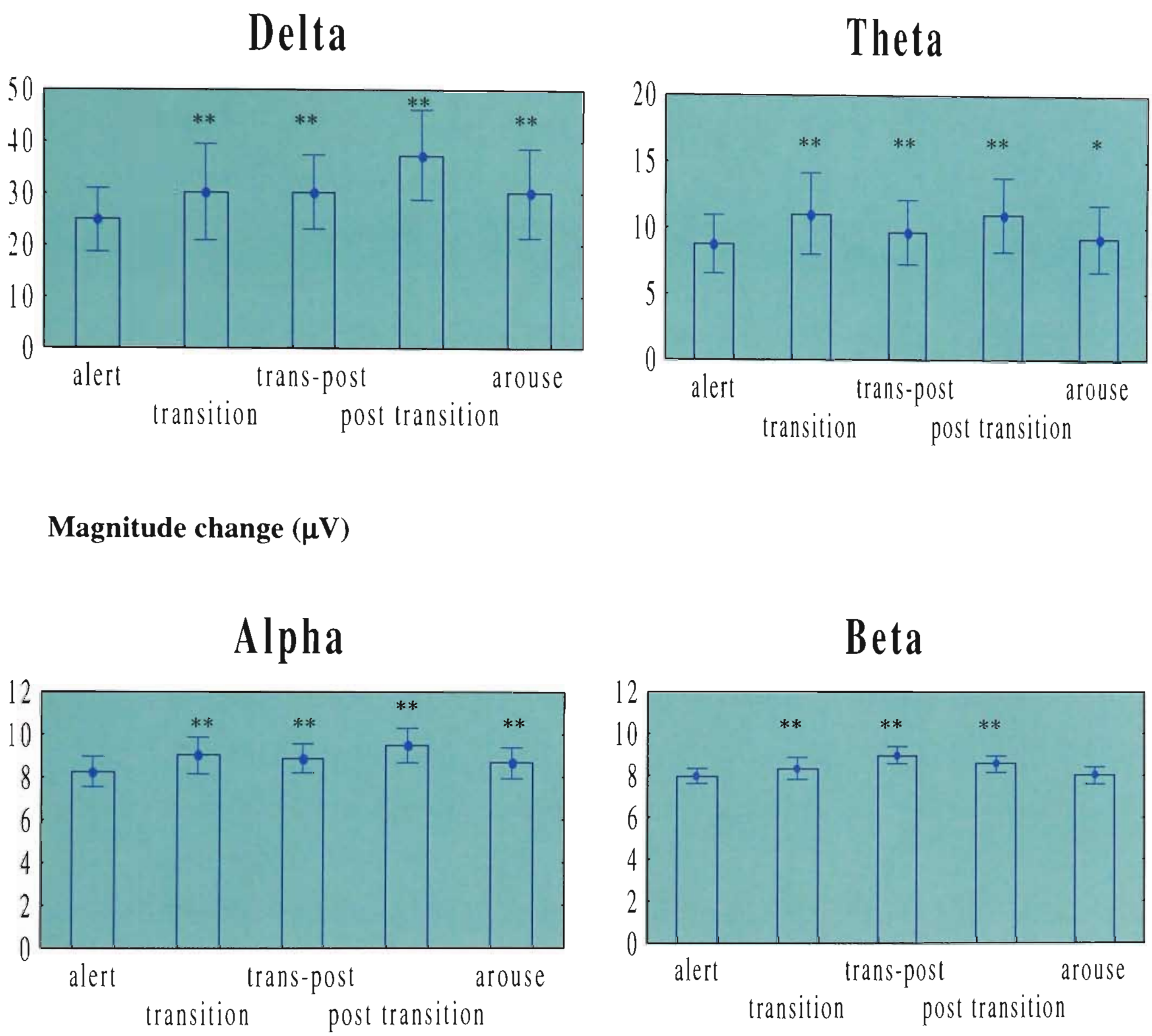
Figure 3.1 The EEG amplitude response during driver fatigue over all 19 channels



* $p<0.05$ ** $p<0.01$

Note: Error bars (standard deviation) are shown.

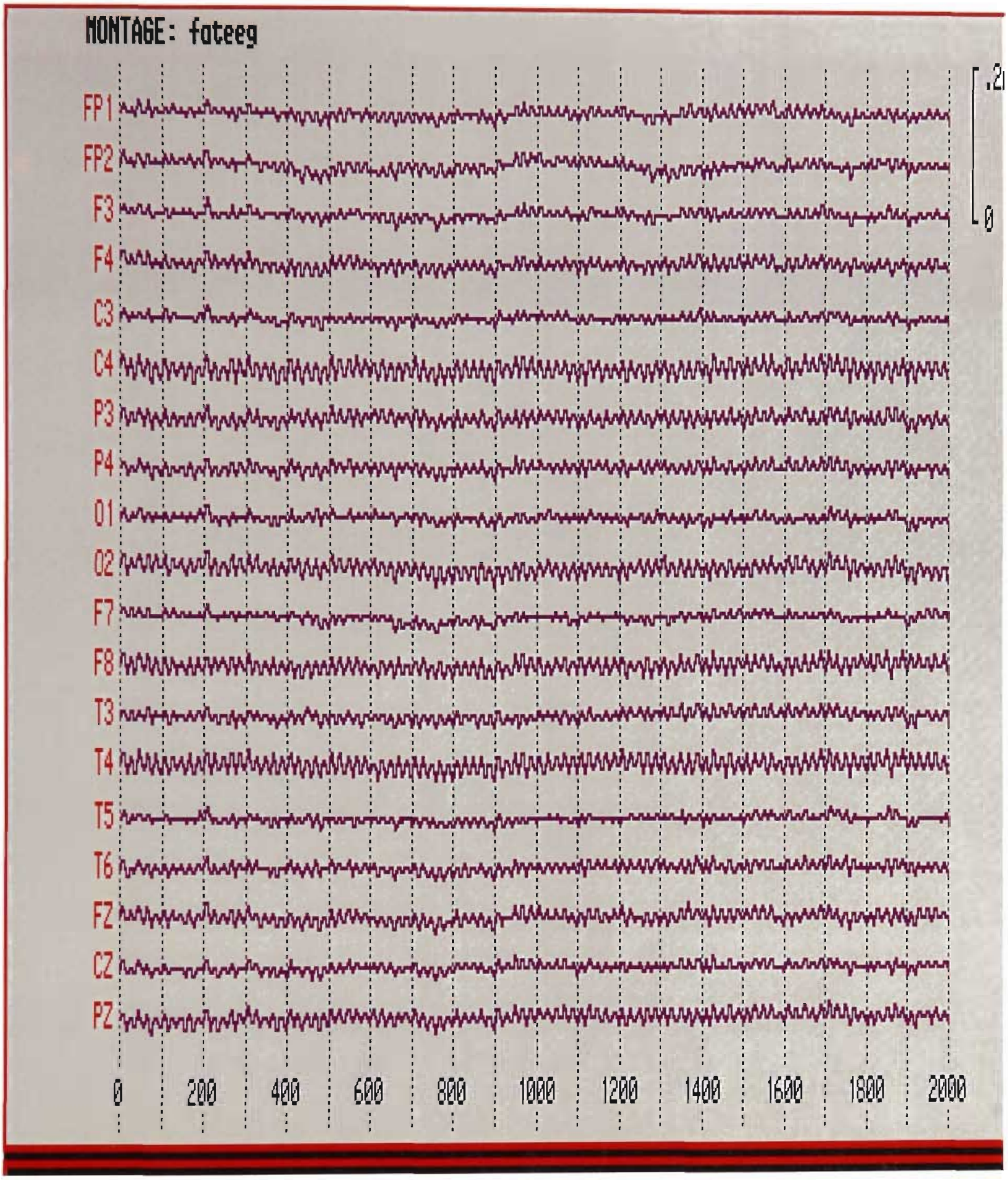
Figure 3.2 The EEG magnitude response during driver fatigue over all 19 channels



* $p<0.05$ ** $p<0.01$

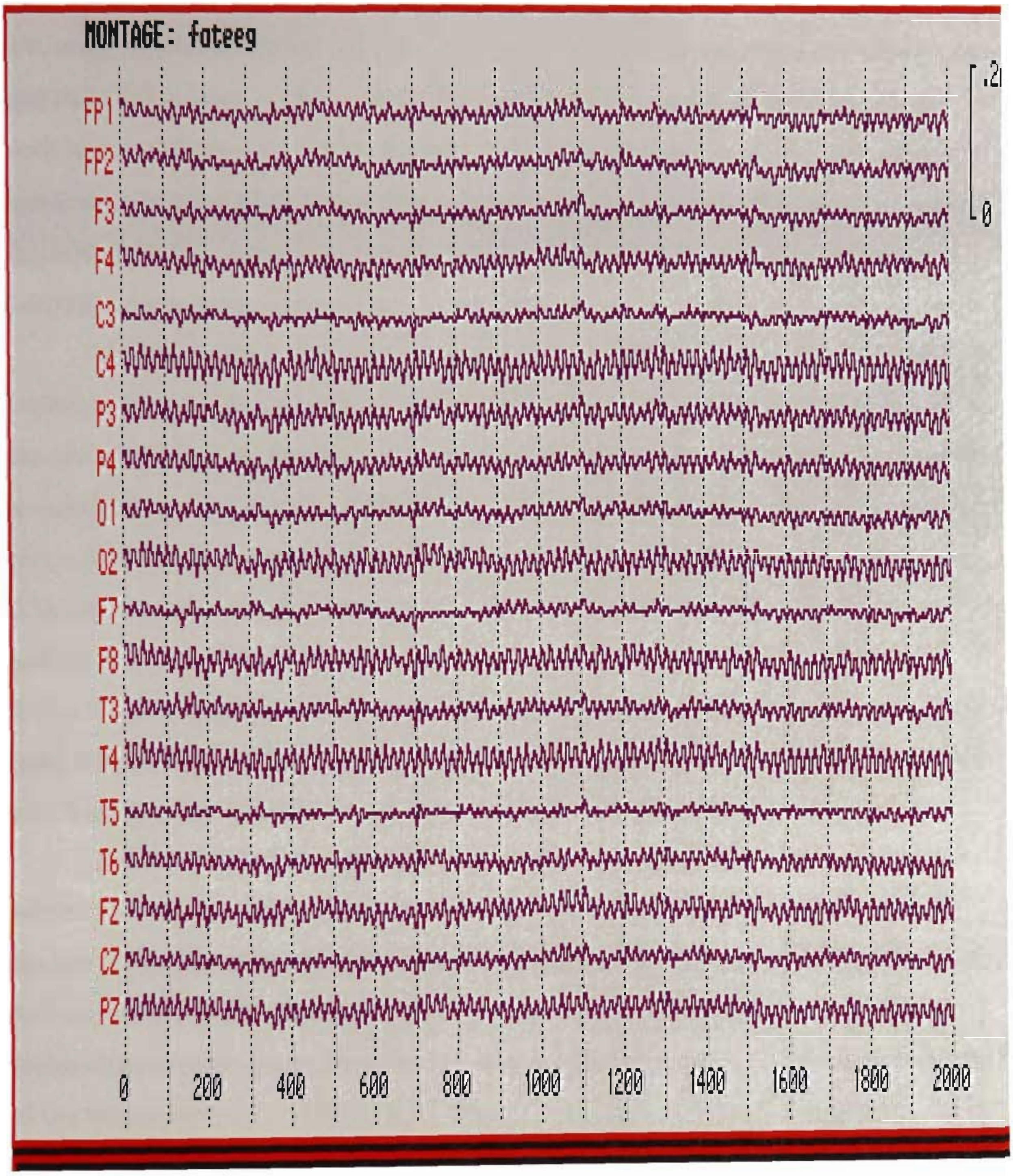
Note: Error bars (standard deviation) are shown.

Figure 3.3 Shows the EEG activity during the alert phase in all 19 channels



Note: EEG channels are represented on the left y-scale. Amplitude (µV) is displayed in the upper right corner.

Figure 3.4 Shows the EEG activity during the transition to fatigue phase in all 19 channels



Note: EEG channels are represented on the left y-scale. Amplitude (μV) is displayed in the upper right corner.

To derive the changes in EEG activity during the different phases of fatigue the data was subtracted from the alert baseline and summarised in Table 3.3. During the initial phase of transition to fatigue, the largest change in amplitude, compared to the alert baseline, was found in the delta and theta bands (1.68 ± 3.35 μV and 0.75 ± 1.24 μV, respectively; p<0.0001 for both). Similarly, the change in magnitude for the delta and theta bands were 5.45 ± 11.11 μV and 2.31 ± 3.78 μV, respectively; p<0.0001 for both (refer to Table 3.3). Comparatively, the amplitude changes in the alpha and beta bands were smaller (0.25 ± 0.32 μV, p<0.0001 and 0.03 ± 0.13 μV, not significant, respectively). The magnitude changes were 0.75 ± 1.12 μV and 0.37 ± 0.63 μV, p<0.0001 for both respectively.

Table 3.3 shows that the increased delta and theta levels persisted or increased further as fatigue progressed and maximum increase was observed during the post transitional phase (amplitude: 5.36 ± 3.17 μV and 0.76 ± 1.23 μV, p<0.0001 for both, respectively and magnitude: 12.67 ± 10.63 μV and 2.26 ± 3.56 μV, p<0.0001 for both, respectively). Alpha changed the most during the post-transitional phase (amplitude: 0.38 ± 0.31 μV and magnitude: 1.24 ± 1.08 μV, p<0.0001 for both, respectively). Beta activity was maximum during the transitional-post transitional phase (amplitude: 0.19 ± 0.13 μV and magnitude: 1.01 ± 0.54 μV, p<0.0001 for both, respectively). On arousal from fatigue, the amplitude and magnitude changes came close to that seen during the alert baseline (see Figures 3.1 and 3.2), especially for theta and beta activity.

Figures 3.5, 3.6, 3.7 and 3.8 show examples of the raw EEG activity from a subject in the delta, theta, alpha and beta bands. The plotted amplitude waveforms on the left of the figures correspond to the EEG magnitude (μV) (refer to Figures 3.5 and 3.6) and power (μV^2) (refer to Figures 3.7 and 3.8) on the right side of the display (delta= blue, theta= green, alpha= red, beta= orange). Figures 3.5- 3.8 show examples of the magnitude (refer to Figures 3.5 and 3.6) and power (Figures 3.7 and 3.8) in the delta, theta, alpha and beta bands in the FZ, CZ, PZ, O1 and O2 sites for the alert and transition to fatigue phase. The increase in delta and theta activity during fatigue is clearly indicated in Figures 3.6 and 3.8 as compared to the alert state (note the increase in the numerical values and the increase in the delta= blue and theta= green colours on the right of Figure 3.6 and 3.8).

Table 3.3 The average change in EEG amplitude and magnitude from the alert baseline during drowsiness (n=35)

EEG Band	Transitional	Transitional-Post transitional	Post-Transitional	Arousal
Amplitude (μV)				
Delta	1.68 ± 3.35**	2.26 ± 2.91**	5.36 ± 3.17**	1.90 ± 3.19**
Theta	0.75 ± 1.24**	0.32 ± 1.09**	0.76 ± 1.23**	0.13 ± 1.05
Alpha	0.25 ± 0.32**	0.19 ± 0.27**	0.38 ± 0.31**	-0.11 ± 0.27**
Beta	0.03 ± 0.13	0.19 ± 0.13**	0.11 ± 0.12**	0.01 ± 0.12
Magnitude (μV)				
Delta	5.45 ± 11.11**	5.50 ± 9.44**	12.67 ± 10.63**	5.24 ± 10.57**
Theta	2.31 ± 3.78**	0.90 ± 3.28**	2.26 ± 3.56**	0.45 ± 3.36*
Alpha	0.75 ± 1.12**	0.63 ± 0.98**	1.24 ± 1.08**	0.40 ± 1.01**
Beta	0.37 ± 0.63**	1.01 ± 0.54**	0.57 ± 0.53**	0.04 ± 0.55

Note

The results are reported as mean ± sd

The changes are calculated as functional state minus alert for all phases

* $p<0.05$ ** $p<0.0001$

The EEG magnitude spectrum for the delta, theta, alpha and beta bands in the FZ, CZ, PZ, O1 and O2 sites for the alert phase and transition to fatigue phase are shown in Figures 3.9 and 3.10. An increase in the magnitude spectral activity is noted in the fatigue phase as compared to the alert baseline (note the increase in magnitude values and the delta= blue and theta= green colours on the right of Figure 3.10). The spectrum analysis plot is fast Fourier transform based. Spectrums are derived using 256-point raw waveform.

Figure 3.5 Shows the EEG magnitude during alert in the FZ, CZ, PZ, O1 and O2 sites

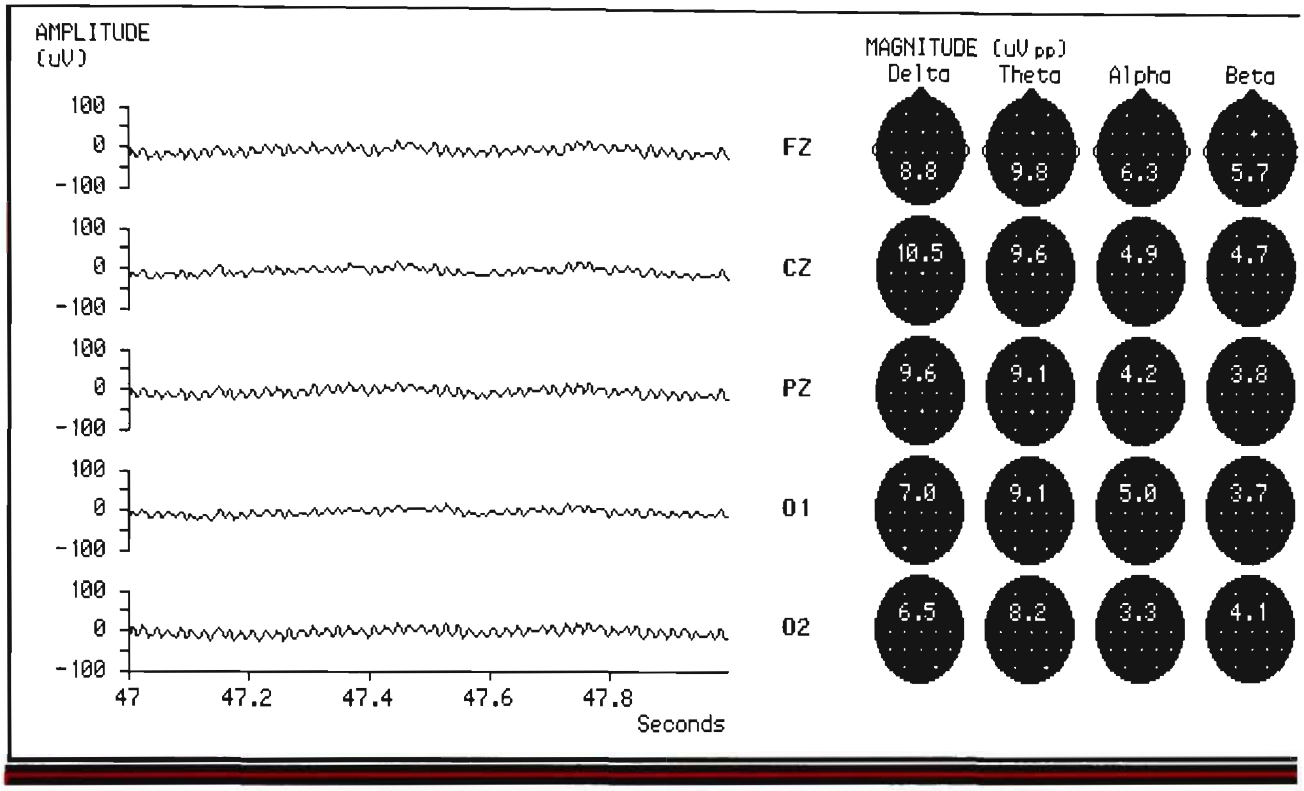


Figure 3.6 Shows the EEG magnitude during transition to fatigue phase in the FZ, CZ, PZ, O1 and O2 sites

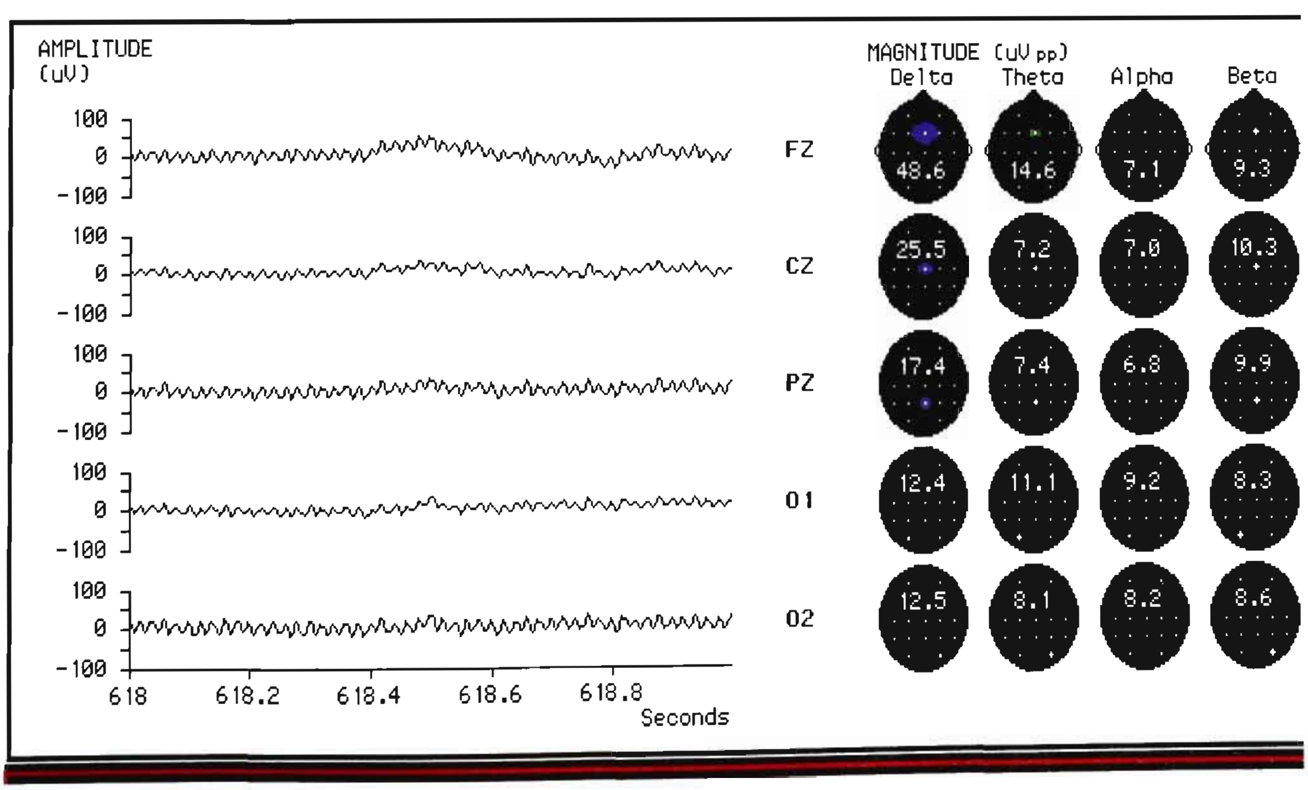


Figure 3.7 Shows the EEG power during alert in the FZ, CZ, PZ, O1 and O2 sites

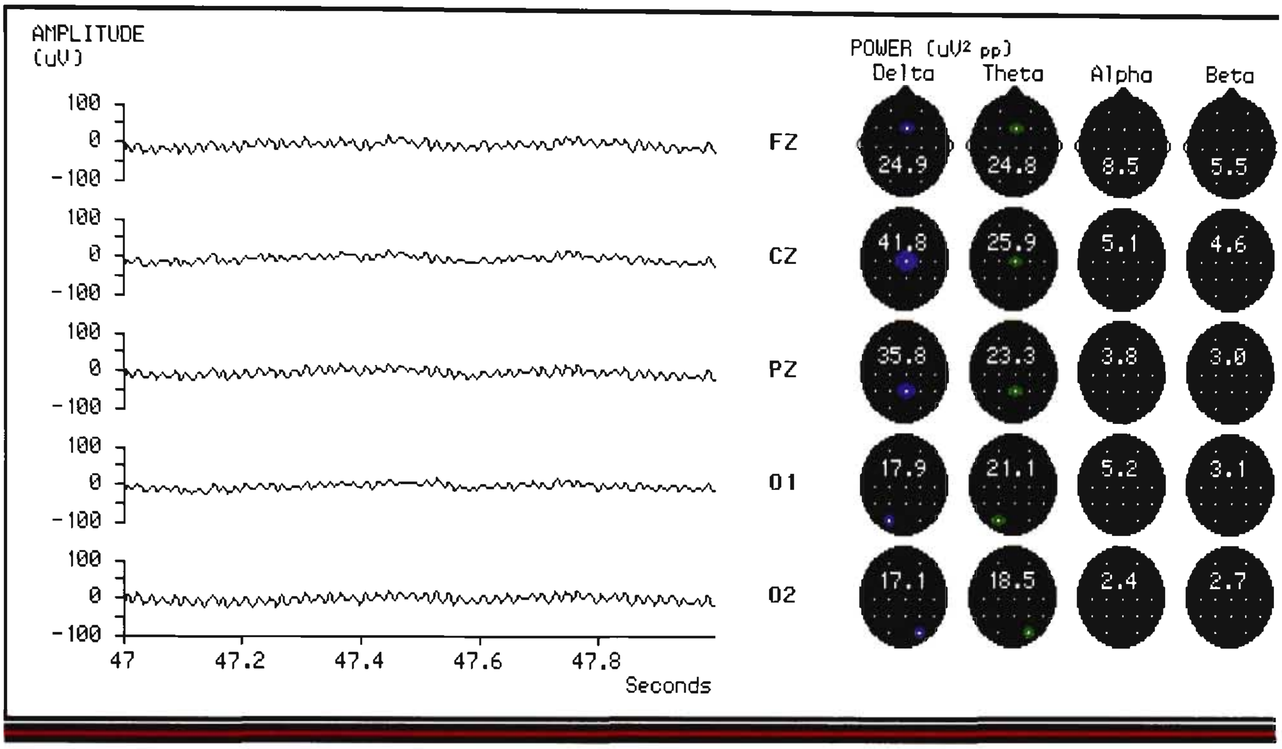


Figure 3.8 Shows the EEG power during transition to fatigue phase in the FZ, CZ, PZ, O1 and O2 sites

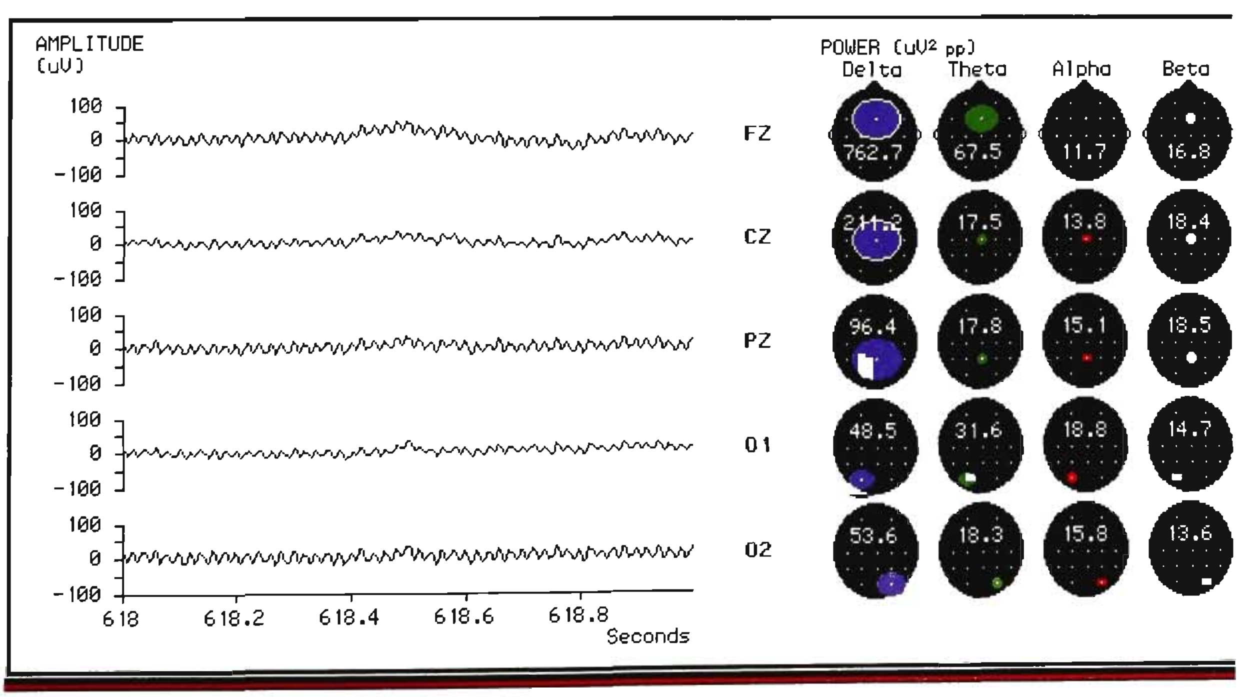


Figure 3.9 Shows the EEG magnitude spectral activity during an alert state in the FZ, CZ, PZ, O1 and O2 sites

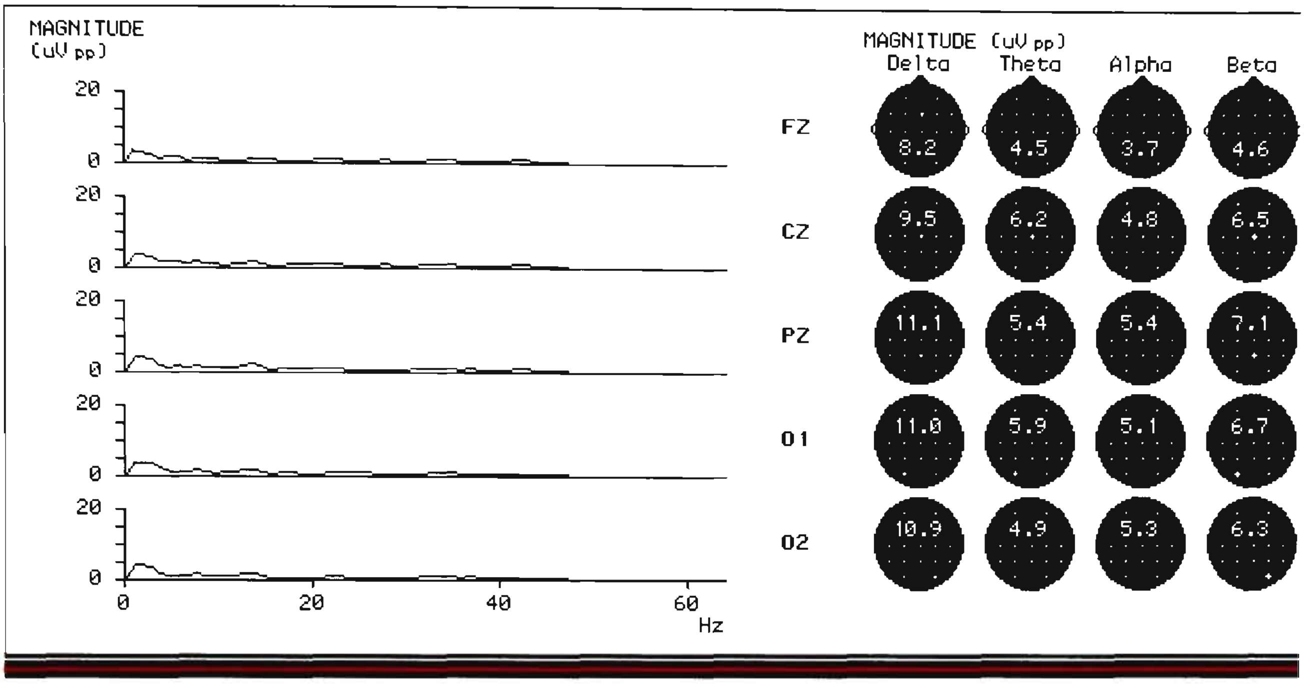
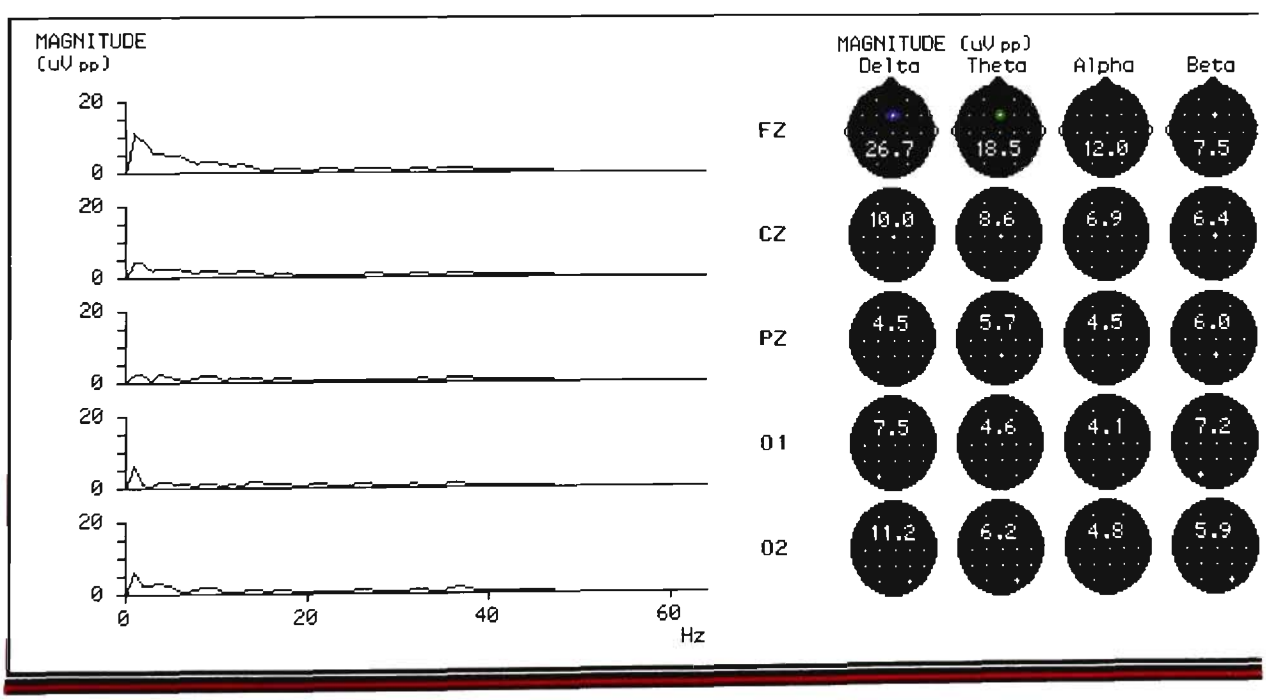


Figure 3.10 Shows the EEG magnitude spectral activity during transition to fatigue state in the FZ, CZ, PZ, O1 and O2 sites



Figures 3.11 and 3.12 show topograph displays, which summarises EEG data in a colour-coded map. In the topograph, the magnitude and power values are calculated for defined frequency bands, for different electrode sites in areas of the scalp. The values are colour coded and plotted to produce a continuous colour map. Each column of oval topograph shows the activity in a selected frequency band. The bottom of each column shows the bandwidths, which are theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz).

Each oval topograph depicts a view of the head from above. The forehead is at the top and the left and right ears are at the left and right sides respectively. The colour scale displayed as a bar to the left of the ovals represents low (blue) to high power (red). The bottom row of the oval topograph is labelled 'REL' (relative). This row maps the full colour-scale spectrum across the entire amplitude range of the three bands. Each topograph is colour coded to indicate how much power it contains relative to the other two topographs.

The top row of oval topographs is labelled 'ABS' (absolute). When one band has less activity relative to another band, it is difficult to clearly see the distribution of power in that band because of the few colours mapped into it. The absolute frequency measurement solves this problem by mapping the full colour-scale spectrum into each band. Figure 3.11 shows the EEG activity of alertness that is presence of alpha and beta activity (indicated by presence of more red colour in the alpha and beta band). Figure 3.12 shows the topograph during fatigue showing an increase in slow wave activity, that is, theta in both relative and absolute cases (indicated by presence of more red colour in the theta band). Note the simultaneous decrease in alpha and beta activity (indicated by a decrease in the red colour in the alpha and beta bands).

Figure 3.11 Shows the topograph of EEG activity in the 1= theta, 2= alpha and 3= beta bands during an alert state

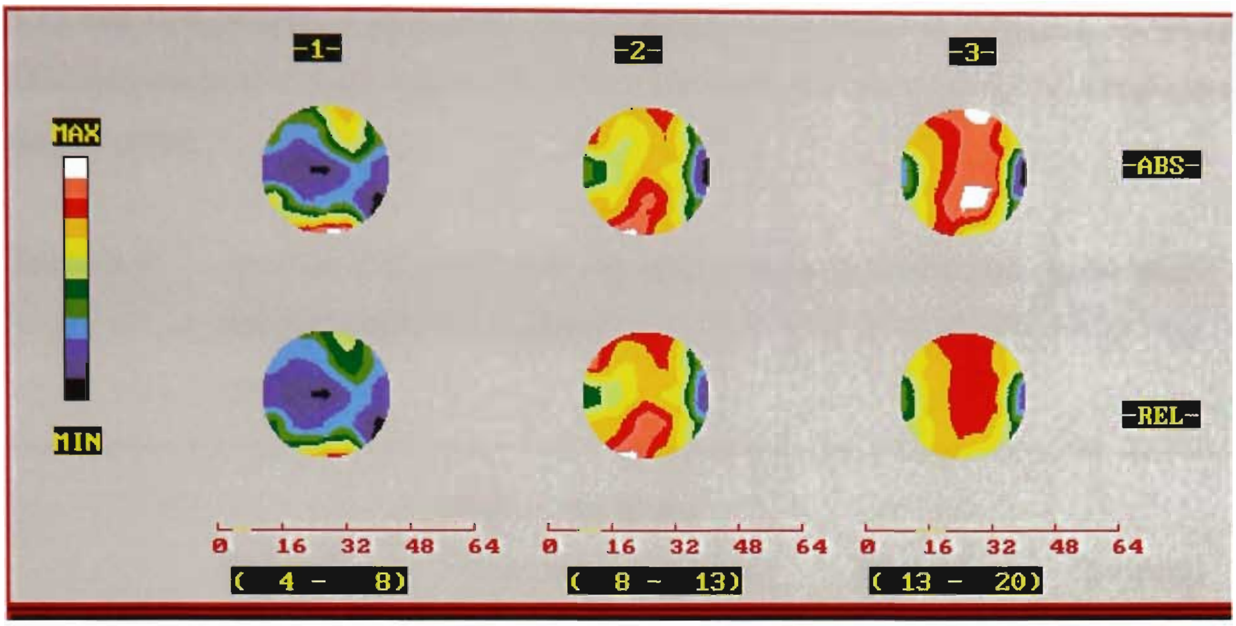
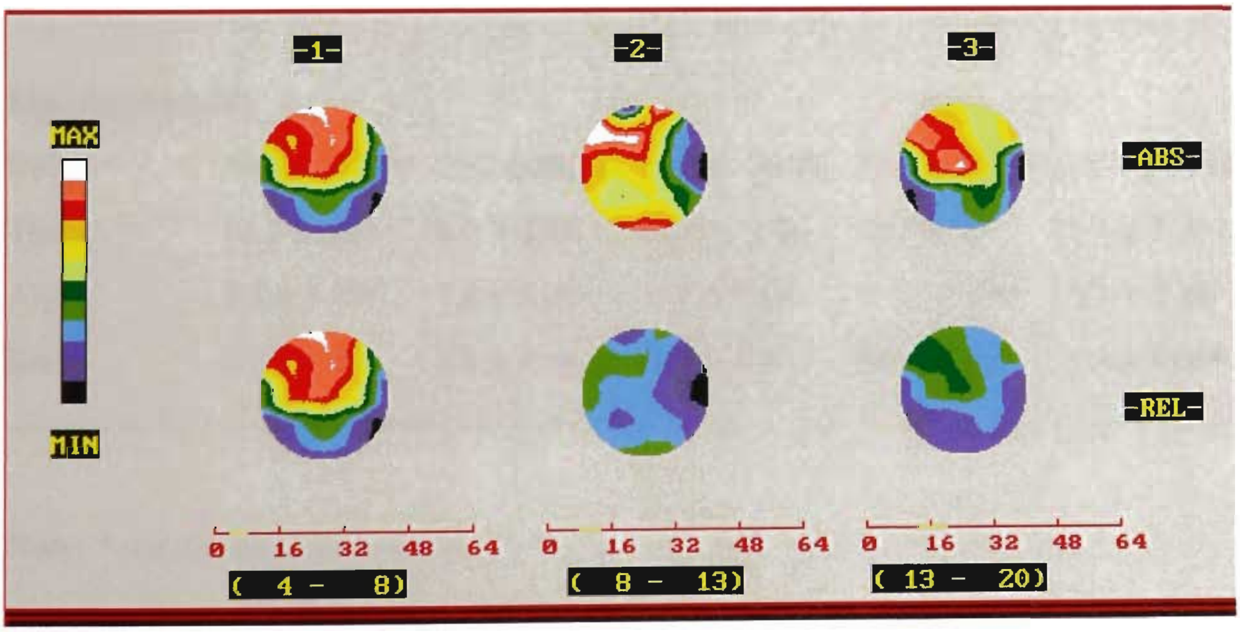


Figure 3.12 Shows the topograph of EEG activity in the 1= theta, 2= alpha and 3= beta bands during transition to fatigue phase



The data was also analysed to identify which section of the brain showed the largest changes during fatigue. This comparison was made during the transitional phase of fatigue. Table 3.4 shows the EEG activity in the different sites on the brain. Figures 3.13 and 3.14, which are graphical representations of the values in Table 3.4, shows the EEG amplitude and magnitude in the different sites on the brain during the transition to fatigue phase.

Table 3.4 Average EEG amplitude and magnitude in different sites on the brain during transition to fatigue
(n=35)

	Sites on the brain				
	Frontal	**Temporal**	**Central**	**Parietal**	**Occipital**
Amplitude (μV)					
Delta	13.1 ± 9.70*	8.1 ± 8.57	9.0 ± 8.58	9.0 ± 8.59	7.8 ± 8.23
Theta	4.6 ± 1.88*	2.5 ± 0.65	3.3 ± 0.81	3.2 ± 0.76	2.8 ± 0.69
Alpha	2.6 ± 0.94*	2.1 ± 0.73	2.4 ± 0.75	2.5 ± 0.81	2.3 ± 0.77
Beta	1.7 ± 0.49	1.6 ± 0.41	1.7 ± 0.43	1.8 ± 0.53*	1.7 ± 0.55
Magnitude (μV)					
Delta	39.9 ± 26.56*	23.2 ± 20.44	26.6 ± 20.66	25.9 ± 20.28	22.7 ± 20.03
Theta	14.2 ± 6.15*	8.0 ± 2.29	10.4 ± 3.26	10.3 ± 3.01	8.8 ± 2.69
Alpha	9.5 ± 3.19*	7.8 ± 2.90	9.1 ± 3.06	9.5 ± 3.28*	8.7 ± 3.42
Beta	8.2 ± 1.99	7.9 ± 1.98	8.3 ± 2.21	9.0 ± 2.44*	8.9 ± 3.01

Note: * maximum EEG activity

For EEG amplitude, maximum activity was observed in the frontal site for delta (13.1 ± 9.70 μV), theta (4.6 ± 1.88 μV) and alpha (2.6 ± 0.94 μV). In contrast, beta activity was found to be maximum in the parietal site (1.8 ± 0.53 μV). A repeated measures ANOVA revealed a difference in EEG amplitude in the different sites within all bands tested, that is, delta, theta, alpha and beta. The amplitude effects were: delta (F=44.6, df=4, 136, p<0.0001), theta (F=36.4, df=4, 136, p<0.0001), alpha (F=9.8, df=4, 136, p<0.0001) and beta (F=3.1, df=4, 136, p=0.02). A post-hoc analysis using a Scheffé test identified the sites, which were significantly different to the site showing maximum activity. The maximum delta and theta activity in the frontal site was significantly different to activity in all other sites (p<0.0001). Maximum alpha activity in the frontal site was significantly different to alpha activity in the temporal (p<0.0001) and occipital (p=0.02) sites. Maximum beta activity in the parietal site was significantly greater than beta activity in the temporal site (p=0.03).

For the magnitude, maximum activity was observed in the frontal site for delta and theta. Alpha activity was maximum in the frontal and parietal sites, while beta was found to be maximum in the parietal site. For the magnitude effects a repeated measures ANOVA revealed a difference in EEG magnitude in the different sites tested. The magnitude effects were: delta (F=44.1, df=4, 136, p<0.0001), theta (F=33.0, df=4, 136, p<0.0001), alpha (F=9.4, df=4, 136, p<0.0001) and beta (F=3.8, df=4, 136, p=0.005). Scheffé test identified the sites significantly different to the site showing maximum magnitude effects. Maximum delta and theta in the frontal sites were significantly different to delta activity in all other sites (p<0.0001). Maximum alpha activity in the frontal and parietal sites was significantly greater than alpha activity in the temporal site (p<0.0001 for both). Maximum beta in the parietal site was significantly different to beta activity in the temporal site (p=0.03).

Table 3.5 shows the characteristics and mannerisms associated with driver fatigue identified from the video. No eye movements and small fast rhythmic blinks during drowsiness replaced the fast eye movements and the conventional blinks during the awake, alert phases. 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.

Figure 3.13 The EEG amplitude activity during the transitional phase to fatigue in different sites on the brain

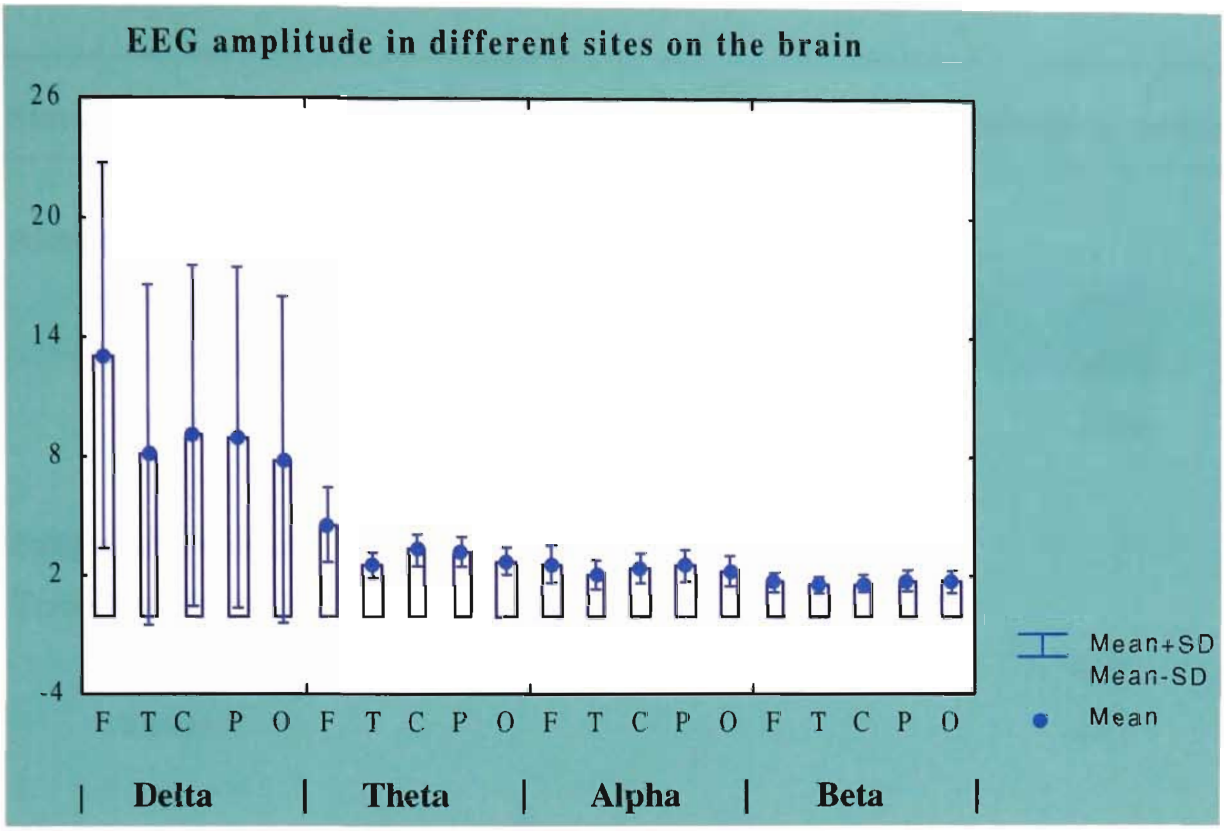
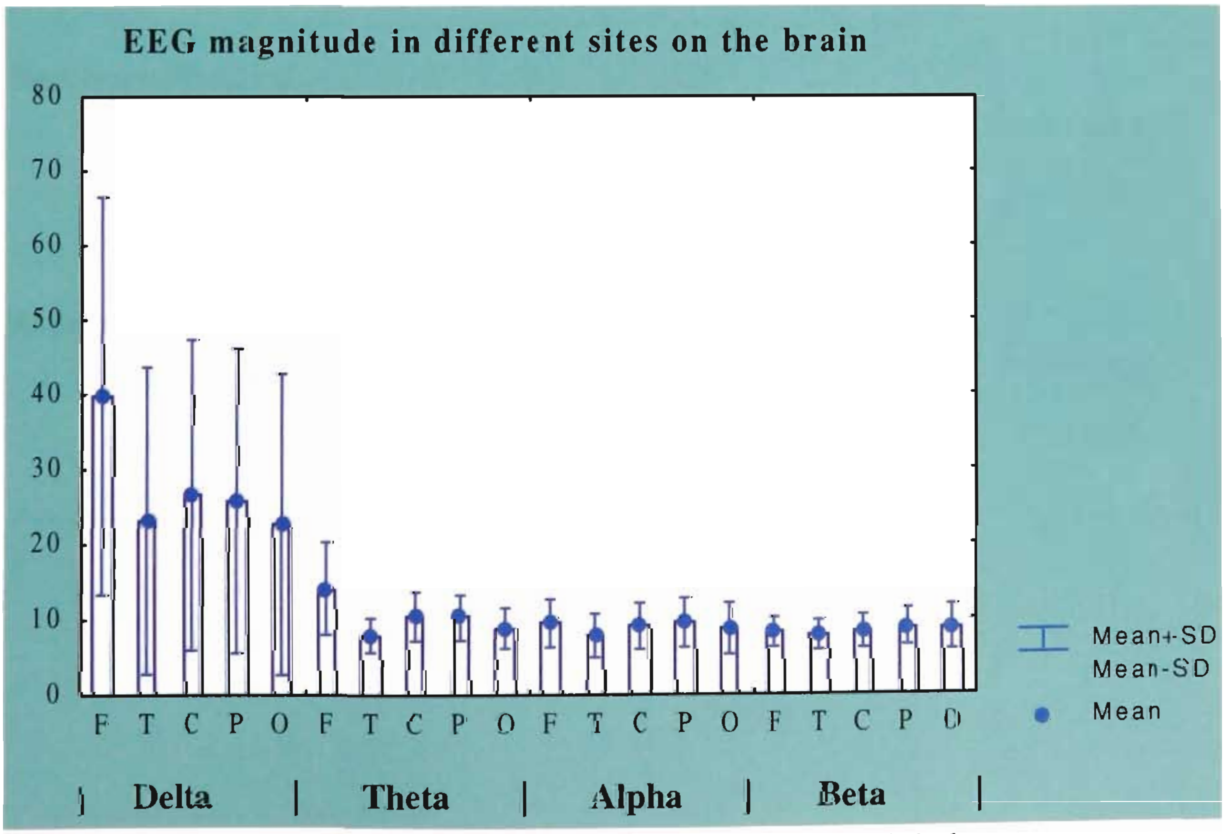


Figure 3.14 The EEG magnitude activity during the transitional phase to fatigue in different sites on the brain



Note: F= frontal, T= temporal, C= central, P= parietal, O= occipital

Table 3.5 The video and EOG indicators of fatigue (n=35)

Status	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 (early drowsiness):	
No eye movement	67%
Yawns	23%
Transitional to post transitional phase, deeper drowsiness:	
Small, fast, rhythmic blinks of low amplitude	46%
Nodding	23%
Post transitional phase, onset of Stage I of sleep	
Slow eye movement and low amplitude slow blinks	100%
Eyes half closed or closed	69%
Arousal from drowsiness:	
Single, vertical eye movement	100%
Slow blinks disappear, replaced by conventional blinks	100%

3.4 Discussion

3.4.1 Driver fatigue and physiological effects

This chapter replicates work conducted by a number of other researchers, however with more robust and stringent study design to negate the methodological limitations of most other studies reported in the literature. In the present study the EEG showed consistent and reliable changes associated with driver fatigue. In the present study delta and theta amplitude were found to increase significantly during transition to fatigue by 20% and 29% ($p<0.0001$); and magnitude by 22% and 26% respectively ($p<0.0001$) (refer to Tables 3.1 and 3.2). Alpha and beta activity also increased though by a smaller degree (amplitude: 9% ($p<0.0001$) and 2% (not significant) and magnitude: 9% and 5% ($p<0.0001$); respectively). These EEG changes were associated with the physical signs of fatigue as identified by the video analysis. This confirmed that the EEG changes were fatigue related.

In previous fatigue research, delta activity change has received little or no attention due to the low frequency signal being influenced by activities such as breathing and movement. However with advancing technology that is capable of removing noise from EEG signals, changes in delta can now be reported reliably and this increases its potential to be used as a neurophysiological indicator of fatigue. The substantial changes in delta associated with fatigue as found in this research strengthens this possibility. In this doctoral research delta activity was found to either persist or increase as fatigue became more severe. This indicates that the drivers were entering a stage where alpha is replaced by lower-frequency EEG activity, commonly recognised as the onset of sleep (O'Hanlon & Kelley, 1977). The EEG theta activity occurs in a variety of mental states including drowsiness. According to Yamamoto and Matsuoka (1990), when long lasting theta waves appear, a rest period should be considered before the subjects become fatigued. Deteriorated performance has been associated with increased theta and changes in alpha intensity while beta activity has also been shown to be altered (Townsend & Johnson, 1979; Wierwille & Ellsworth, 1994). Makeig and Jung (1995) also found changes in theta and alpha waves related to fatigue. In a study of drivers subjected to monotonous tasks, mean EEG activity in the theta and alpha bands increased and higher theta activity accompanied performance impairment (Horváth et al., 1976). The results from this present study confirms the increase observed in theta and alpha activity suggested by prior research, which most likely reflects decreased cortical arousal whilst performing a monotonous task such as driving.

Another study recorded the EEG of 11 train drivers and found that rated 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. The same group of investigators compared day and night-time driving in nine professional drivers on a simulated truck driving task and found EEG associated with sleepiness was higher during night driving (Gillberg et al., 1996). Furthermore, in a field study, these investigators recorded EEG continuously during night and evening drives in a group of eighteen 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. In another study of night driving, EEG was recorded from a parieto-occipital derivation with amplification close to the electrodes (O'Hanlon & Kelley, 1977). The results showed that unskilled drivers had increased power in the alpha band over the duration of the drive compared to skilled drivers. Sleep intruded while the drivers still had their eyes open, and it was accompanied by theta waves, sleep spindles and k-complexes. Interestingly, the drivers had not been aware that they had been driving the car while asleep. From the results of the present research and those of others, it is most likely that the alpha band is sensitive to changes in alertness while the theta and delta bands are necessary for distinguishing lower levels of arousal. While, beta activity in the presence of slow wave activity indicates medium levels of fatigue.

In this study it was found that EEG changes associated with fatigue seems to vary according to the cortical site being assessed (refer to Table 3.3). During onset of fatigue, delta and theta activity was maximum in the frontal regions with substantial activity also observed in the central and parietal areas of the brain. Most of the alpha activity was located in the posterior and frontal regions while beta was prominent in most areas of the brain. This replicates the findings of other researchers who have reported that during drowsiness, there are increases in slow wave activity i.e. progressive temporal, centrofrontal and posterior theta and delta and temporal alpha (Santamaria & Chiappa, 1987a). The same investigators have also found a change in alpha distribution during drowsiness i.e. occipitoparietal alpha spread to anterior areas which became more centrofrontal and temporal alpha (Santamaria & Chiappa, 1987b). The results from the current research and those of others indicate that the various areas of the brain do behave differently during fatigue and therefore it may be useful to utilise an electrode derivation that spans the whole brain.

Other strategies to measure fatigue have also been used. For instance, objective indicators of sleepiness such as the Maintenance of Wakefulness Test, a daytime polysomnographic procedure which assesses the ability to remain awake during soporific situations (Doghramji, et al., 1997). The MSLT has also been used (Carskadon & Dement, 1982) as a neurophysiological technique that assesses drowsiness. Studies have also used the alpha attenuation test (AAT) together with the MSLT and found that the AAT provides practical assessment of daytime sleepiness associated with narcolepsy (Alloway, Ogilvie, & Shapiro, 1997). These tests have generally been utilised in studies on sleep disorders, age and drug effects and long-term measures of sleepiness or circadian effects, which was outside the scope and aims of the current study.

For obvious reasons, it is important in fatigue studies to incorporate an independent and reliable indicator of fatigue such as a video image of the face to verify fatigue status. Consequently, in this research, a video image of the driver's face was recorded, linked in real time with the physiological measures for drowsiness assessment (Table 3.4). Very few studies have applied "facial expression" to drowsiness research (Belyavin & Wright, 1987; Yabuta et al., 1985); and most do not provide evidence of independently validating their fatigue episodes. It was observed that nearly two thirds of the subjects did not have any eye movement and some also showed mannerisms such as yawning and nodding during fatigue. More than half way through the driving task, slow blinks occurred in most subjects with episodes of eye closure. Furthermore, it was observed from the video that the transition to fatigue was not an immediate process, but that periods of drowsy and wake states were also reflected in the EEG. Others also report that the EEG changes during falling asleep is not an immediate process, but periods of fluctuations between wake and sleep i.e. successive 'microsleep' episodes (Harrison & Horne, 1996).

Since there are rich sensory and motor connections between the eye and the brain, eye movement can provide signs of drowsiness. In the current study, the fast eye movements and conventional blinks during awake were replaced by no or slow eye movements and small fast rhythmic blinks during drowsiness. During deeper drowsiness, slow blinks were seen in all the subjects (Table 3.4). These results show the potential of using EOG to identify the physical onset of fatigue. The characteristics of the eye movements (identifiable either on the EOG signal or on the video of the face) are an important factor for the study of alertness levels. The length of time the eyes are closed and the slow eye movements seem to be fundamental parameters (Torsvall & Åkerstedt, 1987). The slow eye movements may be described as unintentional pendular and convergent movements of the eyes (Artaud, et al., 1994). They accompany a reduction in cerebral activation (Artaud, et al., 1994). Others have also identified slow eyelid closure as a reliable estimate of the level of drowsiness (Wierwille & Ellsworth, 1994). In the present study, it was also found that heart rate decreased significantly during fatigue (by 7 beats per minute, $p<0.01$), indicating an autonomic association. Heart rate has been shown to decrease during prolonged and monotonous driving (O'Hanlon & Kelley, 1977). However, more research is required in this area to better understand the autonomic changes associated with driver fatigue.

3.4.2 The methodology used in fatigue studies

As mentioned in the introduction (refer to section 1.13 for details) it is evident from the literature that numerous studies have been conducted on fatigue, however, some of the literature presents equivocal results for several stipulated methodological reasons which include: (a) The variable use of referential and bipolar EEG montages (Broughton & Hasan, 1995). (b) The use of heterogeneous samples. (c) The use of insufficient subject numbers which influences the inter- and even intra-individual variance in the EEG patterns of drowsiness, hence, it is important to have sufficient sample power in such investigations for valid statistical outcomes. (d) Omitting to report the sample size. (e) Testing limited scalp sites may not be adequate since not all brain regions exhibit similar changes (Wright et al., 1995). (f) Only reporting activity in some EEG bands.

It is important to note here that the EEG results may be influenced by inter- and intra-individual variability. To overcome this problem a sufficient sample power was utilised in the present study. For example, EEG data is influenced by individual differences such as introversion-extroversion as well as the relationship between sex and spatial ability (Cacioppo & 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 (Cacioppo & Tassinary, 1990). 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 (Cacioppo & Tassinary, 1990). During drowsiness there is a difference in alpha amplitude due to gender (Santamaria & Chiappa, 1987a). Furthermore, there are age-related differences in drowsiness. Fatigue patterns are also affected by 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.

Even though there is variability in the literature, some firm conclusions can be reached regarding electroencephalography effects during fatigue. In the review of studies that came close to meeting some of the above criteria, the main EEG activity reported were increases in delta, theta and alpha activity (Lal & Craig, 2000b; Torsvall & Åkerstedt, 1988), theta wave persistence (Yamamoto & Matsuoka, 1990) and appearance of grouped alpha waves (Ninomija et al., 1993). Others have reported increases in delta, theta and beta activities (Kiroy et al., 1996) while others have reported increases in delta and theta only (Makeig & Jung, 1996). In the current doctoral research, large increases in delta and theta were observed during fatigue and smaller change in alpha and beta. Therefore, from prior studies and the present research, fatigue is most likely to be associated with increases in slow wave activities with smaller variations in alpha and beta activity. The next chapter will go onto discuss the psychological factors associated with driver fatigue.

Chapter Four

Psychological and Self-reported Assessment of Fatigue and Drowsiness in Non-professional Drivers

4 Fatigue and Psychological Effects

Electrophysiology in the form of recording the electrical potentials on the scalp using EEG has made possible the scientific investigation of the brain (Darrow, 1947). Yet EEG is still relatively new in the area of investigating the psychology of fatigue. Few studies have investigated the psychological associations of mood states, anxiety levels and locus of control with fatigue. Also, studies on the psychological links to physiological changes such as EEG or EOG during fatigue are scarce. Investigating the psychological traits that are linked to fatigue will provide a better understanding of this complex functional state of the body and will hopefully lead to better driver fatigue management.

4.1 Psychological Implications of Fatigue

As discussed in Chapter 1, driver fatigue has been specifically defined as a state of reduced mental alertness that impairs performance of a range of cognitive and psychomotor tasks including driving (Williamson et al., 1996). It generally impairs human efficiency when individuals continue working after the onset of their fatigue state. However, task performance during driving may be influenced by psychological factors because individuals differ in attention and anxiety status (Broadbent, Broadbent, & Jones, 1986). Regardless of task type, the longer an individual works continuously at that task, the less efficient performance becomes (Grandjean, 1970). As well as resulting in a decline in mean performance over time, fatigue is usually associated with increased variability in response timing as the task progresses. Fatigue is also associated with a change in the focus of attention. An early study of sustained performance in a flight simulator by Bartlett (1943) showed that as performance time on task increased, changes in attention with an increase in errors occurred. Variable attention and anxiety status may possibly influence the ability to attend to a driving task. It has been suggested that fatigue could be experienced differently by drivers with different personality and temperament (Brown & Eng, 1967a). Lal et al. (1998) have recently 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 et al., 1997). Although some studies have examined the neurophysiological concomitants of anxiety, firm conclusions about regional brain function associated with anxiety have been difficult to validate. Investigative approaches have measured regional brain metabolism (e.g. blood flow, blood oxygenation, glucose metabolism) and the alpha band of the scalp EEG, which is considered to be inversely related to activity because power in this frequency band decreases during mental effort (Shagass, Straumanis, & Overton, 2000). Unfortunately, the brain regions that have been shown to be associated with anxiety have varied considerably from study to study and across methodologies.

Are certain brain waves and psychological traits associated with better vigilance? Yamamoto and Matsuoka (1990) suggested that when long lasting theta waves appear, a rest period should be considered before the subjects become fatigued. Deteriorated performance has been associated with increased theta and changes in alpha intensity while beta activity has also been shown to be altered (Townsend & Johnson, 1979; Wierwille & Ellsworth, 1994). Makeig and Jung (1995) also found changes in theta and alpha waves related to fatigue. It has been suggested that in order to improve performance of people who are involved in long-term monitoring activities and monotonous tasks, such as drivers and operators, they should be taught to suppress theta (Andreassi, 2000c). Studies involving psychological factors, EEG and attention are not numerous, but those that exist have produced interesting data. The question that needs further clarification is how and why theta production influences cognitive or motor task performance.

Research on the psychological associations of driver fatigue is scarce and therefore it is an important issue that needs investigation. Understanding the psychological links to fatigue could provide useful insights for better fatigue management such as improving task performance and increasing attention levels in drivers. Therefore the aim of the present study involved the investigations of the psychological associations during the transition from alertness to fatigue/drowsiness during a driver simulator task.

The hypotheses generated for this investigation were:

1) Some psychological factors will be associated with the EEG changes that occur during fatigue.
2) Negative psychological factors such as increased anxiety, negative mood states and lack of personal control will be associated with driver fatigue.

4.2 Methods

4.2.1 Subjects

Thirty-five subjects (26 males and 9 females) who were current non-professional drivers, aged 34 $\pm$ 21 years (range: 21-52), were recruited from a large tertiary institution and the local community and randomly assigned to the study. For complete details on these subjects refer to Chapter 2. To qualify for the study, subjects had to have no contraindications such as severe concomitant disease, alcoholism, drug abuse and psychological or intellectual problems likely to limit compliance. This was assessed via interview and lifestyle and general questionnaires.

4.2.2 Study protocol

The full details for the procedures, experimental intervention and statistical analysis are provided in Chapter 2. Briefly, the study was conducted in a temperature-controlled laboratory (22-24° C) as the subjects performed a standardised sensory motor driver simulator task. The driving task consisted of 5 to 10 minutes of active driving to familiarise the subject with the driving equipment and video screen feedback. This was followed by driving for approximately two hours at a speed less than 80 km/hr till the subjects showed physical signs of fatigue, which was determined from a video recording (refer to Chapter 2 for information on the video validation of fatigue).

Simultaneous EEG measures were obtained. Nineteen channel EEG was recorded according to the International 10-20 system (Fisch, 1991b). Anxiety, mood states and locus of control were evaluated immediately before the driving task. Trait anxiety and state anxiety were measured using the Spielberger State-Trait Anxiety Inventory (Spielberger et al., 1983). The Profile of Mood States provided a measure of six mood states: tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia and confusion-bewilderment (McNair et al., 1971). Locus of control

(LCB) of behaviour, a control efficacy measure, provided a measure of the subject's perception of the relation between events and their behaviour (Craig et al., 1984). The State Anxiety Inventory was re-administered immediately after the driving task. Fatigue levels immediately before and after the driving task were evaluated by a one item scale created specifically for this research study called the 'fatigue state question' which asked the subjects to respond to the following: 'Presently I feel fatigued (tired, drowsy)'. The choice of response ranged from 1-not at all, 2- slightly, 3-moderately and 4-markedly. For further details on all the psychological questionnaires administered in this study refer to Chapter 2.

4.2.3 Statistical analysis

The EEG was defined in terms of frequency bands including delta (0-4 Hz), theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) (Fisch, 1991b). For each band the average EEG magnitude (μV) and maximum amplitude (μV) were computed. The EEG data was compared for these phases to an alert baseline, which was identified from the video recording of the subject during the driving task (refer to Chapter 2). Note that the EEG changes found during the transitional phase of fatigue have been reported in a previous chapter (refer to Table 3.1 in Chapter 3). The score for each psychological measure was correlated to the average EEG change in each of the four bands during the transition to fatigue using Pearson's correlation. The site showing the maximum correlation with a psychological factor was reported. Multiple regression was then used to identify which of the psychological variables contributed significantly to the EEG variability associated with fatigue. The multiple regression was performed only with the EEG changes in the sites on the brain which showed significant correlation with the psychological variables. Since the psychological analysis in this study was exploratory, all significant results and trends to significance were identified. The conservative significance level was set at $p<0.01$ for all the correlation performed. However since the investigation was exploratory, all p values <0.05 is reported for the correlation. The significance level for the multiple regression was set at $p<0.05$.

4.3 Results

The subjects scored in the normal range for the psychological measures. The mean trait anxiety score was 36 ± 8.4, locus of control was 23 ± 8.6, and total mood score was 44 ± 24.4. The pre-study state anxiety of 32 ± 11.6 was not significantly different to the post-study state anxiety, which was 31 ± 9.1. The 'fatigue state question' identified subjects as slightly fatigued before the study and moderately to extremely fatigued after the study. Refer to Table 4.1 for the subject response on the individual items on the 'fatigue state question'. The following correlation results are a typical representation for the entire brain. Table 4.2 shows all the individual psychological variables that significantly correlated with the EEG changes during transition to fatigue. The following psychological associations were found with changes in EEG amplitude during transition to fatigue. Delta activity was associated with increased Trait Anxiety ($r=0.40$, $p=0.02$), post-study State Anxiety ($r=0.42$, $p=0.01$), Tension-Anxiety ($r=0.40$, $p=0.02$), Vigor-Activity ($r=-0.44$, $p=0.009$), Fatigue Inertia ($r=0.39$, $p=0.02$) and pre-study fatigue state ($r=0.37$, $p=0.03$). Theta activity was associated with Trait Anxiety and control efficacy ($r=0.35$, $p=0.04$ for both) and post-study fatigue state ($r=0.44$, $p=0.009$). Alpha and beta were associated with Fatigue-Inertia ($r=0.36$, $p=0.03$ and $r=0.43$, $p=0.009$, respectively). Beta activity was also significantly associated with pre-study fatigue state ($r=0.49$, $p=0.003$). For the magnitude changes, only delta showed trends of association. Delta activity was associated with Trait Anxiety ($r=0.36$, $p=0.03$), pre- and post-study State Anxiety, Tension-Anxiety, post-study fatigue state ($r=0.40$, $p=0.02$ for all four) and Vigor-Activity ($r=-0.36$, $p=0.03$). Figures 4.1, 4.2, 4.3 and 4.4 show some examples of significant linear regression and correlation between various psychological factors and delta, theta, alpha and beta amplitude changes during transition to fatigue, respectively (reported in Table 4.2). Figures 4.5 and 4.6 shows examples of linear regression lines and correlation between psychological factors and changes in delta magnitude during transition to fatigue.

Table 4.1 The number (percentage) of subjects responding to individual items on the Likert 'fatigue state question' immediately before and after the driving task (n=35)

Fatigue State Item:	**'Presently, I feel fatigued (tired, drowsy)'**			
Response	**not at all**	**slightly**	**moderately**	**markedly**
n (%) before driving	5 (14.3%)	14 (40%)	13 (37.1%)	3 (8.6%)
n (%) after driving	1 (2.9%)	5 (14.3%)	23 (65.7%)	6 (17.1%)

Table 4.2 Showing all correlation between the average EEG changes across the entire brain and psychological variables for p<0.05

Psychological Measure			EEG band	
	Delta	**Theta**	**Alpha**	**Beta**
Amplitude associations				
Trait Anxiety	0.40/0.02	0.35/0.04	-	-
Post State-Anxiety	0.42/0.01	-	-	-
Control Efficacy	-	0.35/0.04	-	-
Tension Anxiety	0.40/0.02	-	-	-
Vigor-Activity	**-0.44/0.009**	-	-	-
Fatigue-Inertia	0.39/0.02	-	0.36/0.03	**0.43/0.009**
Pre-study Fatigue State	0.37/0.03	-	-	**0.49/0.003**
Post-study Fatigue State	-	**0.44/0.009**	-	-
Magnitude associations				
Trait Anxiety	0.36/0.03	-	-	-
Pre State Anxiety	0.40/0.02	-	-	-
Post State Anxiety	0.40/0.02	-	-	-
Tension Anxiety	0.40/0.02	-	-	-
Vigor-Activity	-0.36/0.03	-	-	-
Post study Fatigue State	0.40/0.02	-	-	-

Note: Results are reported as correlation *(r)/p value*.

Significant correlation with p values of <0.01 are in bold.

Figure 4.1 A positive linear regression line of delta amplitude changes with Trait Anxiety

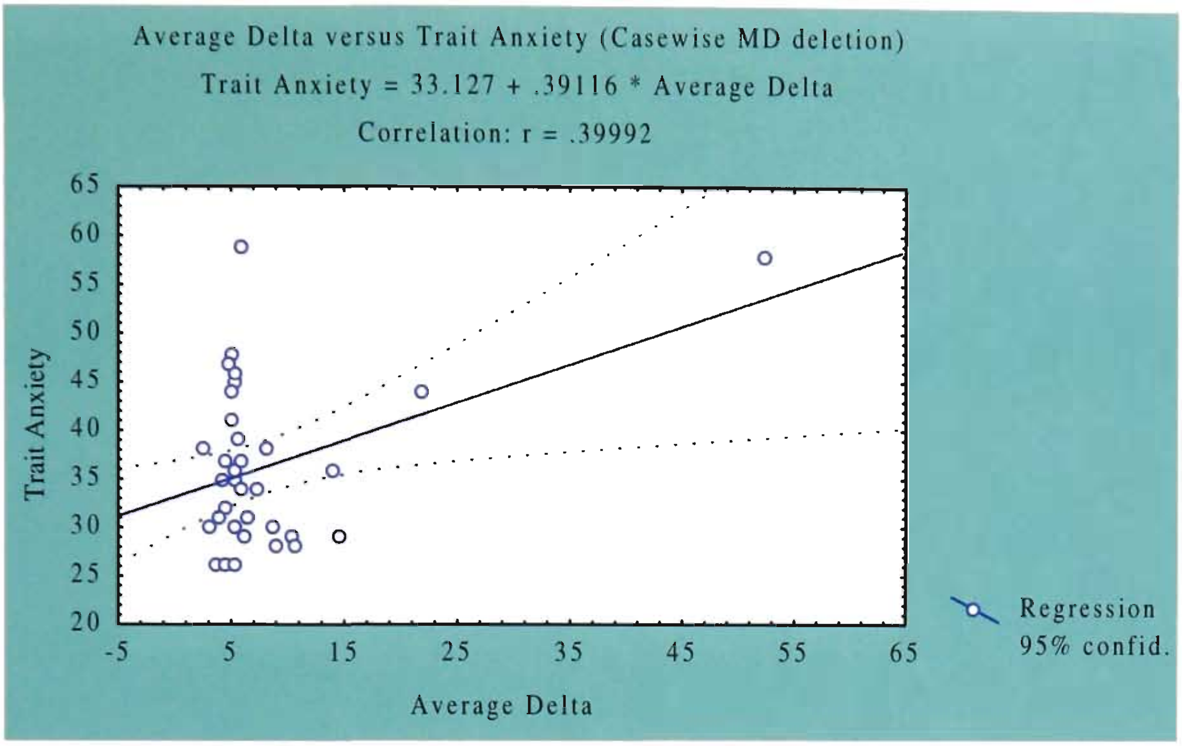


Figure 4.2 A positive linear regression line of theta amplitude changes with Control Efficacy

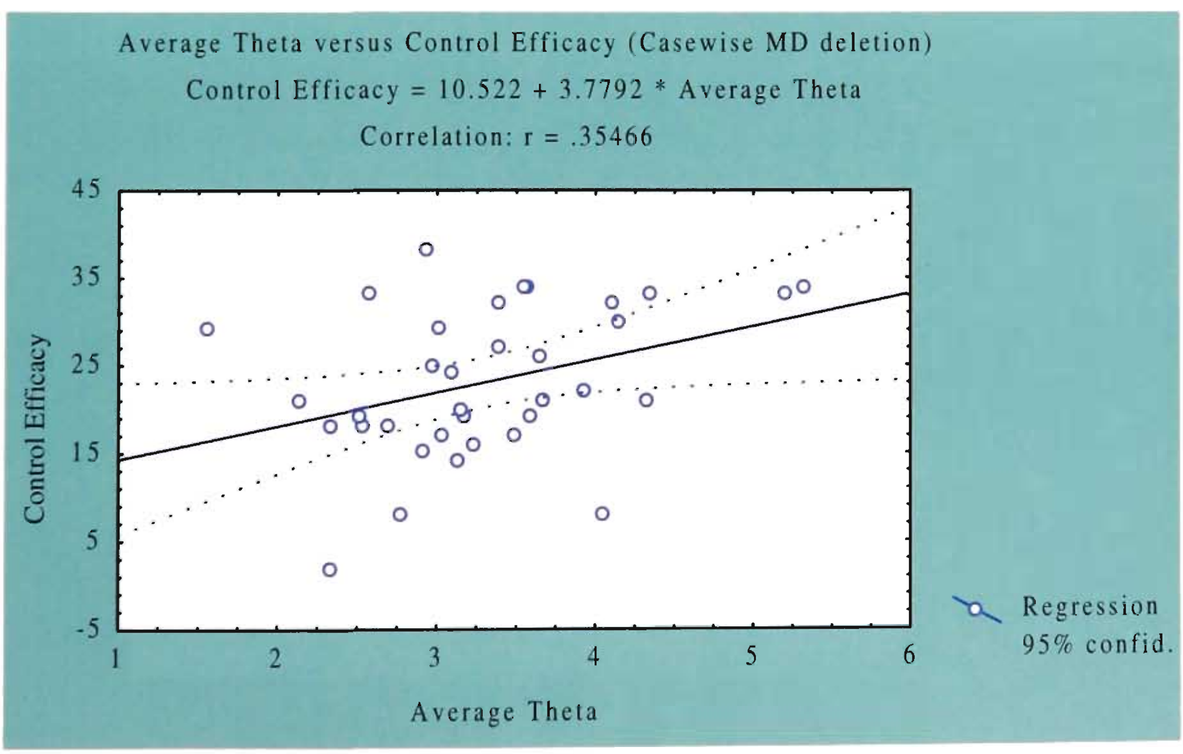


Figure 4.3 A positive linear regression line of alpha amplitude changes with Fatigue-Inertia

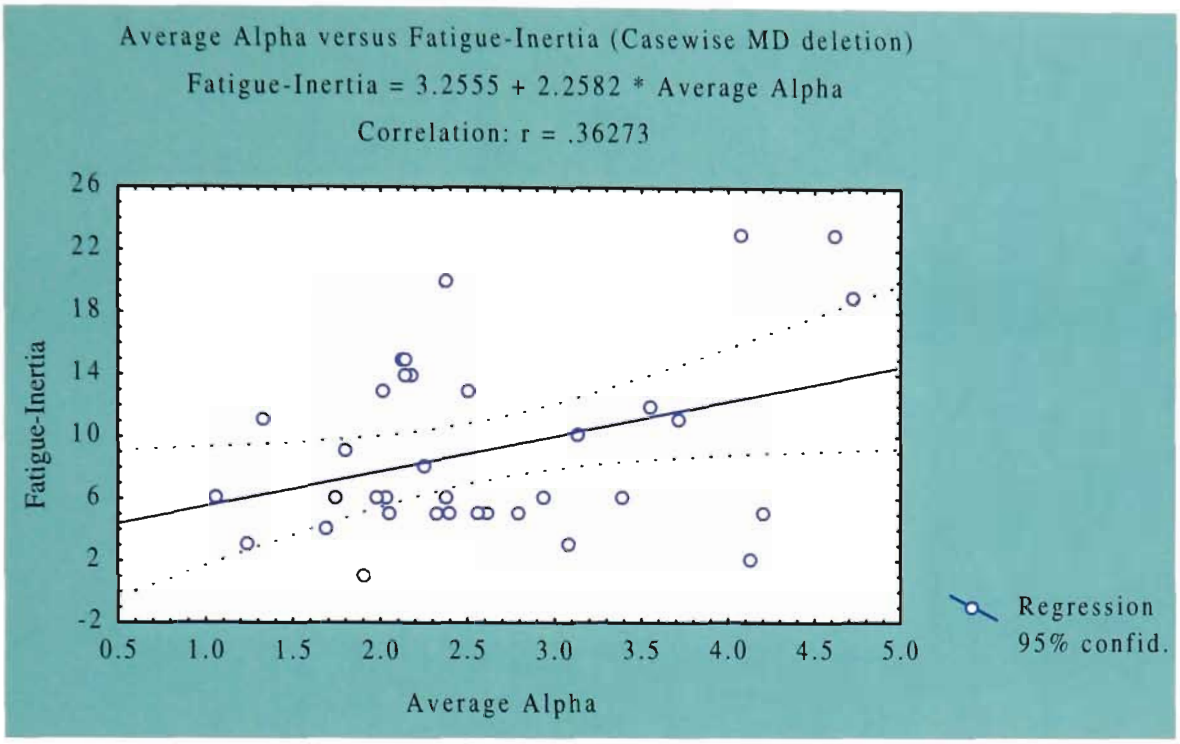


Figure 4.4 A positive linear regression line of beta amplitude changes with pre-study fatigue state

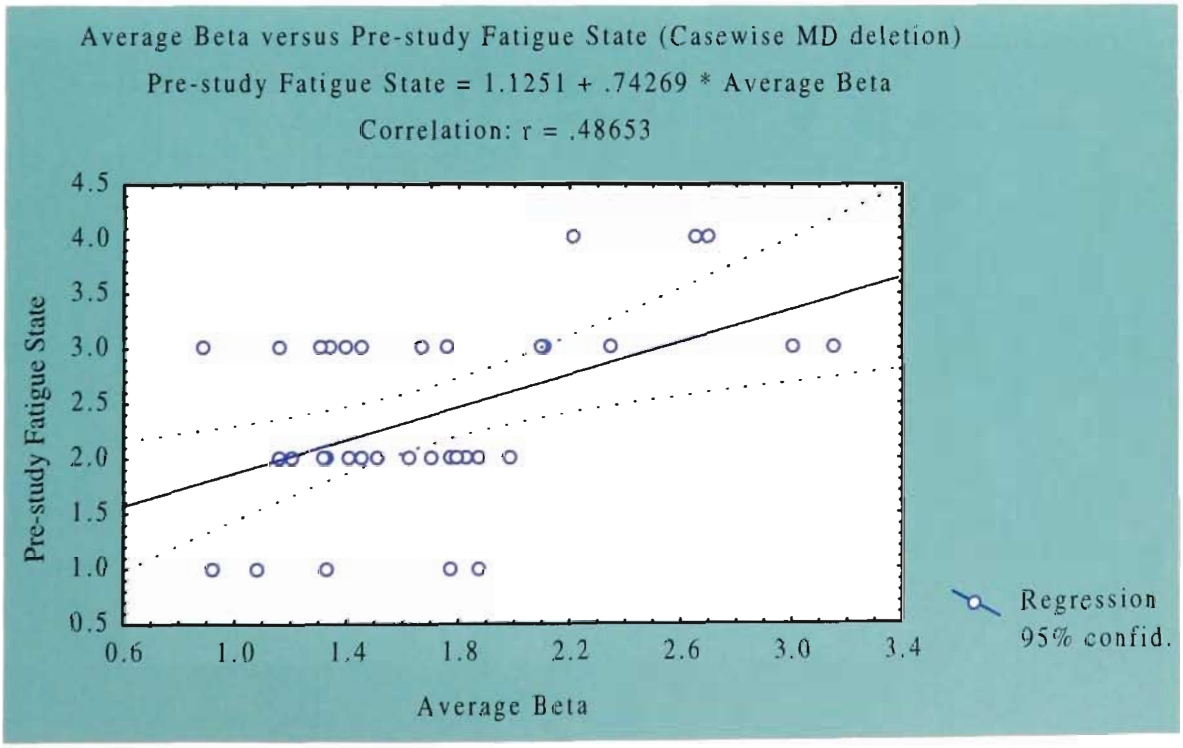


Figure 4.5 A positive linear regression line of delta magnitude changes with Tension-Anxiety

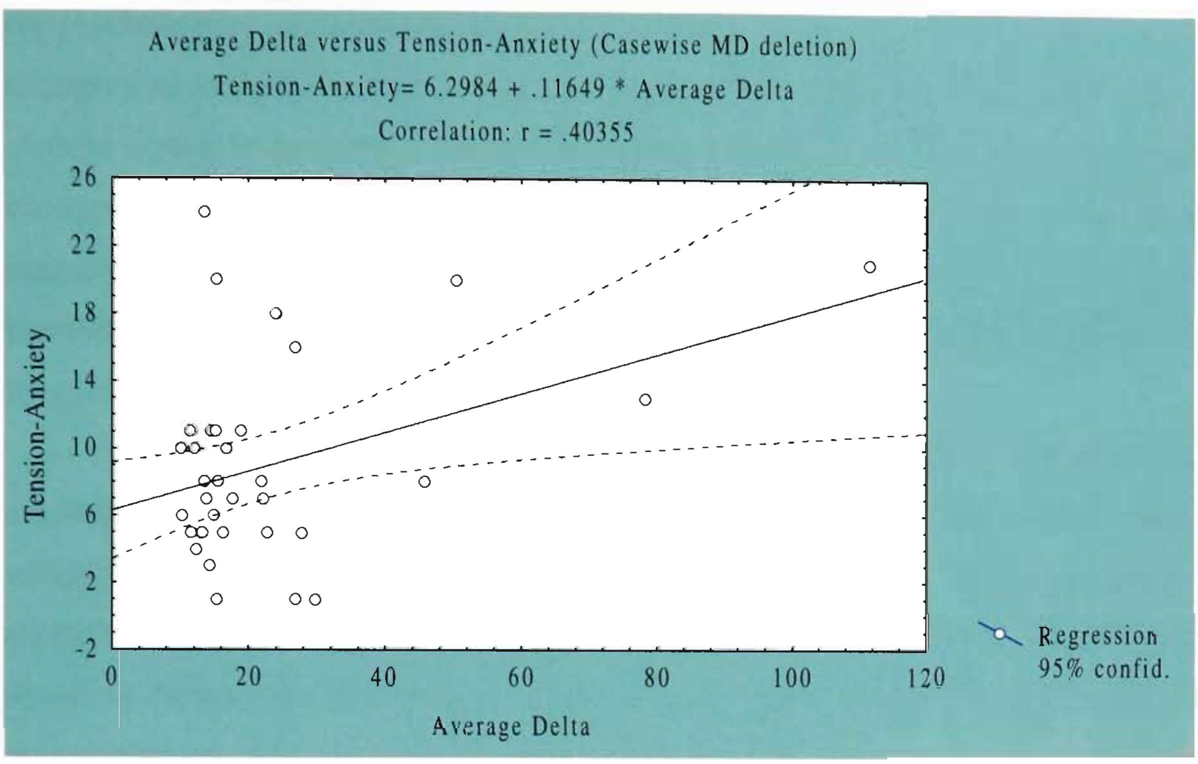


Figure 4.6 A negative linear regression line of delta magnitude changes with Vigor-Activity

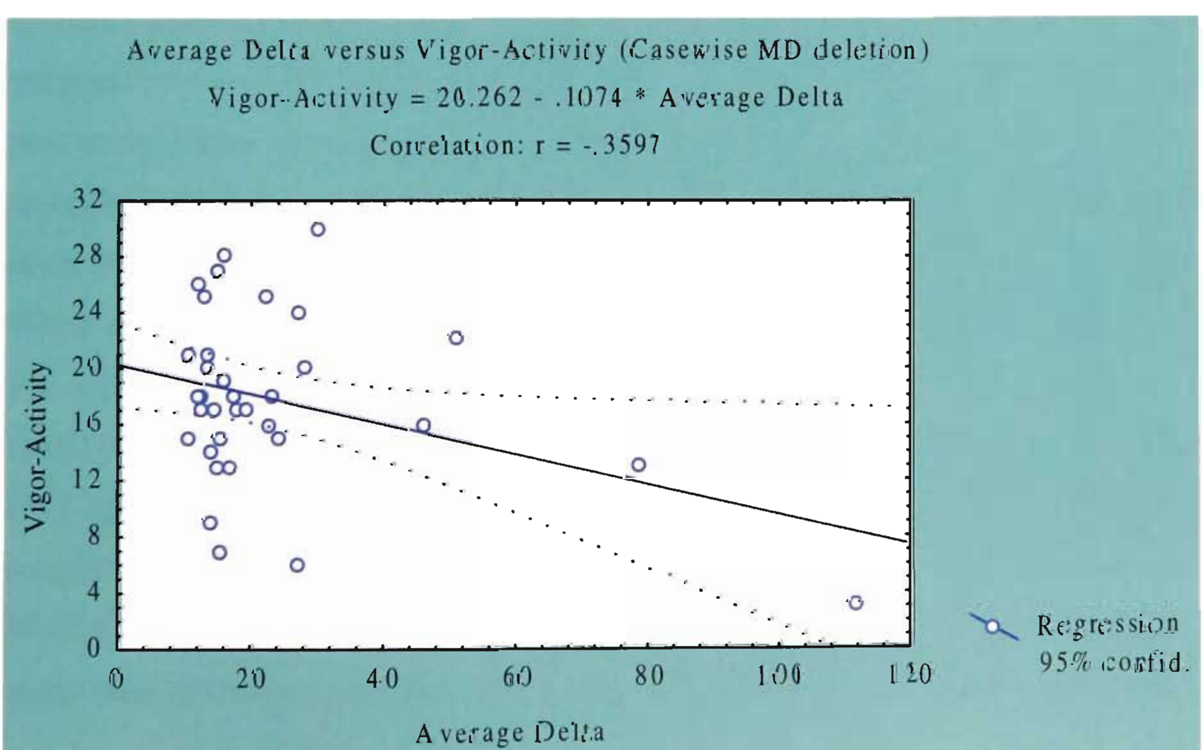


Table 4.3 shows the non-significant correlation (for all the p values greater than 0.05) between the EEG changes and the psychological variables. Since the psychological investigation was an exploratory analysis it is interesting also to identify the psychological variables that were close to being significant. Delta amplitude changes had a trend to correlate with post-study fatigue state ($p=0.06$). Trait anxiety showed a trend to correlate with alpha amplitude changes ($p=0.06$). Delta magnitude changes and Fatigue-Inertia associations tended towards significance ($p=0.08$). Theta magnitude changes and control efficacy levels and pre-study Fatigue State tended towards significance ($p=0.07$ and $p=0.08$, respectively). Tension anxiety and beta magnitude activity was also close to significance ($p=0.07$).

Only psychological variables that correlated with EEG changes at $p<0.05$ were entered into a standard multiple regression analysis to determine those variables that uniquely contributed to changes in EEG signals associated with fatigue in different sites on the cortex. The multiple regressions that had an overall significance of $p<0.05$ are shown in Tables 4.4a, 4.4b, 4.4c, 4.4d and 4.4e. The regression for the frontal region was significant ($F=2.49$, $df=6, 28$, $p<0.05$, $R=0.60$, $R^2=0.35$, adjusted $R^2=0.21$) for six psychological variables (Trait anxiety, Tension-Anxiety, Vigor-Activity, Fatigue-Inertia and pre- and post-study state anxiety) together explaining 35% of the variance in delta activity during fatigue (Table 4.4a). However, the only individual factor that was significant in the regression equation was Fatigue-Inertia ($p<0.04$). Twenty four percent of theta variability ($F=5.0$, $df=2, 32$, $p<0.01$, $R=0.49$, $R^2=0.24$, adjusted $R^2=0.19$) in the temporal region of the brain was significantly explained by Trait anxiety ($p=0.04$) and post study fatigue status ($p=0.03$) (Table 4.4b). Together Trait anxiety, locus of control and post study fatigue state explained 26% of theta variability in the central area of the brain ($F=3.72$, $df=3, 31$, $p<0.02$, $R=0.51$, $R^2= 0.26$, adjusted $R^2= 19\%$) (Table 4.4c). When all three variables were entered into the regression, only post study fatigue status was significant ($p<0.05$). Fatigue-Inertia ($p=0.04$) and pre study fatigue status ($p=0.006$) accounted for 33% of beta variability in the occipital region during fatigue ($F=7.78$, $df=2,32$, $p<0.01$, $R=0.57$, $R^2=0.33$, adjusted $R^2=0.29$) (Table 4.4d). For the magnitude changes, the regression was significant ($F=3.2$, $df=2,32$, $p<0.05$, $R=0.41$, $R^2=0.17$, adjusted $R^2=0.11$) for the frontal region with two variables (pre-and post-study state anxiety) explaining 17% of delta variability during fatigue (Table 4.4e).

Table 4.3 All non-significant correlation between the average EEG changes across the entire brain and psychological variables for p<0.05

Psychological Measure			**EEG band**	
	Delta	**Theta**	**Alpha**	**Beta**
Amplitude associations				
Trait Anxiety	-	-	0.32/0.06	0.13/0.45
Pre State-Anxiety	-	0.26/0.13	0.08/0.63	0.19/0.27
Post State-Anxiety	-	0.29/0.10	0.11/0.52	0.24/0.16
Control Efficacy	-	-	0.18/0.29	-0.10/0.60
Tension-Anxiety	-	0.19/0.28	0.17/0.34	0.28/0.10
Depression-Dejection	0.05/0.79	0.06/0.72	-0.09/0.59	-0.14/0.42
Anger-Hostility	-0.04/0.82	-0.19/0.29	-0.21/0.23	-0.23/0.19
Vigor-Activity	-	-0.21/0.22	-0.89/0.61	-0.25/0.15
Confusion-Bewilderment	0.19/0.27	0.26/0.13	0.26/0.14	0.28/0.10
Pre-study Fatigue State	-	0.23/0.19	0.24/0.17	-
Post-study Fatigue State	0.32/0.06		0.14/0.42	0.25/0.15
Magnitude associations				
Trait Anxiety	-	0.24/0.17	0.20/0.24	0.13/0.47
Pre-State Anxiety	-	0.18/0.30	0.09/0.59	0.19/0.26
Post-State Anxiety	-	0.25/0.15	0.13/0.45	0.21/0.22
Control Efficacy	0.17/0.32	0.31/0.07	0.25/0.15	0.12/0.49
Tension-Anxiety	-	0.15/0.39	0.18/0.31	0.31/0.07
Depression-Dejection	0.05/0.77	-0.10/0.57	-0.09/0.63	-0.10/0.55
Anger-Hostility	0.06/0.75	-0.13/0.47	-0.13/0.44	-0.12/0.51
Vigor-Activity	-	0.11/0.52	0.11/0.52	-0.06/0.72
Fatigue-Inertia	0.30/0.08	0.27/0.12	0.25/0.14	0.28/0.10
Confusion-Bewilderment	0.17/0.34	0.15/0.40	0.11/0.52	-0.13/0.47
Pre-study Fatigue State	0.27/0.11	-0.31/0.08	-0.28/0.10	0.28/0.10
Post-study Fatigue State	0.24/0.16	0.17/0.33	-0.13/0.45	-0.17/0.33

Note: Results are reported as correlation (*r*)/significance (*p*).

Table 4.4a Multiple regression analysis of psychological association with EEG delta amplitude changes

Regression Summary for Dependent Variable: **Frontal/Delta**

R= 0.60 R^2= 0.35, Adjusted R^2= 0.21, F (6,28)=2.49, p<0.05*, SE of estimate=8.63

n=35	β	SE of β	B	SE of B	t	p value
Intercept			0.42	13.65	0.03	0.98
Trait Anxiety	0.11	0.21	0.12	0.24	0.52	0.61
Tension-Anxiety	-0.42	0.32	-0.68	0.52	-1.30	0.20
Vigor-Activity	-0.19	0.23	-0.30	0.36	-0.84	0.41
Fatigue-Inertia	0.44	0.20	0.73	0.33	2.21	<0.04*
Pre State anxiety	0.33	0.32	0.28	0.27	1.03	0.31
Post State anxiety	0.12	0.27	0.13	0.28	0.45	0.66

Table 4.4b Multiple regression analysis of psychological association with EEG theta amplitude changes

Regression Summary for Dependent Variable: **Temporal/Theta**

R= 0.49 R^2= 0.24, Adjusted R^2= 0.19, F (2,32)=5.00, p<0.01**, SE of estimate=0.59

n=35	β	SE of β	B	SE of B	t	p value
Intercept			0.61	0.62	0.98	0.33
Trait Anxiety	0.32	0.15	0.03	0.01	2.09	0.04*
Post-study Fatigue	0.35	0.15	0.34	0.15	2.25	0.03*

Table 4.4c Multiple regression analysis of psychological association with EEG theta amplitude changes

Regression Summary for Dependent Variable: **Central/Theta**

$R= 0.51$ $R^2= 0.26$, Adjusted $R^2= 0.19$, $F(3,31)=3.72$, $p<0.02$*, SE of estimate=0.72

n=35	β	SE of β	B	SE of B	t	p value
Intercept			0.96	0.76	1.26	0.22
Trait Anxiety	0.71	0.20	0.02	0.02	0.85	0.40
Locus of Control	0.24	0.20	0.02	0.02	1.21	0.23
Post-study Fatigue	0.34	0.15	0.41	0.19	2.20	0.04*

Table 4.4d Multiple regression analysis of psychological association with EEG beta amplitude changes

Regression Summary for Dependent Variable: **Occipital/Beta**

$R= 0.57$ $R^2= 0.33$, Adjusted $R^2= 0.29$, $F(2,32)=7.78$, $p<0.002$**, SE of estimate=0.47

n=35	β	SE of β	B	SE of B	t	p value
Intercept			0.77	0.26	3.01	0.005
Fatigue-Inertia	0.31	0.15	0.03	0.01	2.07	<0.05*
Pre-study Fatigue	0.43	0.15	0.28	0.10	2.93	0.006**

Table 4.4e Multiple regression analysis of psychological association with EEG delta magnitude changes

Regression Summary for Dependent Variable: **Frontal/Delta**

$R= 0.41$ $R^2= 0.17$, Adjusted $R^2= 0.11$, $F(2,32)=3.20$, $p<0.05$*, SE of estimate=25.0

n=35	β	SE of β	B	SE of B	t	p value
Intercept			3.03	15.27	0.20	0.84
Pre State anxiety	0.14	0.24	0.32	0.55	0.58	0.58
Post State anxiety	0.29	0.24	0.86	0.70	1.22	0.23

Note

SE= Standard Error, β= the standard regression coefficient

B= unstandardized regression coefficient

Other multiple regression that did not show significance for the psychological association with the EEG magnitude for the different sites on the brain are represented in Tables 4.4f, 4.4g, 4.4h, and 4.4i. for comparison purposes.

Table 4.4f Multiple regression analysis of psychological association with EEG delta magnitude changes

Regression Summary for Dependent Variable: **Temporal/Delta**

R= 0.46 R^2= 0.17, Adjusted R^2= 0.21, F (5,29)=1.55, p=0.21, SE of estimate = 19.66

n=35	β	SE of β	B	SE of B	t	p value
Intercept			5.63	30.1	0.19	0.85
Trait anxiety	0.18	0.22	0.44	0.53	0.82	0.42
Tension-Anxiety	0.16	0.29	0.54	0.99	0.54	0.59
Vigor-Activity	-0.13	0.24	-0.44	0.81	-0.54	0.59
Pre State Anxiety	0.10	0.32	0.17	0.56	0.31	0.76
Post State Anxiety	-0.01	0.29	-0.03	0.65	-0.04	0.97

Table 4.4g Multiple regression analysis of psychological association with EEG delta magnitude changes

Regression Summary for Dependent Variable: **Central/Delta**

R= 0.43 R^2= 0.19, Adjusted R^2= 0.08, F (4,30)=1.73, p=0.17, SE of estimate = 19.83

n=35	β	SE of β	B	SE of B	t	p value
Intercept			-3.97	16.91	-0.23	0.82
Trait Anxiety	0.17	0.22	0.43	0.53	0.80	0.43
Tension-Anxiety	0.19	0.29	0.67	1.00	0.68	0.50
Pre State anxiety	0.04	0.30	0.07	0.54	0.14	0.89
Post State anxiety	0.10	0.27	0.22	0.62	0.35	0.73

Table 4.4h Multiple regression analysis of psychological association with EEG delta magnitude changes

Regression Summary for Dependent Variable: **Parietal/Delta**

R= 0.42 R^2= 0.17, Adjusted R^2= 0.06, F (4,30)=1.57, p=0.21, SE of estimate = 19.64

n=35	β	SE of β	B	SE of B	t	p value
Intercept			14.58	29.17	0.50	0.62
Tension-Anxiety	0.19	0.29	0.67	0.99	0.68	0.50
Vigor-Activity	-0.10	0.24	-0.32	0.81	-0.39	0.70
Pre State anxiety	0.11	0.32	0.19	0.56	0.35	0.73
Post State anxiety	0.07	0.27	0.15	0.60	0.25	0.80

Table 4.4i Multiple regression analysis of psychological association with EEG delta magnitude changes

Regression Summary for Dependent Variable: **Occipital/Delta**

R= 0.44 R^2= 0.19, Adjusted R^2= 0.05, F (5,29)=1.39, p=0.26, SE of estimate = 19.48

n=35	β	SE of β	B	SE of B	t	p value
Intercept			9.76	29.83	0.33	0.75
Trait Anxiety	0.19	0.22	0.46	0.53	0.87	0.39
Tension-Anxiety	0.22	0.29	0.73	0.98	0.74	0.46
Vigor-Activity	-0.15	0.25	-0.50	0.81	-0.62	0.54
Pre State anxiety	-0.06	0.32	-0.10	0.55	-0.18	0.86
Post State anxiety	0.03	0.29	0.06	0.64	0.10	0.92

The subjects also completed a self-rated Fatigue State questionnaire before the simulated driving task. The results of physical and mental fatigue states of the subjects and the individual fatigue items are shown in Table 4.5.

Table 4.5 The self-rated Fatigue State questionnaire: scored according to number (percentage) of subjects responding in each category

Fatigue State	**Number of subjects in each category**		
	same as usual	worse	much worse than usual
Physical Fatigue			
I get tired easily	26 (74.3%)	7 (20%)	2 (5.7%)
I need to rest more	23 (65.7%)	11 (31.4)	1 (2.9%)
I feel sleepy or drowsy	23 (65.7%)	11 (31.4)	1 (2.9%)
I can no longer start anything	31 (88.6%)	3 (8.6%)	1 (2.9%)
I am always lacking in energy	24 (68.6%)	11 (31.4%)	-
I have less strength in my muscles	27 (77.1%)	8 (22.9%)	-
I feel weak	30 (85.7%)	4 (11.4%)	1 (2.9%)
I can start things without difficulty, but get weak as I go on	26 (74.3%)	9 (25.7%)	-
Mental Fatigue			
I have problems concentrating	27 (77.1%)	6 (17.1%)	2 (5.7%)
I have problems thinking clearly	29 (82.9%)	4 (11.4%)	2 (5.7%)
I have more slips of the tongue, or have problems finding the correct word	24 (68.6%)	8 (22.9%)	3 (8.6%)
I have problem with eyestrain	25 (71.4%)	7 (20%)	3 (8.6%)
I have problems with memory	30 (85.7%)	1 (2.9%)	4 (11.4%)

4.4 Discussion

The nature of driving requires cognitive effort, such as sustained vigilance, selective attention, complex decision-making and the exercise of largely automated perceptual motor-control skills (Brown, 1994). In early research, fatigue was conceptualised as a generalised response to stress experienced over time (Cameron, 1973). In other words fatigue was viewed as not only the experience of symptoms associated with continuous work but also as the individual's ability to cope with the stressful demands that are responsible for those symptoms. Fatigue could therefore be viewed as a condition determined by both physiological and psychological factors. Since psychological and physiological changes are thought to be associated with fatigue, the current research aimed to isolate any psychological factors that were associated with physiological changes in the EEG that occur during fatigue. It was found that EEG changes occurring during the transition to fatigue in a simulated driving task were associated with psychological factors such as anxiety and mood. This suggests that psychological factors can influence fatigue status and hence driving performance. 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, it was found that increased trait and state anxiety, and negative mood states such as Tension-Anxiety and Fatigue-Inertia were associated with EEG indicators of fatigue such as increased delta and theta levels. The results showed that having higher levels of anxiety were associated with higher levels of theta activity suggesting increased anxiety status raises the potential to become fatigued. In this 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 quite impressive. The results also indicate that having a higher Tension-Anxiety level, suggesting heightened musculoskeletal tension was also associated with an increased risk of experiencing fatigue. The Tension-Anxiety mood sub-scale 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 was also positively correlated to the EEG of fatigue. Fatigue-Inertia represents a mood of weariness, inertia and low energy levels. Not surprisingly, Vigor-Activity was negatively associated with increased delta activity occurring during fatigue. As the name suggests, this factor indicates a lack of vigorousness and high energy. Increased trait anxiety levels predicted theta increase and Fatigue-Inertia predicted beta changes during fatigue. Personality traits can be conceptualised as relatively enduring differences among people in specifiable tendencies to perceive the world in a certain way and in dispositions to react or behave in a specified manner with predictable regularity (Spielberger et al., 1983). Trait-anxiety refers to relatively stable individual differences in anxiety-proneness, that is, to differences between people in the tendency to perceive stressful situations as dangerous or threatening and to respond to such situations with elevations in the intensity of their state anxiety reactions (Spielberger et al., 1983). It is important to distinguish the effects of the two types of anxiety (state-trait anxiety and Tension-Anxiety, a mood sub-scale). Distinguishing types of anxiety may clarify the different associations found between brain activity and anxiety. For example, anxious apprehension and anxious arousal have been hypothesised to be psychologically distinct phenomena. Studies on regional brain activity have shown these two to be distinguished neurophysiologically (Heller et al., 1997). Therefore, in studies of brain activity for anxiety and mood states, it is important to specify the type of anxiety under examination.

For practical purposes, fatigue may be conceptualised as the subjective experience of individuals who continue working beyond the point at which they are confident of performing their task efficiently. The experience of fatigue may therefore be regarded as behavioural and physiological feedback that provides a protective function, in that it predisposes the individual's response toward recovery and the avoidance of further stress. The results of this research suggests that being more anxious, having higher levels of psychomotor tension, cognitive inefficiency and low energy levels may hinder performance by raising the chances of becoming fatigued. This is the first study that has identified the possibility that mood states such as vigour, fatigue and anxiety may affect a driver's fatigue state and performance.

From the self-rated Fatigue State questionnaire, it was evident that similar numbers of subjects were suffering from physical (66%-89%) and mental fatigue (69%-86%) on the day of the study, similar to what they normally experience. However, the remainder of subjects reported that their fatigue levels were worse or much worse than usual. Given that the subjective component of fatigue is very important, then questionnaire investigations may be beneficial in the study of driver fatigue. Based on the assessment of the physical fatigue levels (Table 4.5), 12 subjects needed to rest more and felt more drowsy than usual. Eleven subjects reported lack of energy and 8 found less strength in their muscles than usual. Nine subjects found that they could start things without difficulty but they got weaker much more than usual as they continued.

The assessment of physical fatigue denotes the amount of reduced performance of a muscle after stress and is characterised by reduced power and movement. Physical fatigue impairs co-ordination and increases chances of errors and accidents (Grandjean, 1979). Physical fatigue is a complex phenomenon influenced by numerous psychophysiological factors and is associated with: (1) A decline in alertness, mental concentration and motivation. (2) Reduced work output. (3) Weaker and slower muscular contractions. (4) Muscular tremor and localised 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. (10) Increased core temperature (Åstrand & Rodahl, 1986; Basmajian & De Luca, 1985).

From the mental fatigue assessment (refer to Table 4.5), 8 to 11 subjects stated that their concentration, slips of the tongue and eyestrain were worse or much worse than usual. In their present lifestyle, six reported more problems than usual in thinking clearly and five reported more problems with memory. Mental fatigue is believed to be a gradual and cumulative process that is linked to disinclination for any effort, reduced efficiency and alertness and impaired mental performance (Grandjean, 1979; Grandjean, 1988). However, it should be understood that many factors could influence fatigue such as nutrition, physical health (Wisner, 1981), environment, physical activity (Sjoberg, 1980) and recuperation periods (Okogbaa et al., 1994). Mental fatigue leads to a sensation of weariness, feelings of inhibition and impairs everyday activity. Generally, there is no desire for physical or mental effort and there is a heavy, drowsy feeling. A feeling of weariness is not unpleasant if allowed to rest, but can be distressing if an individual is not allowed to rest.

The above findings suggest that self-rated questionnaires can provide useful information on the fatigue experienced by a person in their lifestyle. It can also provide information about fatigue such as the time fatigue occurs and any factors contributing to fatigue. In a survey study of truck drivers, 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. However, it should be pointed out that in the research cited, the subjects were assessed at the end of driving, where symptoms of fatigue are most prominent. In the current doctoral research, the self-reported questionnaire results indicating fatigue in the subjects was reflected by slow wave activity in the EEG that appeared during fatigue (refer to Chapter 3). Another study of night driving also found changes in the EEG alpha and theta bands; and the self-rated fatigue outcome reflected the changes in the EEG data (Torsvall & Åkerstedt, 1983).

It should be noted that to maintain scientific validity, questionnaires alone cannot be the sole indicator/identifier of fatigue symptoms. Objective measures need to accompany these questionnaires for verification of fatigue. Questionnaire and survey research has limitations. For instance, they cannot provide moment-to-moment reports of fluctuations of sleepiness. Also self-report techniques could hardly be considered to measure sleepiness per se. Survey research is also prone to low validity and poor reliability. It would therefore be preferable to include both self-report and objective physiological measures when conducting fatigue related research. Not withstanding this, the findings from this study suggest that fatigue research would benefit from psychological assessments of mood states, anxiety as well as self-reported fatigue levels together with assessment of physiological changes. The chapter that follows reports on the changes that occurs in heart rate and heart rate variability during driver fatigue.

Chapter Five

Heart Rate and Heart Rate Variability as an Indicator of Driver Fatigue Assessment

5 Introduction

For many years investigators have been searching for a reliable and valid physiological index of fatigue. Amongst this heart rate (HR) has been evaluated as a measure, however its association with driver fatigue is still unclear, and more information is needed. In road safety research HR is thought to show an inverse relationship with hours driven (Egelund, 1982). However, light physical activity imposed by vehicle control or psychological stress produced by traffic demands can produce increases in heart rate. Therefore, it would be profitable to use a measure more independent of vehicle manoeuvring and transient traffic events. Heart rate variability (HRV) is known to be independent of such influences (Egelund, 1982) and furthermore, it has the potential value of being a non-invasive measure of autonomic nervous system activity. Therefore, assessment of HRV during driving can provide information on the changes that occur in sympathetic and parasympathetic activity during driving. Before discussing the use of HRV to identify autonomic activity, it is important to understand the autonomic, sympathetic and parasympathetic nervous system activity that HRV measures.

5.1 The Autonomic Nervous System

The autonomic nervous system (ANS) is the regulator and coordinator of activities such as digestion, body temperature, blood pressure, heart rate and many aspects of emotional behaviour (Andreassi, 2000b). The ANS innervates three types of cell: smooth muscle, cardiac muscle, and glandular cells. The main neurotransmitters of the ANS are acetylcholine and norepinephrine. Acetylcholine is the neurotransmitter of the parasympathetic nervous system (cholinergic system) while norepinephrine is a neurotransmitter of the sympathetic nervous system. Organs such as the heart, eyes, stomach and lungs have both parasympathetic and sympathetic input. The sympathetic and parasympathetic division of the ANS differ structurally, functionally, and chemically but work together to maintain homeostasis.

5.1.1 The sympathetic nervous system

The sympathetic nervous system (SNS) controls those activities that are mobilised during emergency and stress situations, the well-known "fight-or-flight" response. The sympathetic reactions include expenditure of energy, the acceleration of heart rate, increased cardiac output, increased blood pressure, increased blood flow to the voluntary muscles, decreased blood flow to internal organs, and increased sweating (Andreassi, 2000b). Thus, the sympathetic response to threat is very adaptive because it enhances survival.

5.1.2 The parasympathetic nervous system

The parasympathetic nervous system is the system for rest, repair, relaxation and restoration of energy stores. The reactions under control of this system include decreases in heart rate and blood pressure, arousal, resting and sleep (Andreassi, 2000b). Although the sympathetic and parasympathetic systems have contrasting functions, the activities are integrated and not antagonistic. The systems tend to act in a complementary fashion with a great deal of reciprocity that usually enables a smooth flow of activities and behaviour.

5.2 Physiological and Autonomic Implications of Heart rate and Heart Rate Variability effects during Fatigue and Drowsiness

5.2.1 Heart rate variability

The sinus rhythm heart rate varies with time. This variability depends on physiologic control systems, including the sympathetic and parasympathetic autonomic nervous systems. Short-term heart rate changes occur because of autonomic responses. The variation of heart rate is mediated by the sinus (sino-atrial) node via sympathovagal influences. Spectral analysis of HR fluctuation is a well-established method of investigating the autonomic nervous system (Baharav, et al., 1995). HRV is a non-invasive procedure and the readily available computer facilities help to explain why it is rapidly becoming widely used to explore the autonomic nervous system. HRV reflects the status of the heart and the reaction of the autonomic nervous system in compensating for hemodynamic changes. The spectral computations reveal two main components of HRV. The two main spectral regions of interest are (1) a low frequency (LF) component and (2) a high frequency (HF) component. In steady-state conditions, regular fluctuations can be seen in heart rate. These oscillations are due to breathing (respiratory sinus arrhythmia at about 0.25 Hz), a lower 0.1 Hz rhythm and a much slower fluctuation related to sleep, activity and temperature control. The higher frequencies are believed to reflect parasympathetic activity, and lower frequencies are believed to reflect sympathetic activity (Baharav, et al., 1995). The parasympathetic origins of high frequency fluctuations are generally accepted. The interpretation of changes in lower frequencies is controversial. Some believe that LF activity is a composite of parasympathetic and sympathetic influence (Baharav, et al., 1995). Since the neuroautonomic influence at the low end of the spectrum is complex, a useful way to study the autonomic activity by means of spectral analysis is to define a sympathovagal balance or a sympathetic index. The sympathovagal balance or sympathetic index is derived by dividing the LF activity by either the HF activity or total spectral activity, that is, LF: HF or LF: total spectrum (Baharav, et al., 1995; Jaffe et al., 1993).

The monitoring of heart rate is commonly used and reported as a measure of variation in workload and changes in alertness levels. However, there is no such consensus for measurement of heart rate variability. The main cause for this is the use of many different statistical and time-domain scores and also different spectral bands for specifying the different components of HRV. However, Jaffe et al. (1993) have defined the optimal frequency ranges for extracting information of autonomic activity from the heart rate spectrogram. These authors believe that the optimal frequency ranges they describe, provide a more accurate measure of sympathetic (<0.1 Hz and >0.05 Hz and dividing by the total spectral amplitude (0.004-0.5 Hz)) and parasympathetic activity (0.1 Hz to a frequency greater than that of the respiratory sinus arrhythmia) derived from the heart rate spectrogram (Jaffe et al., 1993). Recently standards have also been produced for measuring heart rate variability (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996).

5.2.2 Heart rate variability as an indicator of fatigue/sleepiness and workload

The study of changes in HRV during fatigue is a relatively new area of research. In a passive monitoring task a study found that when fatigue occurred and reduced the subject's attention levels, the initial decrease in HRV was changed into a gradual increase in HRV (O'Hanlon, 1971). In a subsequent field test by the same investigator, subjects driving on long highway circuits showed substantial increases in HRV with driving time (O'Hanlon, 1971). It has been suggested that long working hours (which have a significant relationship to drowsiness) might lower sympathetic nervous activity due to chronic sleep deprivation (Sasaki, et al., 1999). Another study revealed that a decrease in LF components of HRV occurs during sleep, with minimal values evident during non-REM (rapid eye movement) slow-wave sleep (Baharav, et al., 1995). Furthermore, HF components have been shown to increase during sleep onset, reaching maximal values during slow wave sleep. The LF/HF ratio, a measure of the sympathetic index displayed similar changes to those in LF.

Studies have shown cardiac sinus arrhythmia to be highly correlated with mental workload (Vincent, Thornton, & Moray, 1987). These authors also found that the mid-frequency band of the spectrum of HRV, between 0.06-0.14 Hz, decreased substantially in response to increasing demands of a mental task. Others have proposed that sinus arrhythmia decreased as controlled mental effort increased in response to a demanding mental task (Hartley & Arnold, 1994). Furthermore, the mid-frequency component of the heart rate variability spectrum was shown to be free of the influence of respiration rate, motor activity and thermoregulation (Hartley & Arnold, 1994). Accordingly, this measure has been suggested to be one of the best independent, physiological measures of the mental demands of tasks. It is therefore a potential candidate for measuring fatigue arising from the demands of vehicle driving (Hartley & Arnold, 1994).

5.2.3 Heart rate variability as an indicator of driver fatigue

Heart rate has been used as a physiological measure of workload especially during driving conditions. Heart rate generally decreases during prolonged night driving (Riemersma et al., 1977). Another study found that the variability of heart rate and feelings of fatigue were associated with deterioration in driving (Harris, et al., 1972), while others have reported distinctly higher heart rate variability among drivers of motor vehicles after long test-drives (O'Hanlon, 1971). This observed rise in total HRV was interpreted as a sign of diminished alertness. Others have also shown a significant relationship between increased HRV and the distance of driving and concluded that the 0.1 Hz HRV was a sensitive indicator of driver fatigue (Egelund, 1982).

5.2.4 Relationship between heart rate variability and electroencephalography during fatigue/sleepiness

Some investigators have shown that changes in HRV precede recordable changes in brain activity (Otzenberger, Simon, Gronfier, & Brandenberger, 1997). They demonstrated that beat-to-beat HRV and EEG activity were closely linked during sleep. These authors also suggested that using spectral analysis of the sleep EEG allows a more detailed description of brain activity than visual EEG sleep stage scoring. They found continuous changes in HRV preceding variations in sleep EEG activity, with larger more regulated interbeat variations when sleep becomes lighter and, conversely, with smaller and less coordinated interbeat variations when sleep becomes deeper. This has implications for the different stages of fatigue where the deeper stage of fatigue is generally characterised as Stage I of sleep. To date, no study has investigated the correlation between HRV and EEG activity during different fatigue stages in humans.

The aim of this particular study was to examine the changes in HRV during the transition from alert to early (transitional phase) and deep fatigue states (post-transitional phase) during a driver simulator task. A further aim was to compare the sensitivity of the 'LF: HF' ratio and 'LF: total spectral activity' ratio in providing a measure of the sympathetic index. Another aim of the research was to identify the relationship between changes in two physiological indicators i.e. variables derived from the electrocardiogram (ECG) and EEG during driver fatigue. The hypotheses generated for this investigation were that during transition from an alert to a fatigue/drowsy state during a monotonous, simulated driving task there will be:

1) A decrease in HR and a decrease in total HRV
2) An increase in sympathetic activity and a corresponding decrease in parasympathetic activity.
3) An association between heart rate fluctuations and EEG activity.

5.3 Methods

For complete details on the general experimental procedure and study design refer to Chapter 2.

5.3.1 Subjects

Thirty-five non-professional drivers (26 males and 9 females), aged 21-52 (34 $\pm$ 21) years, were recruited from a tertiary institution and the local community and randomly assigned to the study. Refer to Chapter 2 for details on subject recruitment and experimental procedures.

5.3.2 Study protocol

All subjects performed a standardised sensory motor driver simulator task in a temperature-controlled laboratory. The subjects were familiarised with the driving apparatus during 5-10 minutes of active driving. This was followed by approximately two hours of driving (speed < 80 km/hr) till the subjects started to show signs of fatigue and drowsiness indicated on a video recording.

Whilst driving, simultaneous ECG and EEG measures were taken. Three lead analogue ECG were recorded via disposable electrodes (Red dot, Ag/AgCl, Health Care, Germany) placed on the chest, one reference and two active electrodes. Just before and immediately after the driving task pulsated heart rate was measured. EEG measures were obtained from nineteen channels according to the International 10-20 system (Fisch, 1991b) (refer to Chapter 2 for complete details on EEG methodology).

5.3.3 Data acquisition and analysis

The ECG and EEG data were acquired using a physiological data acquisition monitor (Neurosearch-24, Lexicor, USA). Each beat-to-beat heart rate recording period was for a duration of one second and comprised of 256 data points. Each sequence of successive heartbeat was sampled at equidistant time points, which is important when using fast Fourier transform (FFT) (Bates, Hilton, Godfrey, & Chappell, 1997). Total sampling time for all the subjects was between 30-45 minutes. An in-house software program was used to convert the binary HR data to a text file. A FFT was then applied on approximately 10 minutes of HR data segments from an alert baseline, 10 minutes from the transitional phase to fatigue and 10 minutes from a post-transitional phase (Santamaria & Chiappa, 1987a). Therefore, a total of thirty minutes of data was analysed for each subject. To compute a HR power spectrum for frequencies above 0.01 Hz, a 5-minute data segment is sufficient for analysis(Appel, Berger, Saul, Smith, & Cohen, 1989). Using 10 minute data segments in this research provided adequate reliability and resolution of the data analysed in the frequency domain. Furthermore, HRV data are non-stationary i.e. it is variable with each heart beat, and performing frequency domain analysis on 10 minute data series makes the effect of non-stationarity negligible and reduces noise effects (Bates et al., 1997). The FFT involved computing a sum of sine waves of different amplitudes and frequencies from the raw HR signal. The FFT produced a HR power spectrogram (unit beats/min^2/Hz). The power spectrum presents the squared amplitude of the sine waves as a function of frequency (Appel et al., 1989). For HRV analysis, the frequencies of interest are <1 Hz. The different regions of HR variability in the power spectrum (area under the curve) computed were composed of the: LF range (0.05-0.1 Hz), HF range (0.1-0.35 Hz) and total spectral range (0.004-0.5 Hz) (according to specifications on optimal frequency ranges for HR spectrogram (Jaffe et al., 1993)).

5.3.4 Statistical analysis

A statistical analysis package, Statistica (Statistica for Windows, V 5.5, 1999, StatSoft, USA) was used for subsequent data analysis. The differences between pulsated HR measured before and after the driving task were compared using paired Student's *t* test. The HR variability in the fatigue phases was compared to the alert baseline using a repeated measures analysis of variance (ANOVA). A post hoc analysis using a Scheffé test was used to determine where the differences existed in the comparison of the means.

The EEG was defined in terms of frequency bands including delta (0-4 Hz), theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) (Fisch, 1991b). For each band the average EEG magnitude (μV) and maximum amplitude (μV) were computed (for details on analysis refer to Chapter 2 and for details on EEG changes during different stages of fatigue refer to Chapter 3). The HR changes from before to after the driving task were correlated to EEG changes (calculated as average EEG activity in the delta, theta, alpha and beta bands across the entire head) during transition to fatigue using Pearson's correlation. To identify EEG links with autonomic activity, the EEG changes in the alert and transition and post transitional fatigue phases were also correlated to the HRV in the LF, HF bands, the total spectrum band and for the LF: HF ratio using Pearson's correlation. The significance level was set at $p<0.05$ for all analyses performed.

5.4 Results

5.4.1 Fatigue, HR and HRV effects

Heart rate was significantly different ($t=5.9$, $df=34$, $p<0.01$) from before (68 ± 11 beats/min) to after the driving task (62 ± 10 beats/min). It had reduced by approximately 6 ± 6 beats/minute, suggesting that the subjects were in a fatigued, sleepy mode at the end of the driving task. This effect was confirmed with the response of subjects to the fatigue state question where the subjects reported moderate to extreme fatigue after the driving task (refer to chapter 4 for details). This negates the fact that sitting for the duration of the study may have induced reductions in heart rate. The mean HR power density computed for the different spectral regions for the alert, transition to fatigue and post-transitional phases are shown in Table 5.1.

Table 5.1 Spectral Power of Heart Rate Variability-effect of fatigue (beats/min^2/Hz)

Spectral Region	Alert	Transition to Fatigue Phase	Post-transitional Fatigue Phase
LF: 0.05-0.1 Hz	$4.03 \times 10^2 \pm 2.30 \times 10^2$	$3.90 \times 10^2 \pm 2.32 \times 10^2$	$4.01 \times 10^2 \pm 2.26 \times 10^2$
HF: 0.1-0.35 Hz	$8.91 \times 10^2 \pm 6.44 \times 10^2$	$6.47 \times 10^2 \pm 6.0 \times 10^2$	$6.74 \times 10^2 \pm 5.73 \times 10^2$
Total: 0.004-0.5 Hz	$17.91 \times 10^2 \pm 10.77 \times 10^2$	$15.36 \times 10^2 \pm 9.74 \times 10^2$	$16.11 \times 10^2 \pm 9.53 \times 10^2$
LF: HF	$54.9 \times 10^{-2} \pm 31.7 \times 10^{-2}$	$73.5 \times 10^{-2} \pm 38.3 \times 10^{-2}$	$73.1 \times 10^{-2} \pm 39.0 \times 10^{-2}$
LF: total spectrum	$23.5 \times 10^{-2} \pm 6.7 \times 10^{-2}$	$25.7 \times 10^{-2} \pm 7.0 \times 10^{-2}$	$25.6 \times 10^{-2} \pm 7.1 \times 10^{-2}$

(LF band optimised according to Jaffe et al., 1993)

As shown in Table 5.1, HRV decreased in the HF region from the alert to the fatigue phases. The HR variability in the HF region was highest during alert and the lowest in the transitional phase. On the other hand, LF region did not show a change from the alert to the fatigue phase. There was an increase in the LF: HF ratio and the LF: total spectrum ratio in the fatigue phases compared to the alert baseline. Total HRV was also found to decrease during transition to fatigue.

An ANOVA analysis on the different spectral components of HR variability revealed differences between the three phases tested. The effects were: LF: ($F=0.44$, $df=2,68$, $p=0.65$, ns), HF ($F=8.2$, $df=2, 68$, $p<0.0007$), total power: ($F=4.2$, $df=2,68$, $p=0.02$). As mentioned previously (refer to section 5.2.1) autonomic activity can be obtained using spectral analysis to define a sympathovagal balance or a sympathetic index i.e. the LF: HF or LF: total spectral activity ratios (Baharav, et al., 1995; Jaffe et al., 1993). The ANOVA effects on LF: HF were also significantly different for the three phases (F=14.9, df=2,68, p=0.000004). Table 5.1 also shows the LF: total spectrum, calculated according to the optimal description of the sympathetic index as a division of the LF band by the total spectral amplitude (Jaffe et al., 1993). Using this method substantial differences were evident between the three phases (F=11.59, df=2,68, p=0.000047).

In the post hoc analyses the transitional and post transitional fatigue phases were compared to the alert baseline for HR variability in the LF, HF and total spectrum regions. The results are summarised in Table 5.2. The analysis showed that the HR variability in the LF region was not different for the three phases. The HF region during the transitional phase and the post-transition phases were significantly different to the alert baseline (p=0.002 and p=0.007, respectively). The total HR variability during transition to fatigue was significantly different to the alert baseline (p=0.02) but the post transitional phase was not different to the alert baseline (p=0.15, ns). The LF: HF ratio in the two fatigue phases were significantly different to the alert phase (p=0.000052 and p=0.000076, respectively). A similar outcome was observed for the LF: total spectrum ratio when the fatigue phases were compared to the alert baseline (p=0.00028 and 0.0007, respectively). Since both the LF: HF ratio and the LF: total spectrum ratio are equally sensitive in defining sympathetic activity, only LF: HF ratio is incorporated into all following analyses.

Table 5.2 A comparison of the fatigue phases to the alert baseline using post-hoc comparison of the means (Scheffé test)

Spectral Region	**Scheffé Test**	
	Alert versus transition	Alert versus post transition
LF: 0.05-0.1 Hz	0.69	0.99
HF: 0.1-0.35 Hz	0.002**	0.007**
Total: 0.004-0.5 Hz	0.02*	0.15
LF: HF	0.000052**	0.000076**
LF: total spectrum	0.00028**	0.0007**

Note: p values are shown, * p<0.05, ** p<0.01

5.4.2 Association between cardiovascular and EEG changes during fatigue

The mean HR decrease from before to after the driving task was significantly associated with theta (r=-0.36, p=0.03) and alpha (r=-0.34, p=0.04) changes during transition to fatigue. Beta activity tended towards association (-0.31, p=0.07) while delta did not show any significant correlation with HR changes (r=-0.26, p=0.14, ns).

The correlation results of the spectral components of HR variability versus the EEG amplitude and magnitude changes are shown in Table 5.3 and 5.4, respectively for the alert baseline, transition phase and the post transitional phase to fatigue. During the alert phase the alpha and beta amplitude activity were linked to HR variability for LF: HF (r=0.46, p=0.006 and r=0.60, p<0.0001). Alpha and beta activity were also associated with LF: HF (r=0.51, p=0.002 and r=0.43, p=0.01, respectively) during transition to fatigue. Furthermore, theta activity was linked with HR variability in the HF band (r=-0.35, p=0.04). During the post-transitional phase to fatigue, HR variability in the HF region was linked to beta activity (r=-0.34, p=0.045). The LF: HF ratio was linked with alpha and beta activity (r=0.50, p=0.002 for both). Figures 5.1 and 5.2 show examples of the correlation and linear regression between LF: HF and the changes during transition to fatigue in alpha and beta amplitude.

The EEG magnitude changes showed links with beta activity and LF: HF (r=0.48, p=0.003) during the alert phase. During transition to fatigue, beta was associated with HRV in the LF region (r=0.36, p=0.03) and in the total spectrum (r=0.38, p=0.02). There were no associations between EEG magnitude changes and HRV in the post-transitional phase.

Table 5.3 Associations between HR variability and EEG amplitude changes

	EEG band			
HRV Factor	**Delta**	**Theta**	**Alpha**	**Beta**
Alert				
LF	-0.16/0.36	0.20/0.25	0.20/0.24	0.19/0.28
HF	-0.22/0.20	-0.18/0.30	-0.18/0.30	-0.21/0.22
Total Spectrum	0.22/0.20	-0.15/0.38	0.10/0.58	-0.09/0.62
LF: HF	0.21/0.23	0.29/0.09	0.46/0.006**	0.60/<0.0001**
Transition to Fatigue				
LF	0.25/0.15	0.11/0.54	0.16/0.36	0.24/0.16
HF	0.12/0.48	-0.35/0.04*	-0.31/0.07	-0.30/0.08
Total Spectrum	0.16/0.35	-0.16/0.35	-0.07/0.67	-0.13/0.47
LF: HF	0.09/0.60	0.31/0.07	0.51/0.002**	0.43/0.01*
Post-transitional				
LF	-0.12/0.49	-0.07/0.70	0.21/0.24	0.12/0.50
HF	0.10/0.57	-0.24/0.17	-0.32/0.06	-0.34/0.045*
Total Spectrum	-0.09/0.61	-0.11/0.53	-0.07/0.68	-0.22/0.20
LF: HF	-0.07/0.67	0.27/0.12	0.50/0.002**	0.50/0.002**

Note: Results are reported as correlation (*r*)/significance (*p*).

* p<0.05, ** p<0.01

Table 5.4 Associations between HR variability and EEG magnitude changes

	EEG band			
HRV Factor	**Delta**	**Theta**	**Alpha**	**Beta**
Alert				
LF	-0.19/0.26	0.15/0.38	0.17/0.32	0.14/0.42
HF	0.20/0.25	0.12/0.50	-0.06/0.74	-0.07/0.70
Total Spectrum	0.20/0.25	-0.14/0.44	0.14/0.44	0.06/0.75
LF: HF	-0.23/0.18	0.06/0.72	0.30/0.08	0.48/0.003**
Transition to Fatigue				
LF	0.21/0.23	0.14/0.43	0.20/0.25	0.36/0.03*
HF	0.30/0.08	0.22/0.20	0.12/0.50	0.33/0.05
Total Spectrum	0.26/0.13	0.25/0.14	0.21/0.22	0.38/0.02*
LF: HF	-0.13/0.45	-0.23/0.17	0.18/0.31	-0.17/0.33
Post Transitional				
LF	-0.09/0.62	0.11/0.52	0.20/0.26	0.17/0.32
HF	0.17/0.34	0.21/0.22	0.05/0.77	0.10/0.57
Total Spectrum	0.08/0.66	0.18/0.31	0.17/0.32	0.12/0.51
LF: HF	-0.20/0.26	-0.15/0.38	0.17/0.32	0.13/0.47

Note: Results are reported as correlation (*r*)/significance (*p*).

* $p<0.05$, ** $p<0.01$

Figure 5.1 The correlation and linear regression between LF: HF and alpha amplitude during transition to fatigue

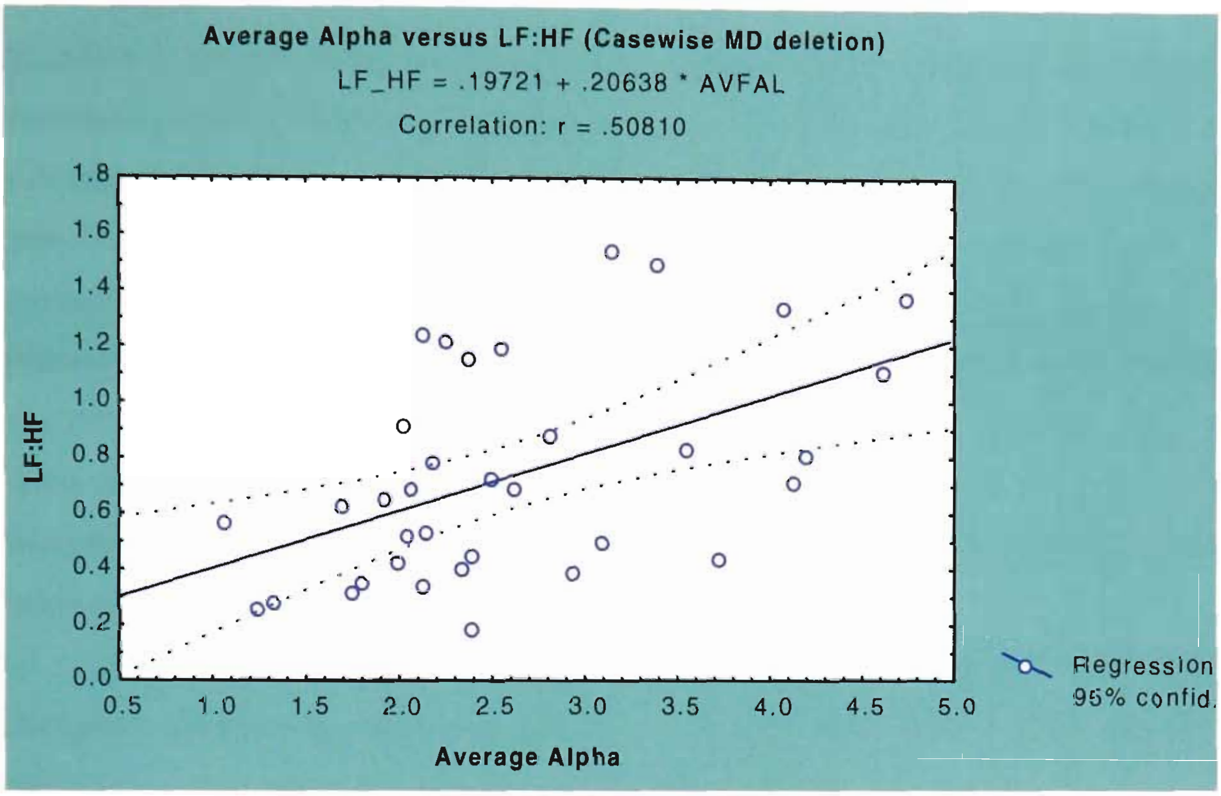
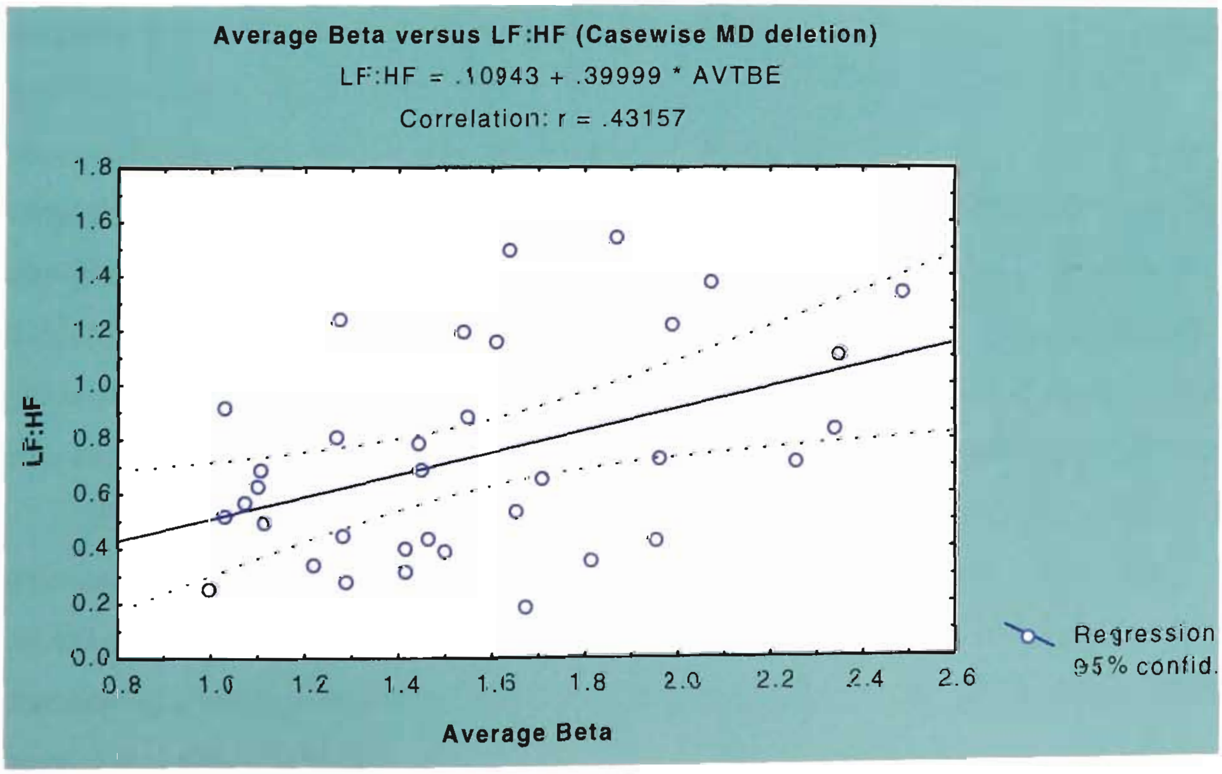


Figure 5.2 The correlation and linear regression between LF: HF and beta amplitude during transition to fatigue



5.5 Discussion

5.5.1 Using spectral analysis of HR to identify autonomic effects during driver fatigue

Significant changes occur in the HR of healthy subjects associated with driver fatigue experienced during a continuous driving task. In this study it was found that there was a substantial decrease in average HR of nearly 6 beats/minute after the simulated driving task. While some of this HR decrease could be due to relaxation, all subjects rated themselves as fatigued (refer to Chapter 4 for details), suggesting fatigue was the primary cause of the HR decrease. From the present study and those of others (Vivoli et al., 1993), it is most likely that the changes found in HR during driving associated with stress and fatigue are mediated through the autonomic nervous system. However, a more elaborate investigation of the autonomic influences during driver fatigue can be achieved by analysing heart rate variability.

Analysis of changes in HRV can be useful in determining the functional state of the body's autonomic systems. One major advantage of HRV analysis is its potential value as a non-invasive measure of sympathetic and parasympathetic autonomic nervous system activity. Studies have utilised the traditional measure of overall or total spectrum variability to indicate the changes in HRV that occurs during fatigue and increased workload (Luczak & Laurig, 1973; O'Hanlon, 1971). It has been reported that in a passive-monitoring task, when fatigue reduced the subject's attention, the initial decrease in HRV changed to a gradual increase (O'Hanlon, 1971). In the present study a similar trend of an initial decrease in HRV of nearly 2.5 x 10^2 beats/min^2/Hz was observed during transition to fatigue. However, as the subjects' progressed into deeper stages of fatigue there was a slight increase in total HRV but it was still lower than the alert baseline by approximately 2.0 x x10^2 beats/min^2/Hz. When using total HRV, it is difficult to explain the changes that are occurring specifically in the sympathetic and parasympathetic nervous system during fatigue. Therefore in the present research, data was also analysed to derive a LF sympathetic index and a HF parasympathetic activity.

The analyses of HRV data showed that the LF region during the fatigue states were not different to the alert baseline. In contrast, decreases of greater than 2 x 10^2 beats/min^2/Hz were observed in the HF region during the transitional and post-transitional phases of fatigue when compared to the alert baseline. HF decreased in the transitional phase to fatigue compared to the alert baseline. It increased slightly from the transitional to the post-transitional phase of fatigue. The results indicate that there was an overall decrease in parasympathetic activity during driver fatigue. Another study observed that the 0.1 Hz HRV increased during six stretches of continuous driving which was linked to a high fatigue situation (Egelund, 1982). However by restricting the sympathetic bands to below 0.1 Hz and above 0.05 Hz and dividing by the total spectral amplitude (Jaffe et al., 1993), a more accurate sympathetic index is derived. This method of deriving the sympathetic index accounts for the parasympathetic fluctuations within the sympathetic band. It has been identified previously that the LF spectrum is influenced by sympathetic and parasympathetic control (Jaffe et al., 1993). Therefore in the present study, calculating sympathetic index by dividing the LF activity by the total spectrum revealed increases in sympathetic activity during the fatigue states incurred from driving. Furthermore, the conventional method of deriving the sympathetic index using the LF: HF ratio displayed similar effects to those for LF: total spectrum ratio.

Therefore the sympathetic index derived from LF: HF ratio shows that the sympathetic activity increased during onset of fatigue and that this increase persisted into the deeper states of fatigue. The autonomic balance is shifted towards sympathetic predominance while parasympathetic activity decreases. The results of the present analysis confirm a previous theory that a direct relationship exists between fatigue and heart rate variability (O'Hanlon, 1971). The increased HRV in this study occurs in the variable denoting the sympathetic index, that is, LF: HF. According to Jaffe et al. (1993), the sympathetic index is considered to be more sensitive than identifying the HRV in the LF region measured for detecting sympathetic effects. Several studies have shown that the sympathetic nervous system has a restricted frequency response (Akselrod, et al., 1985; Saul, et al., 1991), increasing the expectation that the spectral analysis of the time varying HR will allow separation of the sympathetic and parasympathetic systems into different frequency domains. Although sympathetic nervous system mediated HR fluctuations occupy a limited range of the spectrum, parasympathetic system fluctuations do not (Akselrod, et al., 1985). Thus identification of sympathetic activity required showing limited parasympathetic involvement, and in this study this was achieved by deriving a sympathetic index (i.e. LF: HF ratio).

5.5.2 EEG and cardiovascular associations during fatigue

The changes in EEG during fatigue have already been discussed in Chapter 3. The EEG signal may be one of the most predictive and reliable indicators of fatigue

(Artaud, et al., 1994; Erwin & Al., 1973; Volow & Erwin, 1973). Drivers cannot maintain a high level of consciousness when they are mentally fatigued and this is indicative in the EEG, which has been shown in Chapter 3 to produce consistent and reliable changes during fatigue. Lemke (1982) showed that the EEG signal was a promising method for monitoring fatigue in drivers'. Furthermore, researchers have found associations between EEG delta, theta, alpha, beta and sigma waves during driving (Caille & Bassano, 1977; Lal & Craig, 2000c; Torsvall & Åkerstedt, 1983; Torsvall & Åkerstedt, 1987). However, to date no study has investigated the correlation between HRV and EEG during driver fatigue. The present research attempted to identify the relationship between autonomic changes and brain deactivation during driver fatigue by examining the association between HR and EEG changes.

In the present research various components of HRV were correlated with the EEG changes that occurred during a monotonous, driver simulator task. For the EEG amplitude changes in the alert phase, the sympathetic index derived from LF: HF ratio was found to be strongly associated with alpha and beta activity and a similar relationship was observed as the subjects' progressed into the post-transitional phase of fatigue. This indicates that increasing sympathetic activity during fatigue is associated with increases in alpha and beta activity. During the fatigue states, HRV in the HF region was negatively associated with theta and beta activity, indicating that as the EEG of drowsiness increases there is a reduction in parasympathetic activity. The analysis of EEG magnitude showed a relationship between beta activity and the sympathetic index. However, during transition to fatigue as HRV in the LF region and the total spectrum increased, so did beta activity. The relationship here is not clear, since LF and total spectrum alone are not sensitive indicators of autonomic activity. However, it may be speculated that the beta waves occurring during fatigue are associated with an increase in the sympathetic component of autonomic activity suggested by the association with increased HRV in the LF region, which in turn influences the similar relationship observed with total HRV.

Only one other study was identified that investigated the association of HRV and EEG activity and this was during sleep (Otzenberger et al., 1997). No other comparative study was identified investigating this association during fatigue/drowsiness. The investigators of this study evaluated the temporal relationship between HRV and sleep EEG activity (Otzenberger et al., 1997). They found the overnight profiles of HRV and EEG to be related. There were continuous changes in

HRV preceding variations in sleep EEG activity indicating a close relationship between the two physiological variables. In the following chapter the physiological effects during driver fatigue is compared in professional versus non-professional drivers.

Chapter Six

Indicators of Fatigue in Professional Drivers: Truck Drivers and Physiological Effects

6 Introduction to Fatigue in Professional Drivers

Professional drivers are at a risk of driver fatigue due to long hours of driving, shiftwork and disruptions to circadian rhythm. Drivers of heavy-goods vehicles (HGV) and some drivers of public service vehicles regularly deliver freight and passengers, respectively, over long distances. These drivers are at a serious risk from fatigue effects because they are not free to determine their own work schedules and because they have irregular work hours. These drivers may continue to drive beyond a point at which they are capable of dealing effectively with road and traffic demands. In addition, their irregular shifts will force them on occasions to continue driving during troughs in their circadian rhythm, so that performance may decline to sub-optimal levels. Finally, the driving cabs of professional drivers are likely to cause other stressors that interact with fatigue, such as heat, noise, and vibration.

Among those professional drivers who are highly skilled at driving, fatigue may be quite severe before routine driving performance is noticeably affected. At lesser levels of fatigue, however, decreases in physiological arousal, slowed sensorimotor functions and impaired information processing can reduce a driver's ability to respond effectively to unexpected or emergency situations.

6.1 Truck Drivers and Fatigue

Growing evidence suggests that professional drivers present an increasing problem for road safety (Brown, 1994; Fuller, 1980; Miller & Mackie, 1980). Fatigue more than likely impairs their performance. Fatigue occurs commonly among long distance truck drivers and can have serious consequences for both the fatigued driver and road users (Haworth et al., 1989; Haworth et al., 1988). When driving long distances on limited access highways as for instance, most truck drivers do, it is difficult for the driver to maintain attentiveness. These driving conditions are monotonous because there are very few stimuli for example, lack of traffic signals and crossings on highways. As well as increasing the likelihood that drivers will fall asleep at the wheel, fatigue impairs the ability to maintain lateral road position and constant speed (Mackie & Miller, 1978).

In a review on truck and bus driver fatigue, it was found that irregular driving schedules produced greater subjective fatigue, physiological stress, and performance degradation than did regular hours of work (Mackie & Miller, 1978). Fatigue is also a frequently reported phenomenon in night work (Åkerstedt et al., 1982) and therefore, plays a role in night-time accidents. Earlier research has shown that night work within the transport industry (for example, driving of trucks or trains), is also connected with strong increases in subjective and objective sleepiness (Kecklund & Åkerstedt, 1993; Torsvall & Åkerstedt, 1987).

Although sleep deprivation and abnormal sleep/wake schedules are inherent in the trucking industry, it is likely that a substantial percentage of the drivers also suffer from sleep-disordered breathing (sleep apnoea) and obesity and that this prevalent sleep disorder contributes to trucking accidents (Stoohs, Bingham, Itoi, Guilleminault, & Dement, 1995). It is also known that a combination of stress, abnormal sleeping times and sleep-disordered breathing contributes to fatigue effects in these drivers (Stoohs et al., 1995).

6.2 On the Brain Wave Activity of Professional Drivers

It is important in safety management that the physiological characteristics of professional drivers are made clear since they are at risk of fatigue related accidents. In road traffic research, both fatigue and monotony are very significant problems. Drivers cannot maintain a high level of consciousness when they are engaged in a monotonous task and consequently can become mentally fatigued. Brain wave activity research is able to assess levels of consciousness with research showing a relationship between brain wave activity and fatigue (Idogawa, 1991). To better understand the influence of fatigue in professional drivers, it is important to study their brain wave activity.

A previous study showed higher subjective sleepiness and lowered performance, and increased EEG alpha and theta activity during long distance night driving compared to early evening drives in truck drivers (Kecklund & Åkerstedt, 1993). Another study reported higher subjective EEG associated with sleepiness in the night condition compared to daytime in professional drivers on a truck simulator driving task (Gillberg et al., 1996). EEG has also been found to be associated with sleepiness in train drivers (Torsvall & Åkerstedt, 1987). These authors found alpha, theta and delta activity increased with sleepiness.

Another study also stated that drowsiness can be detected by noticing alpha waves in the EEG and then informing the driver automatically, for instance, by giving an electrical or sound stimulus (Idogawa, 1991). It was also observed that when doing a routine and monotonous task such as highway driving, there was lowered activity in the brain. Such a situation, which lacks the input of varied external stimuli, can cause drowsiness. The aim of this study was to examine the physiological changes during the transition from alert to a fatigue/drowsiness state in a driver simulator task in professional truck drivers. Furthermore, the research aimed to clarify any differences in physiological response to fatigue between professional drivers and non-professional drivers (studied in Chapter 3). In considering the human contribution to fatigue associated accidents, it seems necessary to make a distinction between professional drivers and non-professional drivers due to the differing amounts of driving times, habits and environments.

The hypotheses generated for this study included:

1) During transition from an alert to a fatigue state in professional drivers there will be significant increases in the EEG of drowsiness i.e. increases in slow wave activity such as delta and theta.

2) There will be physiological differences in the response to fatigue between professional and non-professional drivers. It is expected that truck drivers will show less fatigue effects because of their increased experience of driving. Therefore, it is hypothesised that their EEG will show less pronounced slow wave activity during fatigue compared to non- professional drivers

6.3 Methods

6.3.1 Subjects

Twenty professional truck drivers (all males), aged 44 ± 11 years and twenty sex-matched non-professional drivers (all males), aged 34 ± 9 years; all of whom were healthy (medication free), were recruited for the study from the local community and by advertisements in the local newspaper (Daily Telegraph). The professional drivers tend to be older than non-professional drivers therefore, were not age matched. The twenty non-professional drivers were randomly selected from the males in the group of thirty-five that were recruited for a previous study reported in Chapter 3. The twenty truck drivers were randomly selected and assigned to the study from a total of fifty that responded to the advertisements. All subjects gave written consent for the study, which was approved by the institutional ethics review committee and carried out in accordance with the institution's guidelines. To qualify for the study all drivers had to meet the following inclusion criteria: no severe concomitant disease, no history of alcoholism and drug abuse and no psychosis, psychological and intellectual problems likely to limit compliance. The truck drivers were paid $100 for participating in the study. The demographics for the truck drivers and the non-professional drivers are provided in Table 6.1. The truck drivers were significantly (t=3.2, df= 38, p=0.003) more obese weighing an average of 91 ± 15.2 kg compared to the non-professional group of drivers who weighed 77 ± 10.8 kg. They were also older compared to the non-professional drivers (t=3.3, df= 38, p=0.002).

Table 6.1 Shows the demographics of the subjects in the study (n=20 professional drivers; n=20 non-professional drivers)

Variable	**Mean ± SD**		**Minimum**		**Maximum**	
	truck	non-professional	truck	non-professional	truck	non-professional
Age	44 ± 11*	34 ± 9.1*	23	21	66	48
Weight (kg)	91 ± 15.2*	77 ± 10.8*	57	59	123	94
Height (cm)	173 ± 23.8	176 ± 6.2	166	168	190	187.5
Head circumference (cm)	59 ± 3.6	57 ± 5.0	54	38.5	71	62
Handedness	20 right handed	20 right handed				
Gender	20 males	20 males				

* p<0.05

6.3.2 *Study protocol*

For the full details on the procedure, experimental interventions used and statistical analyses refer to Chapter 2. The study was conducted in a temperature-controlled laboratory as the subjects performed a standardised sensory motor driver simulator task. The driving task consisted of 5-10 minutes of active driving to familiarise the subject, followed by approximately two hours of monotonous driving (speed < 80 km/hr, very few stimuli) till the subjects showed physical signs of fatigue. Fatigue was assessed using a video monitor (described in Chapter 2). The time taken to fatigue (provided in minutes; refer to section 6.4.2) was identified as the first visible appearance of fatigue related symptoms from the video with simultaneous increase in slow wave activity in the EEG.

Simultaneous EEG measures were obtained during the driving task. The EEG was acquired using a physiological monitor (Neurosearch-24, Lexicor, America). Nineteen channel EEG was recorded according to the International 10-20 system (Fisch, 1991b). A monopolar montage was used i.e. EEG activity was recorded in relation to an inactive reference site (electrodes placed on ear lobes). Sitting brachial blood pressure (BP) was measured using a standard mercury sphygmomanometer, and heart rate (HR) was recorded before and after the driving session.

6.3.3 *Statistical analysis*

The details for data management and statistical analysis are provided in Chapter 2. Briefly, a fast Fourier transform was performed on the EEG data using a spectral analysis package (Exporter, Lexicor, USA). The EEG was defined in terms of frequency bands including delta (0-4 Hz), theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) (Fisch, 1991b). For each band the average EEG magnitude (μV) was computed. Since both magnitude and amplitude show similar effects during driver fatigue (refer to Chapter 3), all comparisons reported in the current chapter are with magnitude changes. Drowsiness was classified into transitional (between awake and absence of alpha), transitional-post transitional (which has characteristics of both), post transitional (early Stage 1 of sleep) and arousal phases (emergence from drowsiness) (Santamaria & Chiappa, 1987a). The differences between 'office' BP and HR measured before and after the driving task 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 using a Scheffé test was used to determine where the differences existed in the comparison of the means. A 2 x 5 repeated measures ANOVA and Scheffé test was also used to identify any differences in the five phases between the professional and non-professional drivers. The significance level was set at $p<0.05$ for all analysis performed. Results are reported as mean and standard deviation of differences.

6.4 Results

All 40 subjects (20 truck and 20 non-professional drivers) completed the study. The systolic BP and HR were similar in both groups. However, the diastolic BP was higher in the truck drivers compared to the non-professional drivers (pre study: t=3.0, df= 37, p=0.004 and post study t=2.6, df= 37, p=0.01). The truck drivers had an average pre-study systolic/diastolic BP of 124 ± 16.8/81 ± 8.8 mm Hg and a post-study BP of 123 ± 15.0/82 ± 9.1 mm Hg. The BP did not change significantly from before to after the study. In contrast, heart rate was significantly lower (t=2.1, df= 34, p=0.047) from before (70 ± 8.6 beats/minute) to after the driving task (65 ± 6.5 beats/minute). Similar to the truck drivers the BP changes in the non-professional drivers did not change significantly from before (121 ± 12.0/73 ± 8.9 mm Hg) to after (119 ± 10.4/ 74 ± 9.7 mm Hg) the driving task. However, heart rate was lower in this group of drivers as well, but not significantly, from before (67 ± 12.3 beats/minute) to after (61 ± 12.0 beats/minute) the driving task. Refer to Table 6.2 for mean BP and HR before and after the driving task. Physical signs of fatigue and drowsiness were evident within 30 minutes of the driving task in all drivers.

6.4.1 The physiological response during the driving task in professional truck drivers

The EEG activity for the delta, theta, alpha and beta bands during the alert baseline, transitional phase to fatigue, transitional-post transitional, post transitional and the arousal phase are shown in Table 6.3.

A repeated measures ANOVA conducted on the magnitude data revealed overall differences in EEG magnitude between the five phases tested. The effects were: delta (F=78.4, df=4, 72, p<0.0001), theta (F=135.4, df=4, 72, p<0.0001), alpha (F=127.4, df=4, 72, p<0.0001) and beta (F=84.5, df=4, 72, p<0.0001).

Table 6.2 Mean cardiovascular effects before and after the driving task (n=20 professional drivers; n=20 non-professional drivers)

Variable	Mean ± SD		Minimum		Maximum	
	truck	non-professional	truck	non-professional	truck	non-professional
Pre-study SBP	124 ± 16.8	121 ± 12.0	100	103	170	149.5
Post-study SBP	123 ± 15.0	119 ± 10.4	92	100	150	134.5
Pre-study DBP	81 ± 8.8*	73 ± 8.9*	65	60	105	89
Post-study DBP	82 ± 9.1*	74 ± 9.7*	72	55	105	94
Pre-study HR	70 ± 8.6	67 ± 12.3	60	48	92	92
Post-study HR	65 ± 6.5	61 ± 12.0	56	42	84	81

* $p < 0.05$; truck versus non-professional drivers

Table 6.3 The average EEG activity during the alert baseline, transitional phase to fatigue, transitional-post transitional, post-transitional and the arousal phase in truck drivers (n=20)

EEG Band	Alert	Transition to Fatigue	Transitional-post transitional	Post-Transitional	Arousal
Magnitude (μV)					
Delta	15.3 ± 2.71	19.1 ± 3.58**	21.5 ± 4.13**	21.6 ± 5.29**	16.4 ± 2.96
Theta	7.8 ± 1.33	7.9 ± 1.33	8.7 ± 1.58**	9.1 ± 1.70**	7.4 ± 1.41**
Alpha	6.6 ± 0.42	6.8 ± 0.52	7.9 ± 0.59**	7.9 ± 0.62**	6.7 ± 0.43
Beta	7.8 ± 0.64	7.7 ± 0.58	9.0 ± 0.55**	8.1 ± 0.50*	7.7 ± 0.50

Note

The results are reported as mean ± sd

* $p < 0.05$ ** $p < 0.01$

The changes in magnitude from the alert baseline during the different fatigue phases are summarised in Table 6.4. The post hoc analyses identified where differences existed in the comparison of the means of the various phases to the alert baseline. The delta, theta, alpha and beta activities in the five phases are represented in Figures 6.1, 6.2, 6.3 and 6.4 respectively. During the initial phase of transition to fatigue, the largest change in magnitude, compared to the alert baseline, was found in the delta band (3.8 ± 4.49 μV, $p<0.0001$). The changes in magnitude for the alpha, theta and beta bands during transition to fatigue were not significantly different to the alert baseline, 0.1 ± 1.89 μV, 0.2 ± 0.67 μV and –0.1 ± 0.86 μV, respectively (refer to Table 6.4).

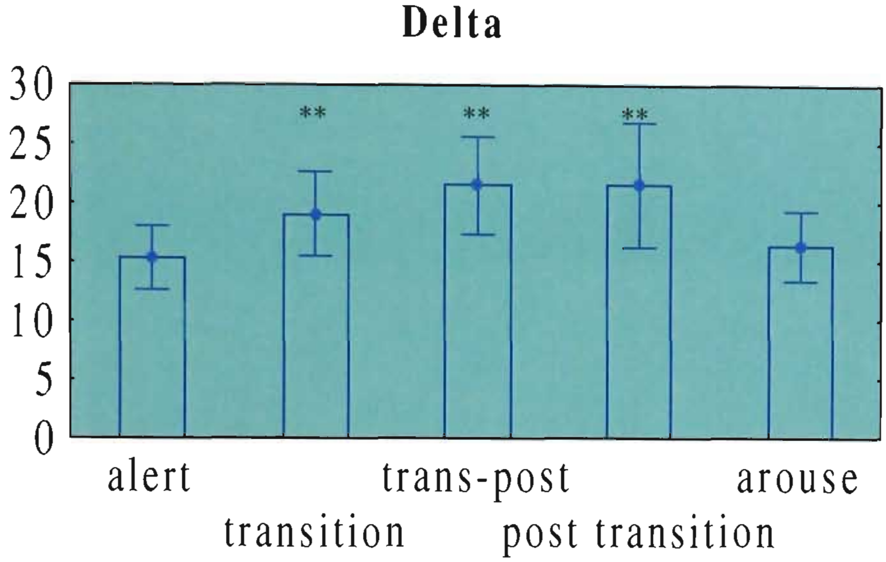
Table 6.4 also shows that the increased delta levels persisted or increased further as fatigue progressed and maximum change was observed during the post-transitional phase (6.3 ± 4.94 μV, $p<0.0001$). Similarly, theta was found to increase the most during the post-transitional phase (1.2 ± 2.16 μV, $p<0.0001$). Alpha was highest during the transitional-post transitional phase, increasing by 1.3 ± 0.79 μV ($p<0.0001$) and this increase persisted in the post-transitional phase (1.3 ± 0.75 μV, $p<0.0001$). Beta increased the most during the transitional-post transitional phase (1.2 ± 0.84 μV, $p<0.0001$). On arousal from fatigue the magnitude changes came close to that seen during the alert baseline except for the theta band, which was significantly lower (-0.4 ± 1.94 μV, $p<0.0001$). Delta, alpha and beta activities were not significantly different during arousal from the alert baseline.

Table 6.4 The changes in EEG magnitude in truck drivers during drowsiness compared to the alert baseline (n=20)

EEG Band	Transition to Fatigue	Transitional-post transitional	Post-Transitional	Arousal
Magnitude (μV)				
Delta	3.8 ± 4.49**	6.2 ± 4.94**	6.3 ± 5.94**	1.1 ± 4.01
Theta	0.1 ± 1.89	0.9 ± 1.33**	1.2 ± 2.16**	-0.4 ± 1.94**
Alpha	0.2 ± 0.67	1.3 ± 0.79**	1.3 ± 0.75**	0.1 ± 0.60
Beta	-0.1 ± 0.86	1.2 ± 0.84**	0.3 ± 0.81*	-0.1 ± 0.81

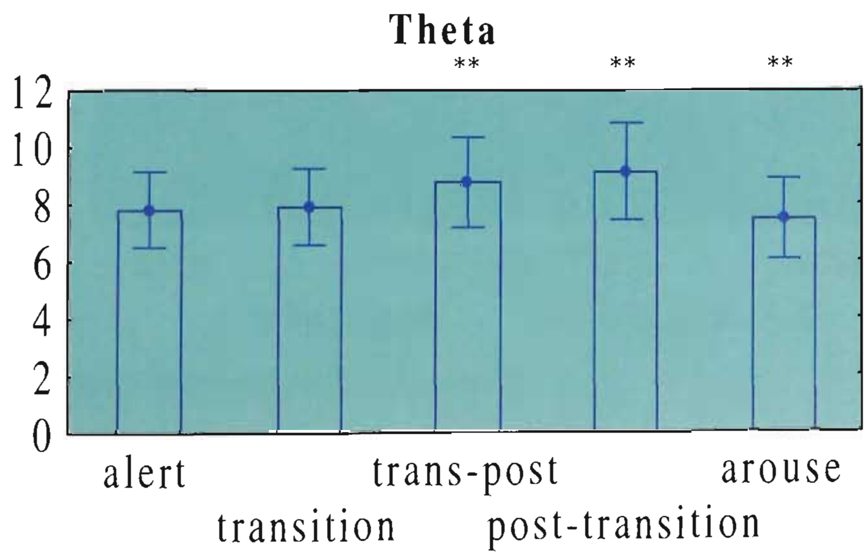
The results are reported as mean ± sd. * $p<0.05$ and ** $p<0.01$ compared to alert phase.

Figure 6.1 The delta magnitude (μV) in professional drivers during alert, transition to fatigue, transitional-post-transitional, post-transitional and arousal phases



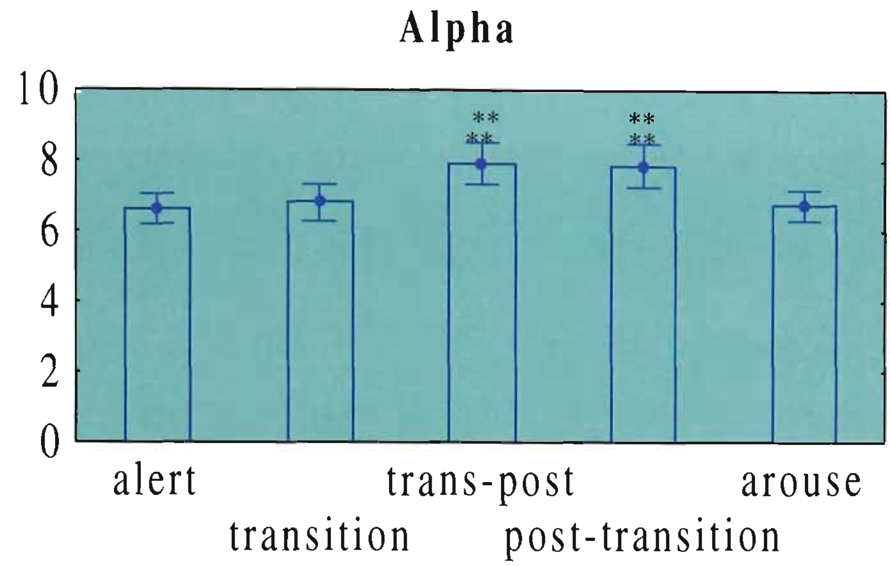
Note: Error bars represent standard deviation

Figure 6.2 The theta magnitude (μV) in professional drivers during alert, transition to fatigue, transitional-post-transitional, post-transitional and arousal phases



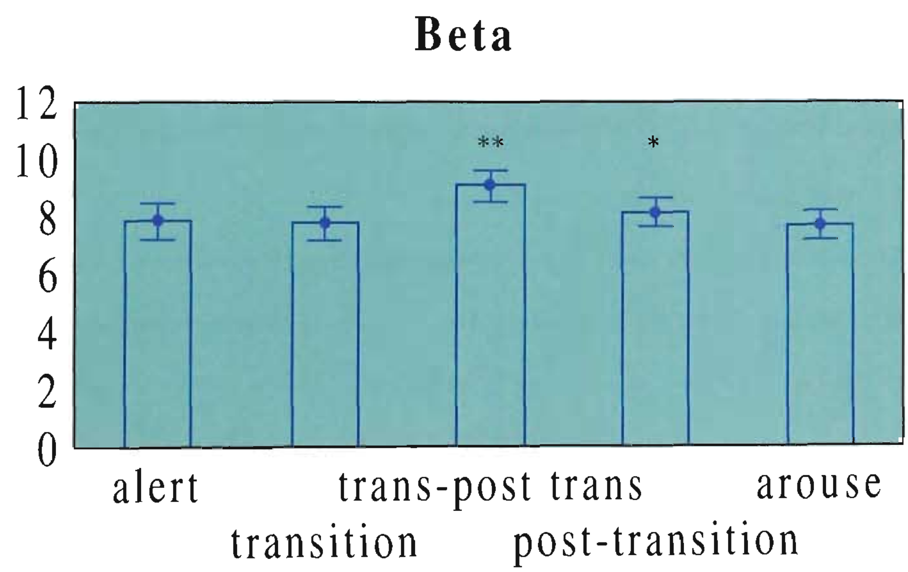
Note: Error bars represent standard deviation

Figure 6.3 The alpha magnitude (μV) in professional drivers during alert, transition to fatigue, transitional-post-transitional, post-transitional and arousal phases



Note: Error bars represent standard deviation

Figure 6.4 The beta magnitude (μV) in professional drivers during alert, transition to fatigue, transitional-post-transitional, post-transitional and arousal phases



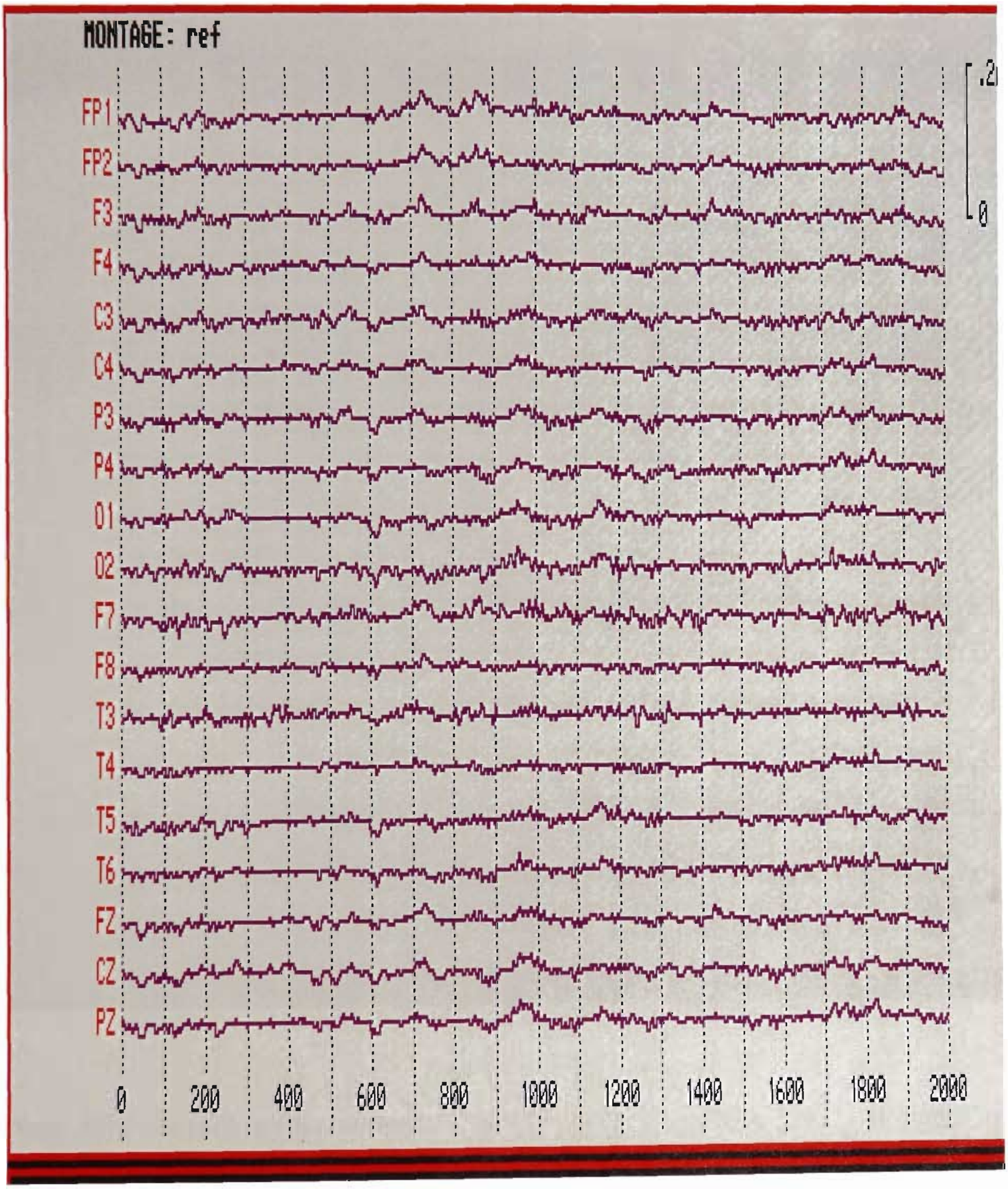
Note: The key for Figures 6.1, 6.2, 6.3 and 6.4

* p<0.05 ** p<0.01

Error bars represent standard deviation

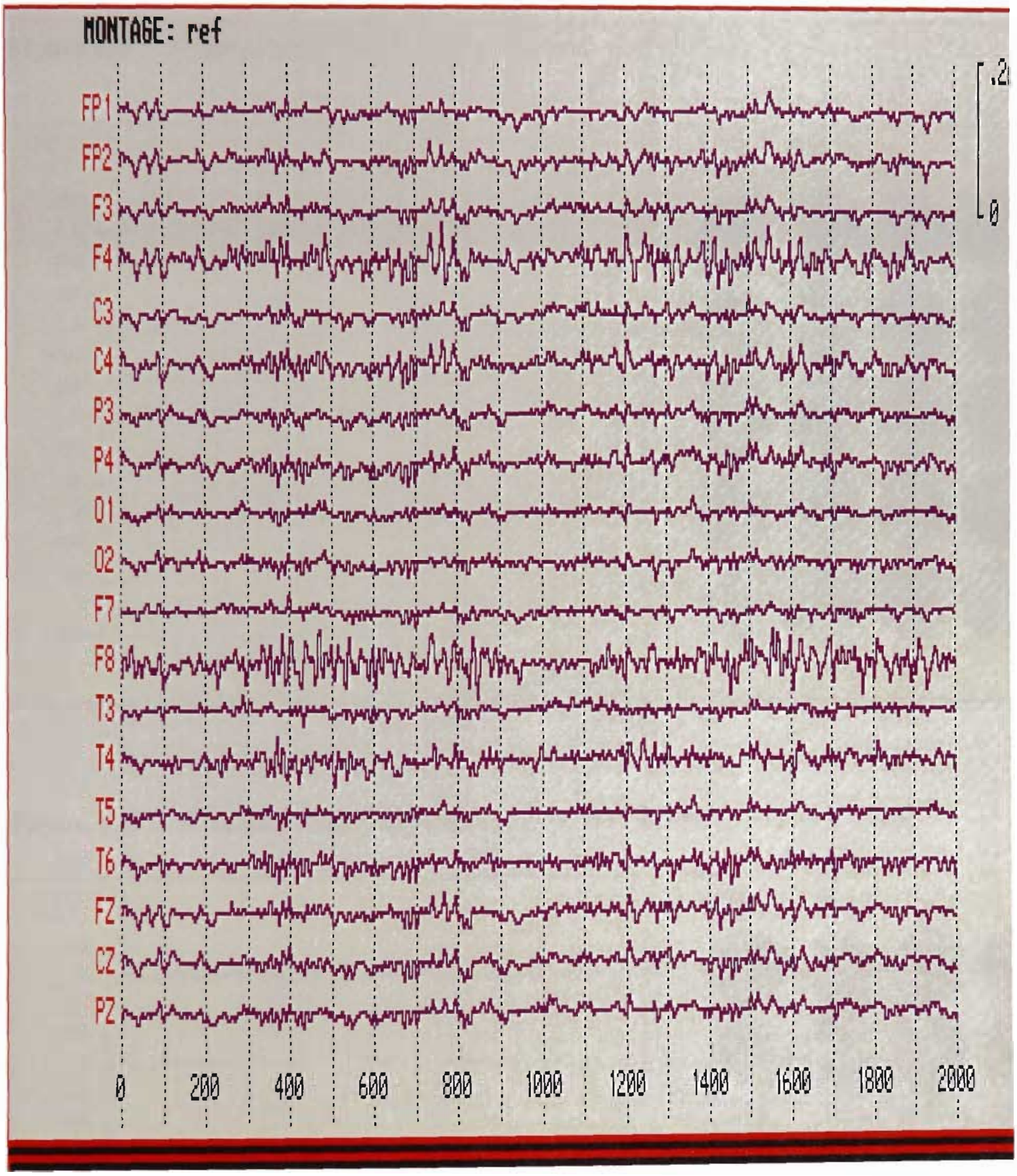
Figures 6.5 and 6.6 show an example of the raw EEG activity during an alert phase and a fatigue state in the same subject. A frontocentral slowing is apparent in Figure 6.6 during fatigue (note EEG activity in the F8, FZ, C3, C4 and CZ sites).

Figure 6.5 Shows an example of the raw EEG activity during the alert phase



Note: EEG channels are represented on the left y-scale. Amplitude (μV) is displayed in the upper right corner.

Figure 6.6 Shows an example of the raw EEG activity during the transition to fatigue phase



Note: EEG channels are represented on the left y-scale. Amplitude (μV) is displayed in the upper right corner.

An example of difference in the EEG magnitude (μV) in the alert and fatigue states are represented in Figures 6.7 and 6.8. There is a clear increase in the magnitude in the delta (shown in blue) and theta (shown in green) bands.

Figure 6.7 Change in EEG magnitude during the alert phase

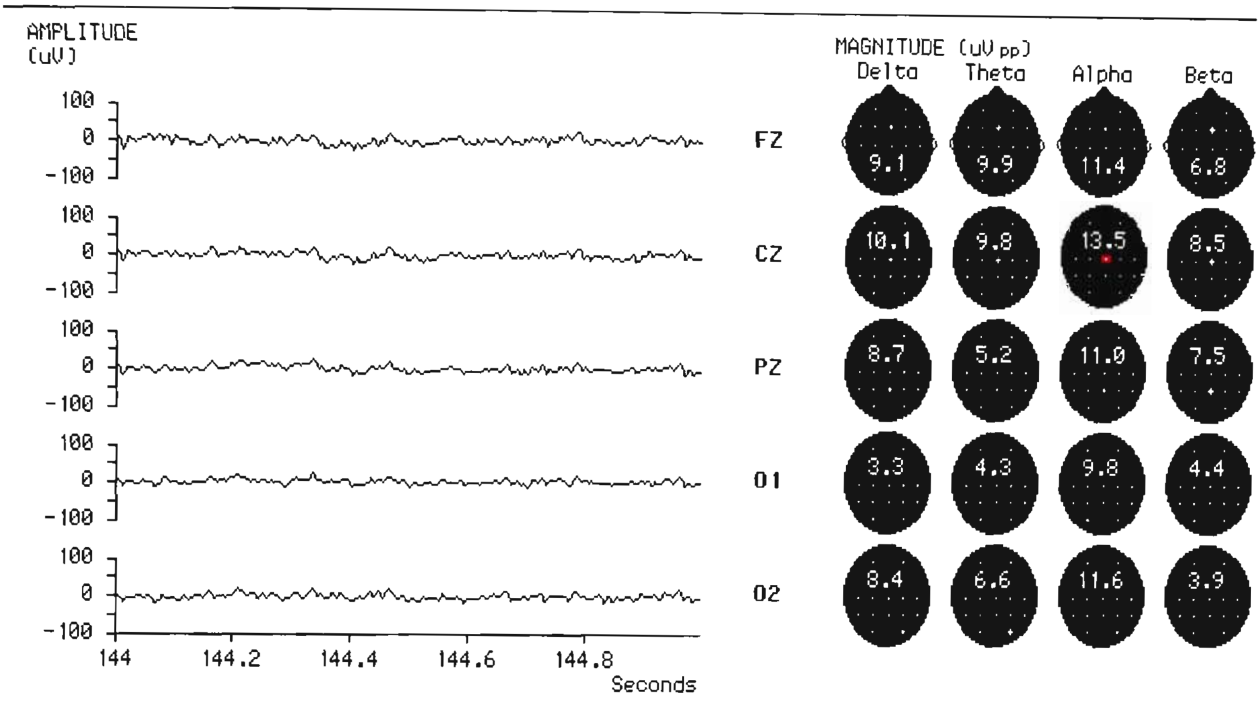
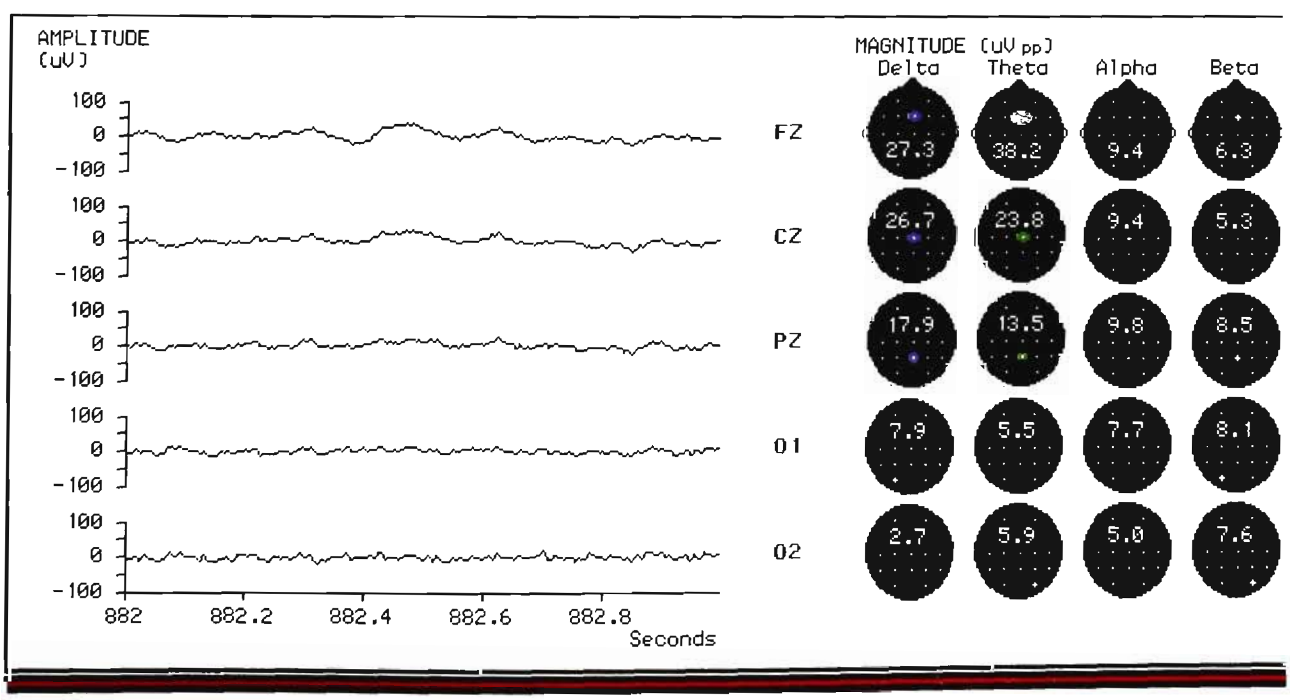


Figure 6.8 Change in EEG magnitude during the transition to fatigue phase



Some examples of the topograph (described in detail in Chapter 3) of the EEG activity in the theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) bands during different phases are shown in Figures 6.9 and 6.10 and 6.11. Red indicates maximum EEG power and blue indicates minimum power according to the scale on the left of the ovals. The ovals depict a view of the head from above. Figure 6.9 shows the increased power in EEG bands of alertness, that is, alpha and beta, indicated by the ovals in the second and third columns. The increased EEG power in the theta band during the transitional phase to fatigue is represented in Figure 6.10. The appearance of beta in the presence of theta and alpha activity during the transitional to post-transitional phase is shown in Figure 6.11.

Figure 6.9 The EEG topograph during the alert phase in a subject in the 1= theta, 2= alpha and 3= beta bands

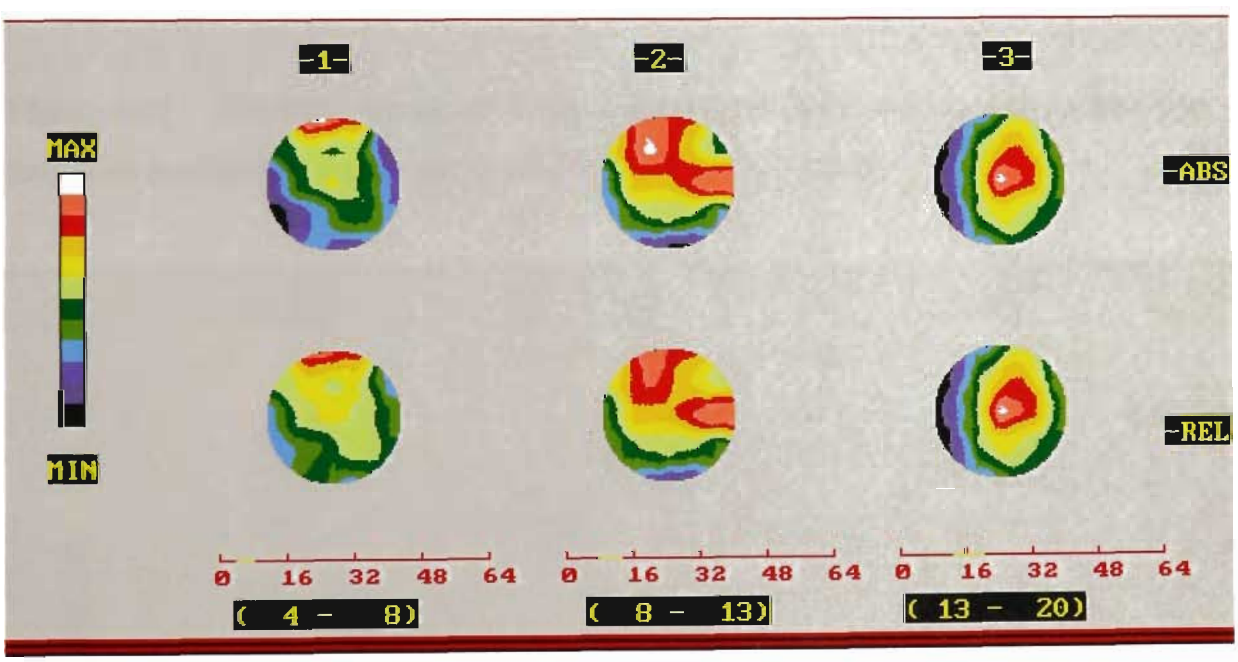


Figure 6.10 The EEG topograph during the transitional phase to fatigue in a subject in the 1= theta, 2= alpha and 3= beta bands

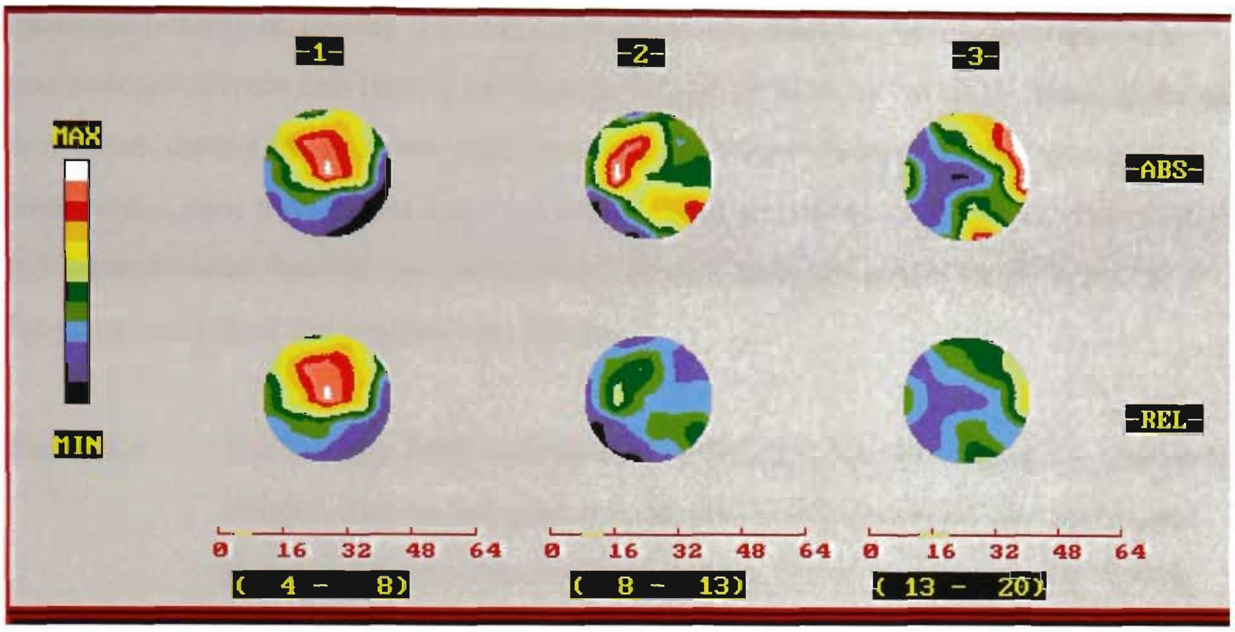
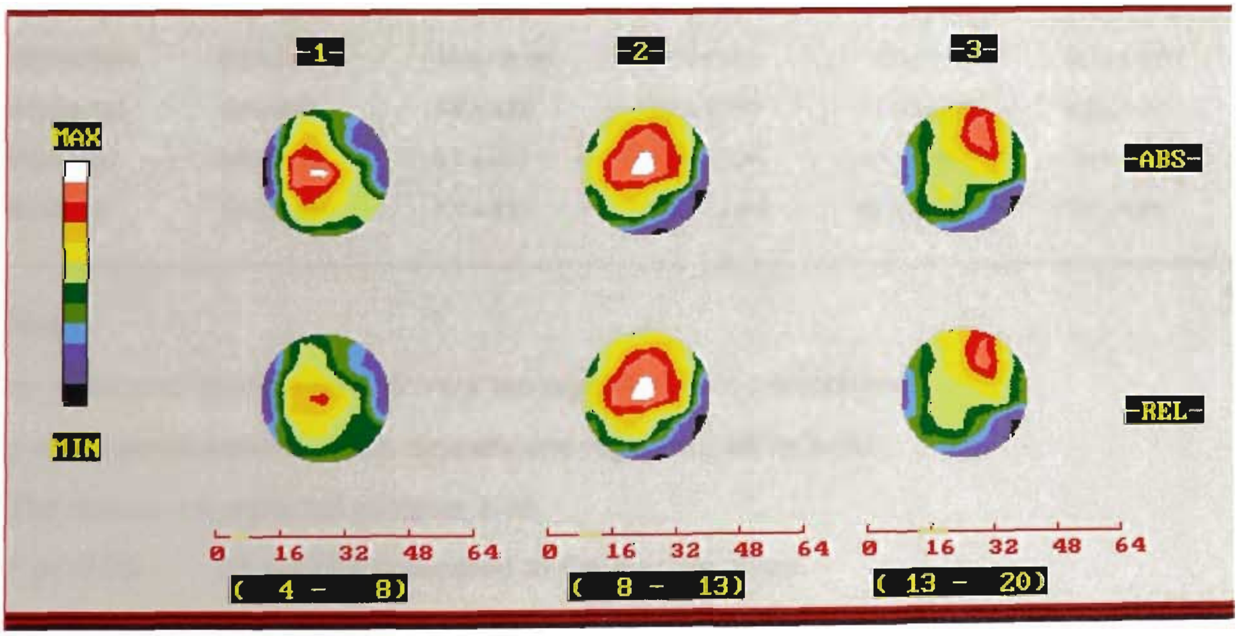


Figure 6.11 The EEG topograph during the transitional to post-transitional phase to fatigue in a subject in the 1= theta, 2= alpha and 3= beta bands



6.4.2 A comparison of the EEG activity in non-professional versus professional drivers

The first visible signs of fatigue and simultaneous EEG of drowsiness occurred after 26 ± 2.3 minutes in truck drivers and after 25 ± 2.8 minutes in the non-professional drivers (not significantly different). The EEG activity in the twenty 'gender-matched' non-professional drivers and twenty professional truck drivers, for the delta, theta, alpha and beta bands during the alert baseline, transitional phase to fatigue, transitional-post transitional, post transitional and the arousal phase are shown in Table 6.5. From Table 6.5 it can be seen that the non-professional drivers had greater EEG activity in the fatigue phases than the professional drivers.

Table 6.5 The average EEG activity during the alert baseline, transitional phase to fatigue, transitional-post transitional, post transitional and the arousal phase in non-professional (np) drivers versus professional (p) drivers (n=20)

EEG Band	Alert	Transition to Fatigue	Transitional-post transitional	Post-Transitional	Arousal
Magnitude (μV)					
Delta (np)	27.8 ± 6.45	37.9 ± 11.06*	31.5 ± 8.15*	48.9 ± 9.83*	30.4 ± 8.27*
Delta (p)	**15.3 ± 2.71**	**19.1 ± 3.58****	**21.5 ± 4.13****	**21.6 ± 5.29****	**16.4 ± 2.96**
Theta (np)	9.6 ± 2.45	12.6 ± 3.44*	10.5 ± 2.58*	12.7 ± 3.07*	8.6 ± 2.31*
Theta (p)	**7.8 ± 1.33**	**7.9 ± 1.33**	**8.7 ± 1.58****	**9.1 ± 1.70****	**7.4 ± 1.41****
Alpha (np)	9.3 ± 0.96	10.0 ± 0.94*	9.7 ± 0.75*	10.7 ± 0.80*	8.7 ± 0.82*
Alpha (p)	**6.6 ± 0.42**	**6.8 ± 0.52**	**7.9 ± 0.59****	**7.9 ± 0.62****	**6.7 ± 0.43**
Beta (np)	8.6 ± 0.38	8.8 ± 0.57	9.5 ± 0.50*	9.2 ± 0.55*	7.4 ± 0.46*
Beta (p)	**7.8 ± 0.64**	**7.7 ± 0.58**	**9.0 ± 0.55****	**8.1 ± 0.50***	**7.7 ± 0.50**

Note

np = the non-professional drivers are represented in normal text

p = the professional truck drivers are represented in bold

The results are reported as mean ± sd

* $p < 0.05$ ** $p < 0.01$ compared to the alert baseline

The relative changes in magnitude for all the phases were calculated as the average magnitude during the phase minus the average magnitude during the alert baseline. The EEG magnitude for all the phases after subtraction of the alert baseline values are shown in Table 6.6 for the non-professional and professional drivers. The EEG response of the 35 non-professional drivers to fatigue has been discussed in Chapter 3. Table 6.5 and 6.6 provides information on the 20 non-professional drivers for comparison purposes only, to similar numbers of 20 professional drivers.

Table 6.6 The average changes in EEG magnitude in non-professional (np) and professional (p) drivers during drowsiness from the alert baseline (n=20)

EEG Band	Transition to Fatigue	Transitional-post transitional	Post-Transitional	Arousal
Magnitude (μV)				
Delta (np)	10.1 ± 12.80*	3.7 ± 10.39*	21.1 ± 7.17*	2.6 ± 10.49*
Delta (p)	**3.8 ± 4.49****	**6.2 ± 4.94****	**6.3 ± 5.94****	**1.1 ± 4.01**
Theta (np)	3.0 ± 4.23*	0.9 ± 3.57*	3.1 ± 3.92*	-0.9 ± 3.37*
Theta (p)	**0.1 ± 1.89**	**0.9 ± 1.33****	**1.2 ± 2.16****	**-0.4 ± 1.94****
Alpha (np)	0.6 ± 1.34*	0.4 ± 1.22*	1.4 ± 1.25*	-0.6 ± 1.26*
Alpha (p)	**0.2 ± 0.67**	**1.3 ± 0.79****	**1.3 ± 0.75****	**0.1 ± 0.60**
Beta (np)	0.2 ± 0.69	0.9 ± 0.63*	0.6 ± 0.67*	-1.2 ± 0.60*
Beta (p)	**-0.1 ± 0.86**	**1.2 ± 0.84****	**0.3 ± 0.81***	**-0.1 ± 0.81**

Note

Results have been derived by subtracting the average magnitude during the alert baseline from the average magnitude during a phase (i.e. transitional, transitional to post transitional, post-transitional and arousal).

np = the non-professional drivers are represented in normal text

p = the professional truck drivers are represented in bold

The results are reported as mean ± sd

* $p<0.01$ ** $p<0.01$ compared to the alert baseline

A comparison of the EEG response in the five phases for truck drivers and non-professional drivers using a 2 x 5 repeated measures ANOVA revealed an overall difference in the means of the two groups for the five phases tested ($p<0.0001$). The effects were: delta ($F=206.8$, $df=9, 162$, $p<0.0001$), theta ($F=110.3$, $df=9, 162$, $p<0.0001$), alpha ($F=365.1$, $df=9, 162$, $p<0.0001$) and beta ($F=65.5$, $df=9, 162$, $p<0.0001$).

A Scheffé test revealed where the differences existed in the comparison of the means for the five phases in the two groups of drivers. The results of the comparison of the two groups of drivers are shown in Table 6.7 and 6.8. Table 6.7 shows the magnitude difference between similar phases in the two groups of drivers.

Table 6.7 Showing differences in EEG between professional and non-professional drivers for the alert, transitional, transitional-post transitional fatigue phases and the arousal phase, significance level according to Scheffé analysis

EEG Band	Alert	Transition to fatigue	Transitional-post transitional	Post-Transitional	Arousal
Magnitude (μV)					
Delta	12.0 ± 6.61**	12.9 ± 10.83**	7.3 ± 8.58**	27.0 ± 10.86**	10.6 ± 8.40**
Theta	1.6 ± 2.62**	4.2 ± 3.41**	1.7 ± 2.99**	3.4 ± 3.41**	1.1 ± 0.74*
Alpha	2.6 ± 1.07**	2.9 ±1.06**	1.6 ± 0.95**	2.8 ± 1.02**	1.7 ± 0.88**
Beta	0.7 ± 0.73**	0.9 ± 0.83**	0.4 ± 0.75	1.1 ±0.71**	-0.4 ± 0.63

Note:

The differences were calculated as:

(mean magnitude in non-professional drivers) minus (mean magnitude in professional drivers)

* p<0.05   ** p<0.01

Table 6.8 shows the corresponding p-values for the comparison. All the frequency bands were significantly higher in magnitude in the non-professional drivers. The differences in all the frequency bands were also significantly different in both groups of drivers (Table 6.7 and 6.8), except for beta activity in the transitional-post transitional and arousal phases. The largest difference between the two groups was found in delta activity with beta showing the smallest difference. The EEG of drowsiness (that is the slow wave activities of delta and theta) was higher in the non-professional drivers during the different fatigue states.

Table 6.8 Showing p values according to Scheffé analysis of differences in EEG between professional and non-professional drivers for the alert, transitional, transitional-post transitional fatigue phases and the arousal phase

EEG Band	Alert	Transition	Transitional-to Fatigue	Post-Transitional post transitional	Arousal
Magnitude (μV)					
Delta	<0.0001**	<0.0001**	<0.0001**	<0.0001**	<0.0001**
Theta	0.00002**	<0.0001**	0.000003**	<0.0001**	0.03*
Alpha	<0.0001**	<0.0001**	<0.0001**	<0.0001**	<0.0001**
Beta	0.002**	0.000001**	0.56	<0.0001**	0.35

6.5 Discussion

6.5.1 Fatigue effects, cardiovascular variables, age and weight

The results show that heart rate was reduced significantly in both professional and non-professional drivers during performance of a continuous, monotonous task of simulated driving. Blood pressure was not significantly influenced by the driving task. Previous studies have reported lower heart rate during sleepiness from night driving (Torsvall & Åkerstedt, 1987). The present study also found that the physical signs of fatigue were evident very early, approximately 30 minutes into the driving task in both groups of drivers. The truck drivers were also found to be more obese weighing an average of 91

± 15.2 kg compared to the non-professional group of drivers who weighed 75 ± 11.5 kg, with similar heights on average. It is believed that truck drivers are more likely to present with daytime fatigue, tiredness, unrestorative sleep, hypertension and higher body weights (Stoohs et al., 1995). Horne (1992) found evidence that truck drivers seem particularly vulnerable to obesity, which is known to exacerbate the problem of sleep apnoea. A substantial percentage of the 20 truck drivers in the present study who were obese possibly suffer from sleep-disordered breathing. This prevalent sleep disorder contributes to trucking accidents (Stoohs, Guilleminault, Itoi, et al., 1994). Furthermore, drivers with sleep apnoea may not be fully aware of their problem. These drivers may not be aware that they are becoming sleepy, and they may get no warning of acute sleep attacks. They will therefore find it difficult or impossible to compensate adequately for their sleep state.

Other studies have also been able to demonstrate sleepiness in relatively short periods of continuous driving for 30 minutes (Gillberg et al., 1996). It may be argued that large effects cannot be expected with task duration as short as 1-2 hours. However, the observation of physical signs of fatigue within 30 minutes in the two different groups of drivers in this study after sleep loss the night before of only 2 hours, suggests it does not take long to fatigue during the performance of monotonous, boring tasks.

6.5.2 Fatigue effects on EEG in professional drivers

The EEG showed consistent and reliable changes associated with driver fatigue. The truck drivers showed substantial increases in delta activity during fatigue incurred from driving. Smaller though significant changes also occurred in theta, alpha and beta activity. On arousal from fatigue the EEG activity observed during the alert baseline was generally restored especially for alpha and beta, which are indicative of alertness, arousal and excitement states. The largest increase in delta, theta and alpha were evident in the post-transitional i.e. deeper stages of fatigue. Beta activity was highest during the transitional to post-transitional phase. A similar presence of beta in the transitional to post-transitional phase has also been observed by Santamaria and Chiappa (1987a) during drowsiness.

6.5.3 *A comparison of fatigue effects on EEG in professional and non-professional drivers*

There was an overall difference between the magnitude of EEG change in the truck and professional drivers. Generally, the EEG activity of drowsiness was greater in the non-professional drivers. It was found that delta activity increased significantly during transition to fatigue in professional drivers by 25% and in the non-professional drivers by 36%. Theta and alpha also increased but by a smaller degree in the non-professional drivers (31% and 7%, respectively, $p<0.01$ for both). Theta and alpha activity did not change significantly in the truck drivers. However, theta increased the most in the truck drivers and non- professional drivers in the post-transitional phase (15% and 40%, $p<0.01$, respectively). Alpha activity increased the most in truck drivers in both the transitional-post transitional phase and the post-transitional phase by 20% ($p<0.01$) and in non-professional drivers in the post transitional phase by 15% ($p<0.01$). During transition to fatigue beta did not increase at all in both groups. However, beta activity was altered the most in the transitional-post transitional phase by 15% and 11% ($p<0.01$) in both the truck drivers and non-professional drivers, respectively.

Slow wave activity such as delta and theta has been shown to be prominent during drowsiness in adults (Santamaria & Chiappa, 1987b). Deteriorated performance has also been associated with increased theta and changes in alpha intensity while beta activity has also been shown to be altered (Townsend & Johnson, 1979; Wierwille & Ellsworth, 1994). Similarly, delta, theta and alpha were found to be associated with various stages of drowsiness during the simulated driving task in both groups of drivers. Makeig and Jung (1995) also found changes in theta and alpha waves related to fatigue. In another 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 et al., 1976). The results from the current study confirm the increases observed in the literature reflecting a decreased cortical arousal that occurs during long monotonous tasks such as driving. Another study recorded the EEG of 11 train drivers and showed that alpha activity was clearly the most sensitive to sleepiness with delta and theta increasing by a lesser extent (Torsvall & Åkerstedt, 1987). In contrast it was found that in professional drivers delta increased the most with theta and alpha showing increases of smaller magnitude.

The non-professional drivers in general showed greater increases in EEG indicators of fatigue such as delta, theta and alpha than truck drivers when compared in most of the similar stages of fatigue. This suggests that the magnitude of fatigue was stronger in the inexperienced non-professional drivers who more than likely do not spend as much time on the road driving and hence the fatigue effects were more severe when compared to the truck drivers. Others have also suggested that drowsiness occurs less in professional drivers because of their driving experience (Idogawa, 1991). This suggests that drivers who could endure monotonous conditions for longer periods of time with smaller changes in brain wave activity levels have an aptitude for professional driving (Idogawa, 1991). Skilled drivers may be able to maintain a high level of alertness for longer than average compared to non-professional drivers. Furthermore, on presentation of an acoustic cue for arousal from fatigue, the truck drivers were more likely to attain the alert levels for delta activity. This indicates that professional drivers can quickly 'snap out' of their fatigue state and attain alert levels when presented with external alerting stimuli whilst driving. One explanation can be that the truck drivers have a longer experience than non-professional drivers as well as of working in sleep deprived conditions. In support of this, other research states that experienced drivers (such as professional drivers) are less vulnerable to fatigue during continuous driving compared to inexperienced drivers (Lisper, Laurell, & Stening, 1973) and the results of the present research confirms this finding. The next chapter provides the results of investigating the reproducibility of physiological changes such as the EEG during driver fatigue.

Chapter Seven

Reproducibility of the Electroencephalography changes from different Sites on the Brain during Driver Fatigue: an intra-session comparison

7 Introduction to Reproducibility of physiological changes during fatigue

7.1 The reproducibility of electroencephalography changes during driver fatigue

For the EEG changes that occur during driver fatigue to be useful in the development of a countermeasure device the EEG response during each onset of fatigue in individuals needs to be reproducible. It should be noted that fatigue during driving is not a continuous process but successive episodes of 'microsleeps' where the subject may go in and out of a fatigue state (Harrison & Horne, 1996). To date no-study has tested the reproducibility of physiological changes that occur during fatigue on different days or even within a session.

Therefore, the aims of this study were:

1) To assess the average EEG changes occurring on the entire brain during fatigue/drowsiness on two separate episodes of the initial transitional phase to fatigue in non-professional and professional drivers.
2) To examine the reproducibility of the EEG changes in a single site on the brain during the transitional phase to fatigue.

The hypotheses tested were:

1) There will be no significant difference in the response of the nineteen EEG sites assessed during the transition to fatigue/drowsiness assessed over time in a driving session.
2) There will be no significant difference in the response of a single EEG site assessed during the transition to fatigue/drowsiness assessed over time in a driving session.

7.2 Methods

7.2.1 Subjects

Thirty-five subjects (26 males and 9 females), described in Chapter 3, who were current non-professional drivers, aged 21-52 (34 ± 21) years, were recruited from a large tertiary institution and the local community and randomly assigned to the study. Details of the subject demographics and study protocol are described in Chapter 3. Twenty professional truck drivers (all males), aged 44 ± 11 years were also recruited by advertisement placed in the local newspaper. Details for the truck drivers and the study intervention are provided in Chapter 6. The intra-session reproducibility of fatigue was tested in these two groups.

7.2.2 Study protocol

For the full details on the procedure, experimental interventions used and statistical analysis, refer to Chapters 2, 3 and 6. The study was conducted in a temperature-controlled laboratory as the subjects performed a standardised sensory motor driver simulator task. The driving task consisted of 5-10 minutes of active driving to familiarise the subject, followed by approximately two hours of monotonous driving (speed < 80 km/hr) till the subjects showed physical signs of fatigue. Fatigue was assessed using a video monitor (described in Chapter 2).

Simultaneous EEG measures were obtained during the driving task. The EEG was acquired using a physiological monitor (Neurosearch-24, Lexicor, America). Nineteen channels of EEG were recorded according to the International 10-20 system (Fisch, 1991b). A monopolar montage was used that is, EEG activity was recorded in relation to an inactive reference site (electrodes placed on ear lobes).

7.2.3 Data and statistical analysis

The details for data management and statistical analysis are provided in Chapter 2. A fast Fourier transform was performed on the EEG data using a spectral analysis package (Exporter, Lexicor, USA). The EEG was defined in terms of frequency bands including delta (0-4 Hz), theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) (Fisch, 1991b). For each band the average EEG magnitude (μV) was computed.

The early stage of drowsiness was classified as the transitional phase, where slow wave activity such as delta and theta activity increase (refer to results in Chapter 3). In order to test the reproducibility of the EEG changes two such transitional phases to fatigue were randomly selected from each subject's EEG trace, linked in real time to a video recording of the subject's face (refer to Chapter 3 for details). The transitional phase of fatigue was identified from the video recording of changes in facial features that occurs during fatigue. The EEG data was averaged for the two groups of subjects (thirty five non-professional and 20 professional drivers) separately to derive a single average value for each of the nineteen sites on the brain. The reproducibility of EEG changes were assessed in the nineteen sites on the brain (that is n=19 observed sites, degrees of freedom for dependent sample comparison =18) during two episodes of fatigue. Data was also compared for a single site on the brain i.e. the central region to observe the effects of non-averaged data (that is n=35 non-professional drivers' EEG were observed at the central site for the two episodes of fatigue, degrees of freedom= 34).

A dependent sample t-test was performed on the nineteen sites to identify the magnitude of intra-session EEG difference during transition to fatigue. The EEG changes within and between driving sessions during the transition to fatigue phase were also assessed for agreement using Pearson's correlation. The significance level was set at $p<0.05$ for all analyses performed. Results are reported as mean and standard deviation of differences.

7.3 Results

All 55 subjects (35 non-professional drivers and 20 truck drivers) completed the study. (Refer to Chapters 3 and 6 for details).

7.3.1 The agreement in EEG response, representative of the whole brain, during the transitional phase to fatigue in non-professional drivers.

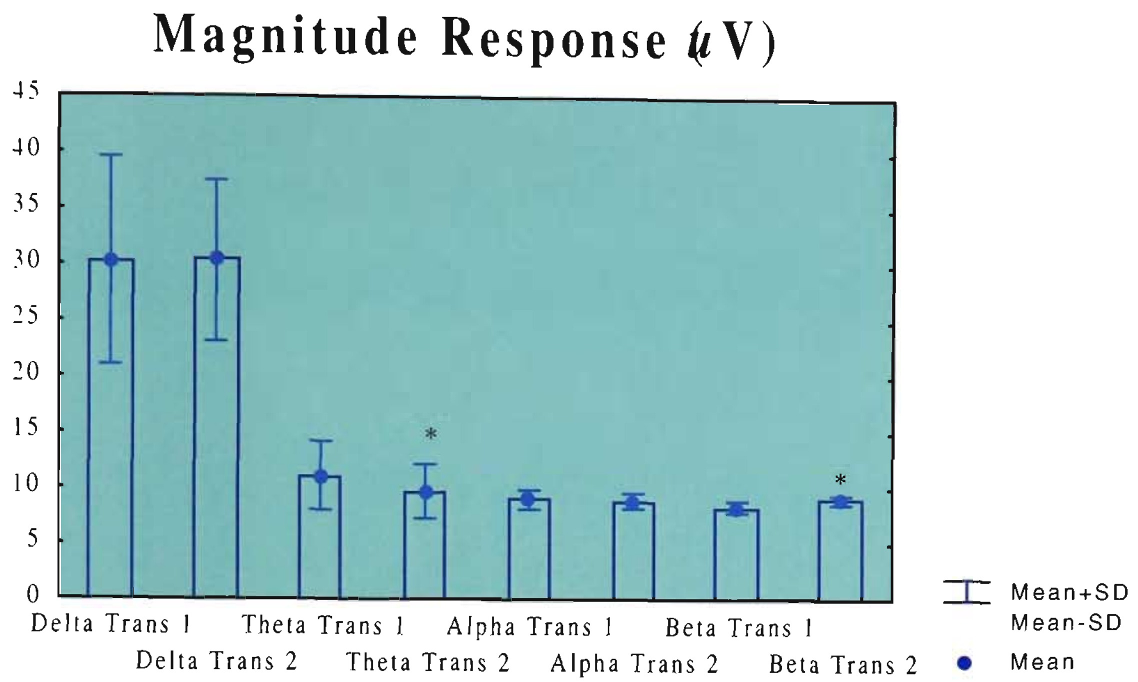
Table 7.1 shows the average EEG changes during the two separate episodes of transition to fatigue within a driving session. Figure 7.1 shows a graphical representation of the results in Table 7.1. The results of a t-test and correlation performed on the EEG changes in two episodes of transition to fatigue are shown in Table 7.2. Theta and beta were significantly different during two episodes of transition to fatigue within a driving session ($t=-8.42$, $df=18$, $p<0.001$ and $t=-8.20$, $df=18$, $p<0.0001$, respectively). Delta and alpha bands were similar over the two fatigue episodes. However, all bands showed highly significant associations during the two episodes of fatigue ($p<0.001$ for all the bands). Figures 7.2, 7.3, 7.4 and 7.5 show the linear regression lines and correlation for the two episodes of fatigue for delta, theta, alpha and beta, respectively.

Table 7.1 The average EEG activity during two different episodes of the transitional phase to fatigue in non-professional drivers. Bonferroni corrections have been applied so that the probability for rejection is $p=0.01$ (i.e. 0.05/4).
(n=35)

EEG Band	**Transition to fatigue (episode 1)**	**Transition to fatigue (episode 2)**
Magnitude (μV)		
Delta	30.3 ± 9.27	30.3 ± 7.18
Theta	11.1 ± 3.07	9.7 ± 2.43 *
Alpha	9.0 ± 0.86	8.9 ± 0.68
Beta	8.4 ± 0.52	9.0 ± 0.40 *

The results are reported as mean ± sd * $p< 0.01$

Figure 7.1 Average EEG magnitude changes during two episodes of transition to fatigue in non-professional drivers (n=35)



Note: Trans 1- Transitional phase to fatigue, episode 1

Trans 2- Transitional phase to fatigue, episode 2

Table 7.2 The results of a dependent sample t-test and Pearson's correlation on the intra-session EEG activity during the transitional phase to fatigue in non-professional drivers. Bonferroni corrections have been applied so that the probability for rejection is p=0.01 (i.e. 0.05/4). (n=35)

EEG Band	**Comparison of two episodes of transition to fatigue**	
	t-test	**correlation**
Magnitude (μV)	df=19	
Delta	t=-0.09, p=0.93	0.97/<0.0001
Theta	t=8.42, p<0.0001	0.99/<0.0001
Alpha	t=1.09, p=0.29	0.81/<0.0001
Beta	t=-8.20, p<0.0001	0.76/<0.0001

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

Figure 7.2 Linear regression line and correlation of delta activity during the two episodes of fatigue in non-professional drivers

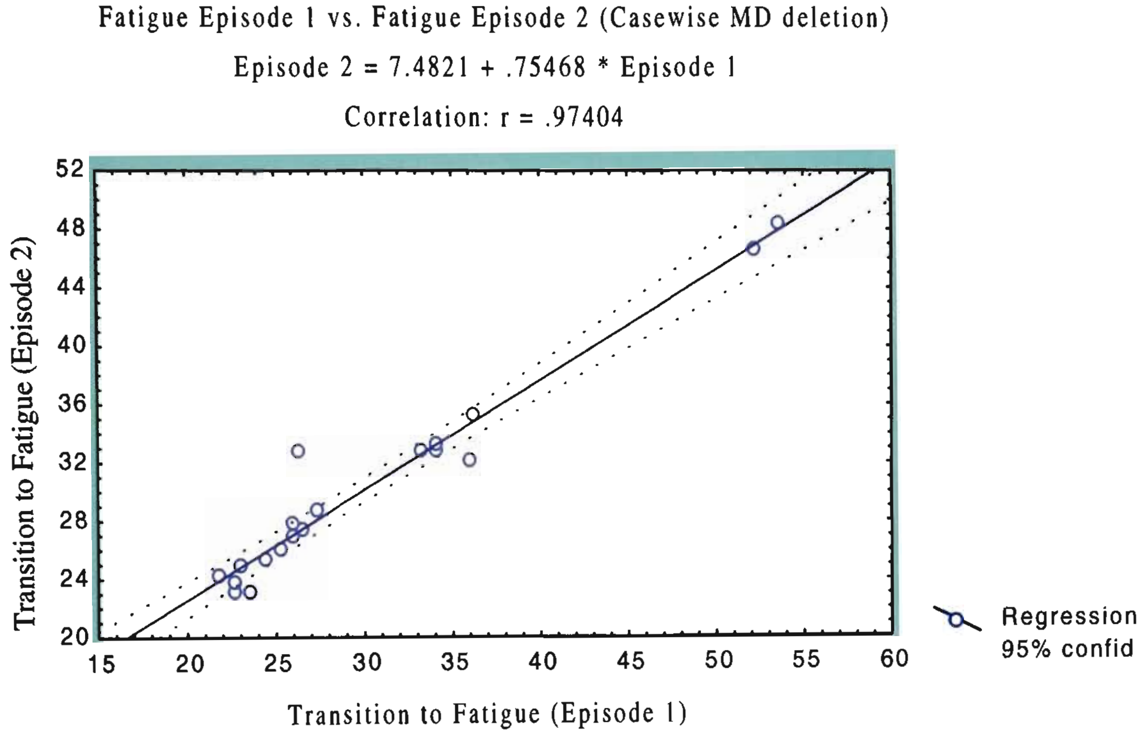


Figure 7.3 Linear regression line and correlation of theta activity during the two episodes of fatigue in non-professional drivers

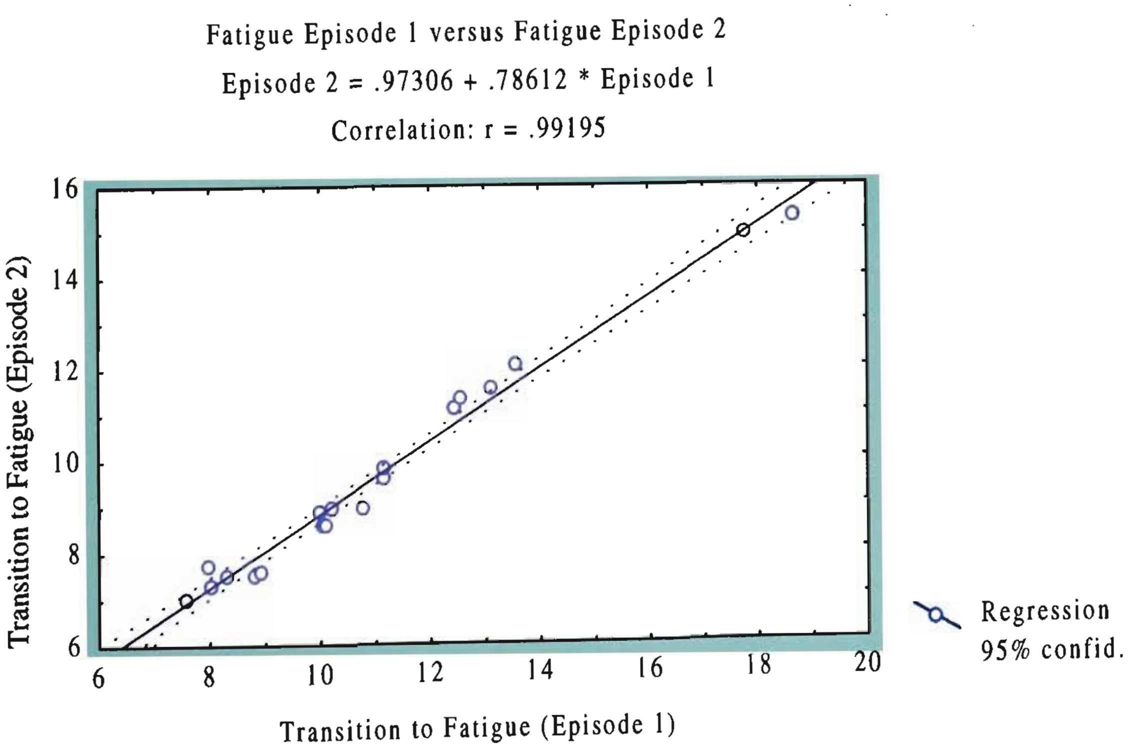


Figure 7.4 Linear regression line and correlation of alpha activity during the two episodes of fatigue in non-professional drivers

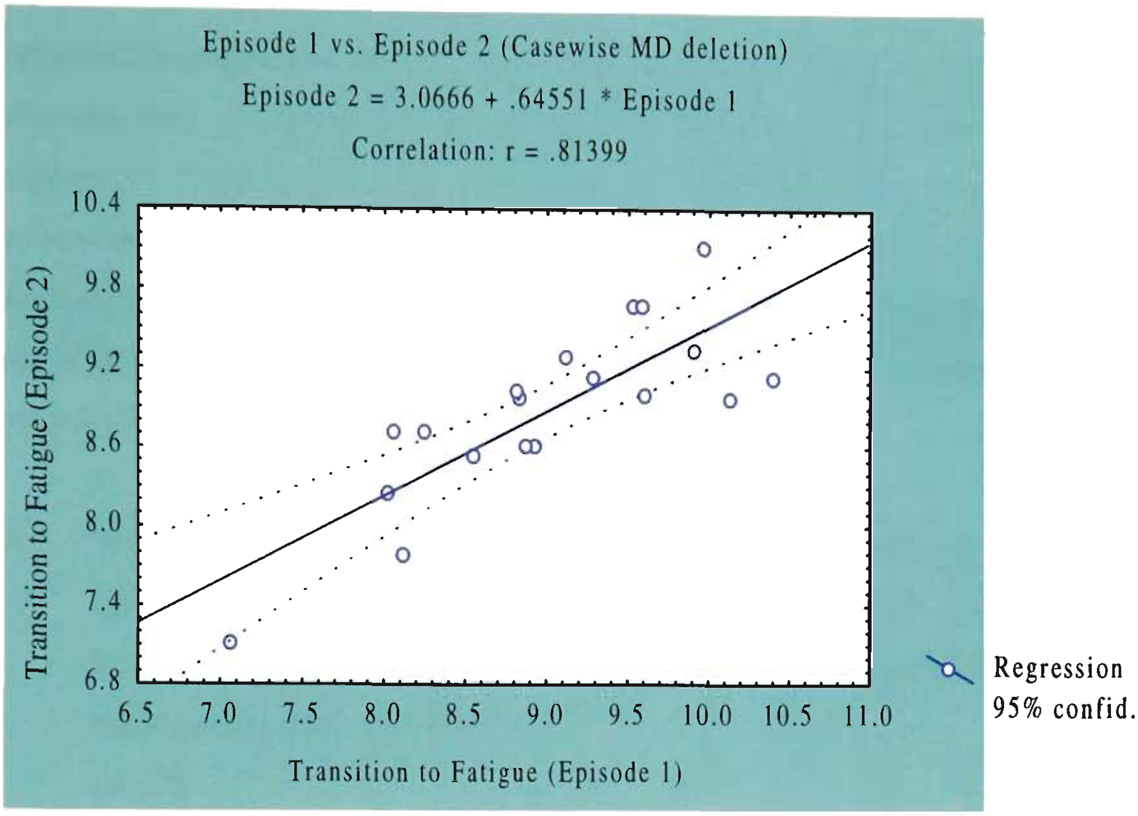
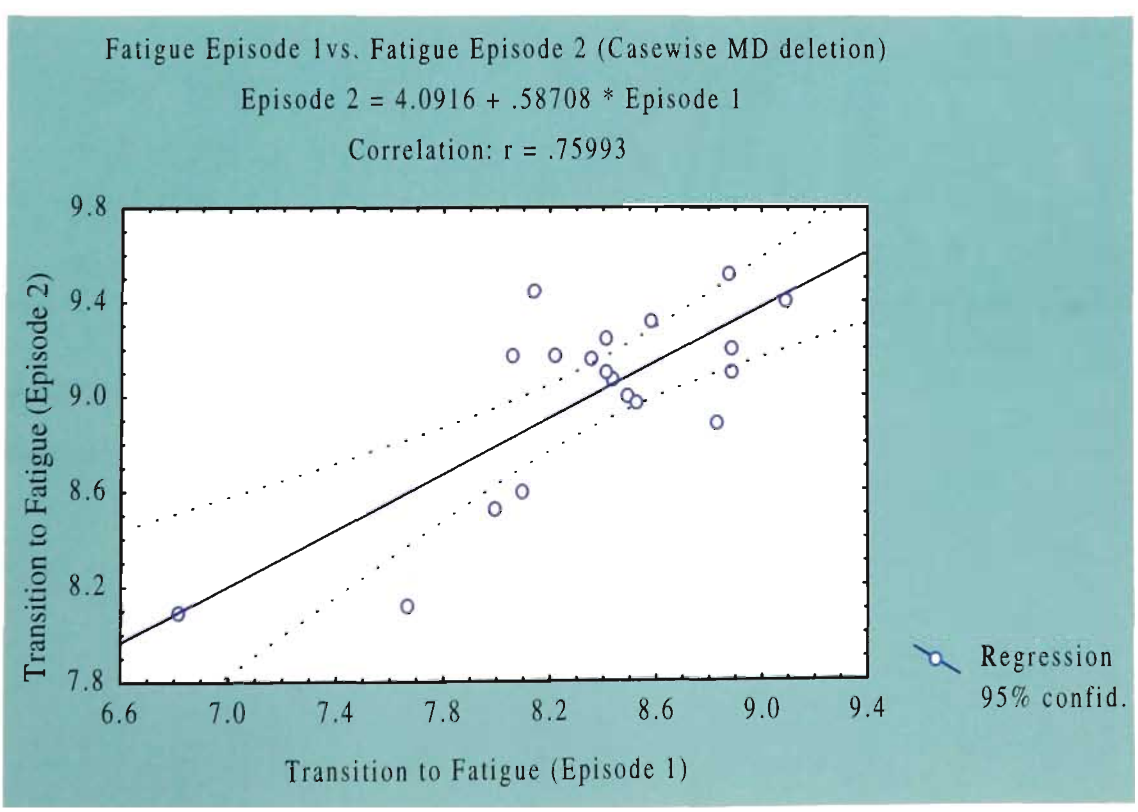


Figure 7.5 Linear regression line and correlation of beta activity during the two episodes of fatigue in non-professional drivers



7.3.2 The agreement in EEG response in a single site (central site (Cz)) during the transitional phase to fatigue in non-professional drivers.

Table 7.3 shows the average EEG changes in the central site of the brain during two separate episodes of transition to fatigue. The results of a t-test and correlation performed on the EEG changes during the two episodes of transition to fatigue are shown in Table 7.4. Theta activity was again significantly different in the two episodes of fatigue recorded from the Cz site ($t=3.24$, $df=18$, $p=0.003$). The other EEG bands showed similar responses in the central site during the two episodes of fatigue. The correlations were highly significant for all bands in the central site during the two episodes of fatigue ($p<0.01$).

Table 7.3 The average EEG activity in the central site during two different episodes of the transitional phase to fatigue in non-professional drivers. Bonferroni corrections have been applied so that the probability of rejection is $p=0.01$ (i.e. 0.05/4).
(n=35)

EEG Band	Transition to fatigue (episode 1)	Transition to fatigue (episode 2)
Magnitude (μV)		
Delta	26.6 ± 20.66	27.7 ± 24.02
Theta	10.4 ± 3.26	9.2 ± 2.56*
Alpha	9.1 ± 3.06	9.2 ± 3.49
Beta	8.4 ± 2.21	9.2 ± 3.08

Note: The results are reported as mean ± sd

* p< 0.01 compared to episode 1

Table 7.4 The results of a dependent sample t-test and Pearson's correlation on the intra-session EEG activity in the central site during the transitional phase to fatigue in non-professional drivers. Bonferroni corrections have been applied so that p=0.01 (i.e. 0.05/4).
(n=35)

EEG Band	**Comparison of two episodes of transition to fatigue**	
	t-test	**correlation**
Magnitude		
(μV)	df= 34	
Delta	t=-0.28, p=0.78	0.51/0.002
Theta	t=3.24, p=0.003	0.73/<0.0001
Alpha	t=-0.58, p=0.57	0.91/<0.0001
Beta	t=-2.21, p=0.03	0.66/<0.0001

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

7.3.3 The agreement in EEG response, representative of the whole brain, during the transitional phase to fatigue in professional drivers.

Table 7.5 shows the average EEG changes during two separate episodes of transition to fatigue within a session in twenty truck drivers. Figure 7.6 shows a graphical representation of the results shown in Table 7.5. The results of a t-test and correlation performed on the EEG changes during two episodes of transition to fatigue are shown in Table 7.6. Figures 7.7, 7.8, 7.9 and 7.10 show the linear regression line and correlation for the two episodes of fatigue for the delta, theta, alpha and beta bands, respectively. As found in the non-professional drivers, theta and beta activity were again more variable in the two episodes of transition to fatigue (t=-8.84, df=18, p<0.0001 and t=9.97, df=18, p<0.0001, respectively) in the professional drivers. However, the EEG changes in all bands were highly correlated during the two episodes of fatigue (p<0.01).

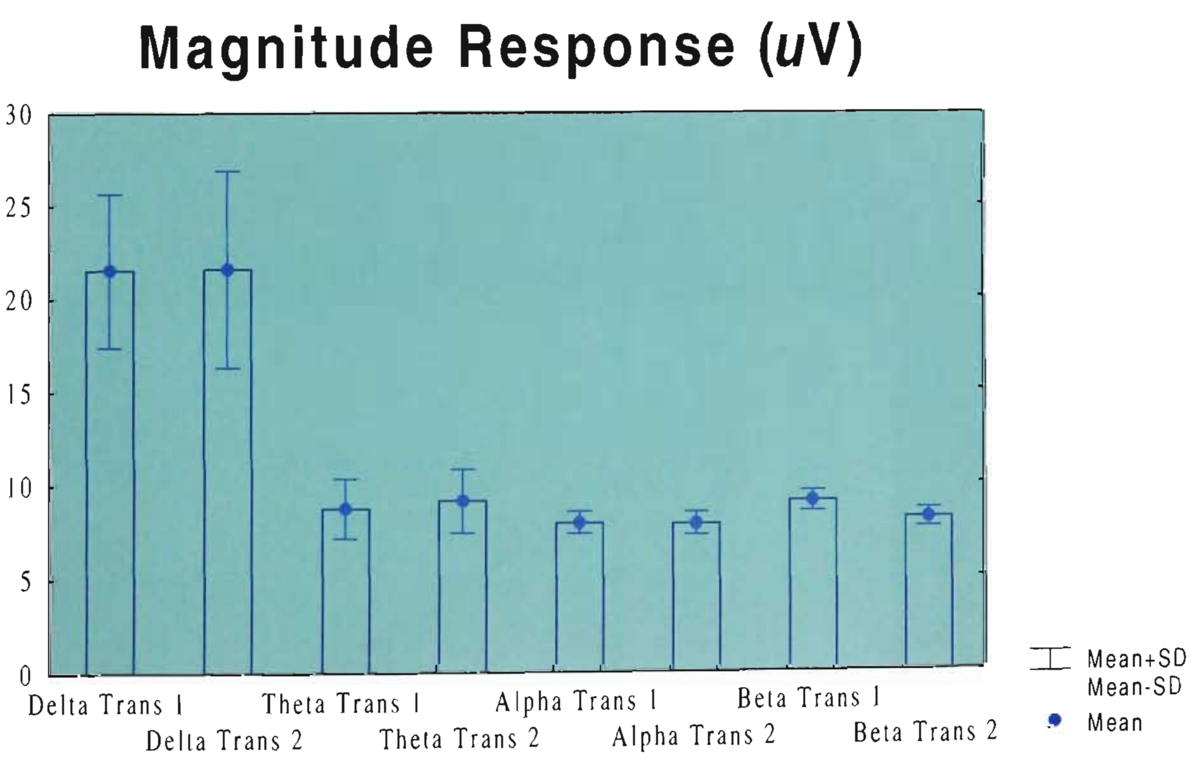
Table 7.5 The average EEG activity, representative of the whole brain during two different episodes of the transitional phase to fatigue in professional drivers. Bonferroni corrections have been applied so that the probability for rejection is p=0.01 (i.e. 0.05/4). (n=20)

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

Note: The results are reported as mean ± sd

* p< 0.01

Figure 7.6 Average EEG magnitude changes during two episodes of transition to fatigue in professional drivers (n=20)



Note: Trans 1- Transitional phase to fatigue, episode 1

Trans 2- Transitional phase to fatigue, episode 2

Table 7.6 The results of a dependent sample t-test and Pearson's correlation on the intra-session EEG activity during the transitional phase to fatigue in professional drivers. Bonferroni corrections have been applied so that the probability for rejection is p=0.01 (i.e. 0.05/4).
(n=20)

EEG Band	Comparison of two episodes of transition to fatigue	
	t-test *	correlation *
Magnitude		
(µV)	df=18	
Delta	t=-0.20, p=0.85	0.96/<0.0001
Theta	t=-8.84, p<0.0001	1.00/<0.0001
Alpha	t=0.49, p=0.63	0.64/0.003
Beta	t=9.97, p<0.0001	0.71/0.001

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

Figure 7.7 Linear regression line and correlation of delta activity during the two episodes of fatigue in professional drivers

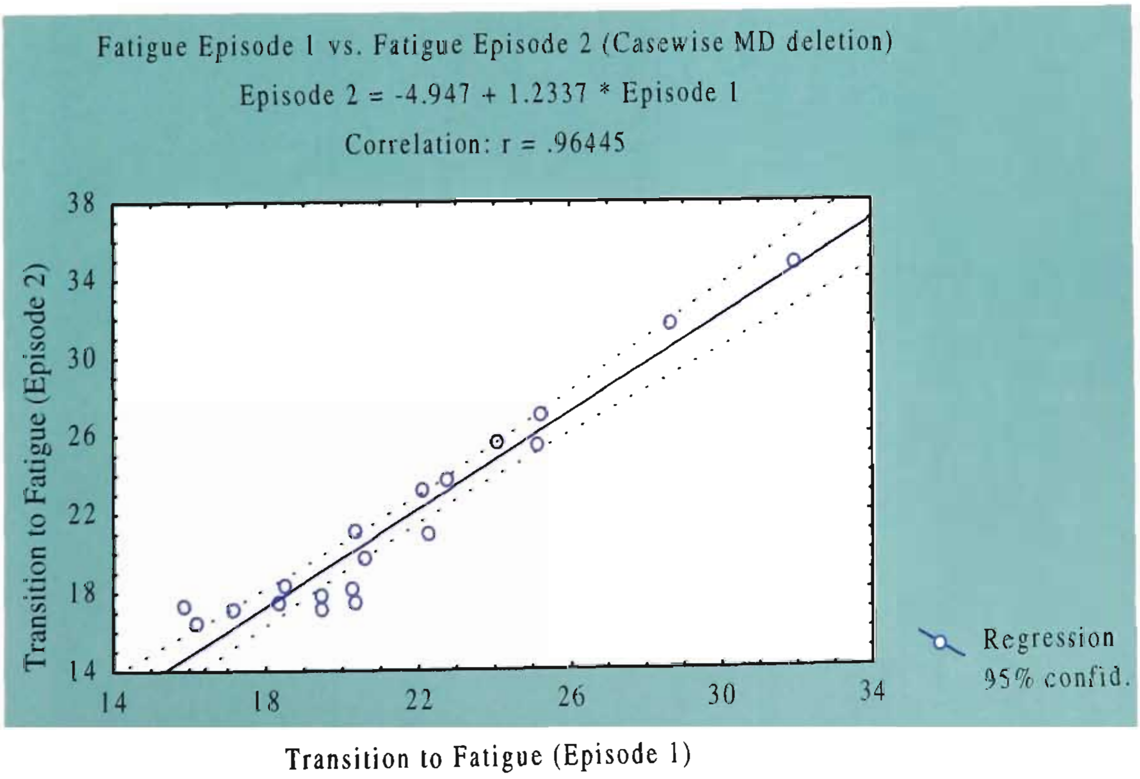


Figure 7.8 Linear regression line and correlation of theta activity during the two episodes of fatigue in professional drivers

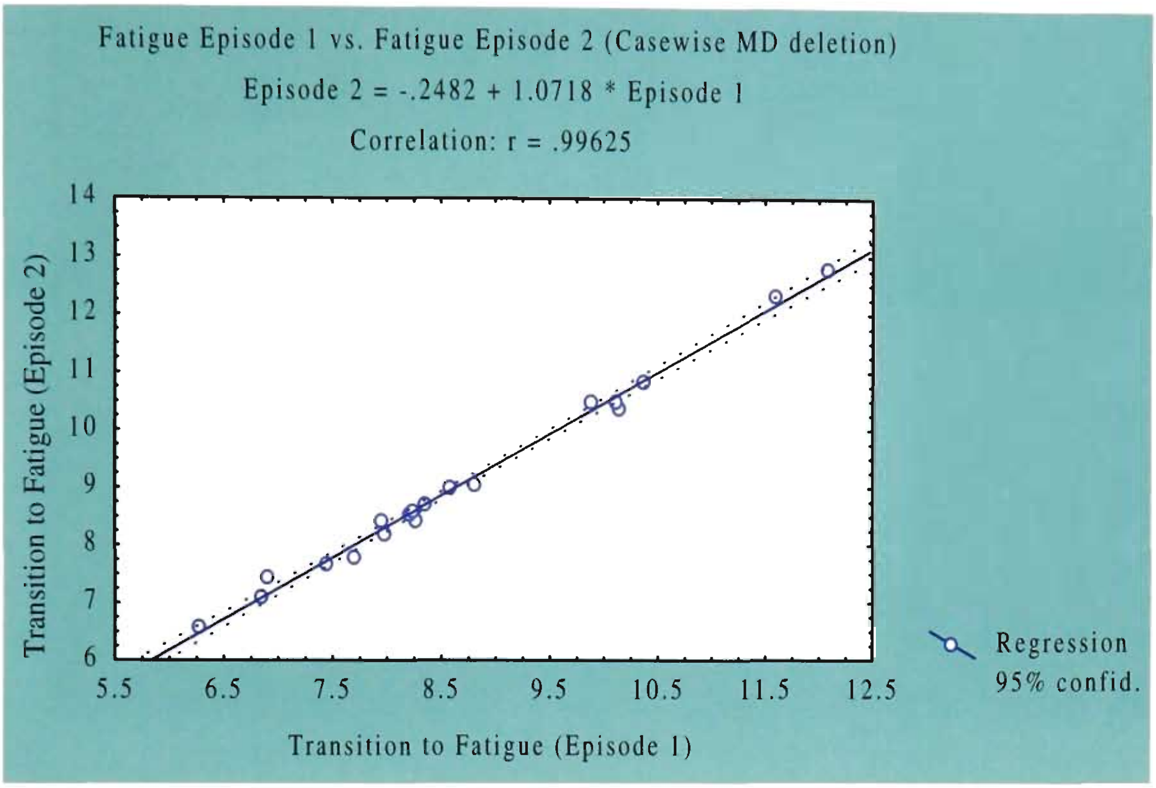


Figure 7.9 Linear regression line and correlation of alpha activity during the two episodes of fatigue in professional drivers

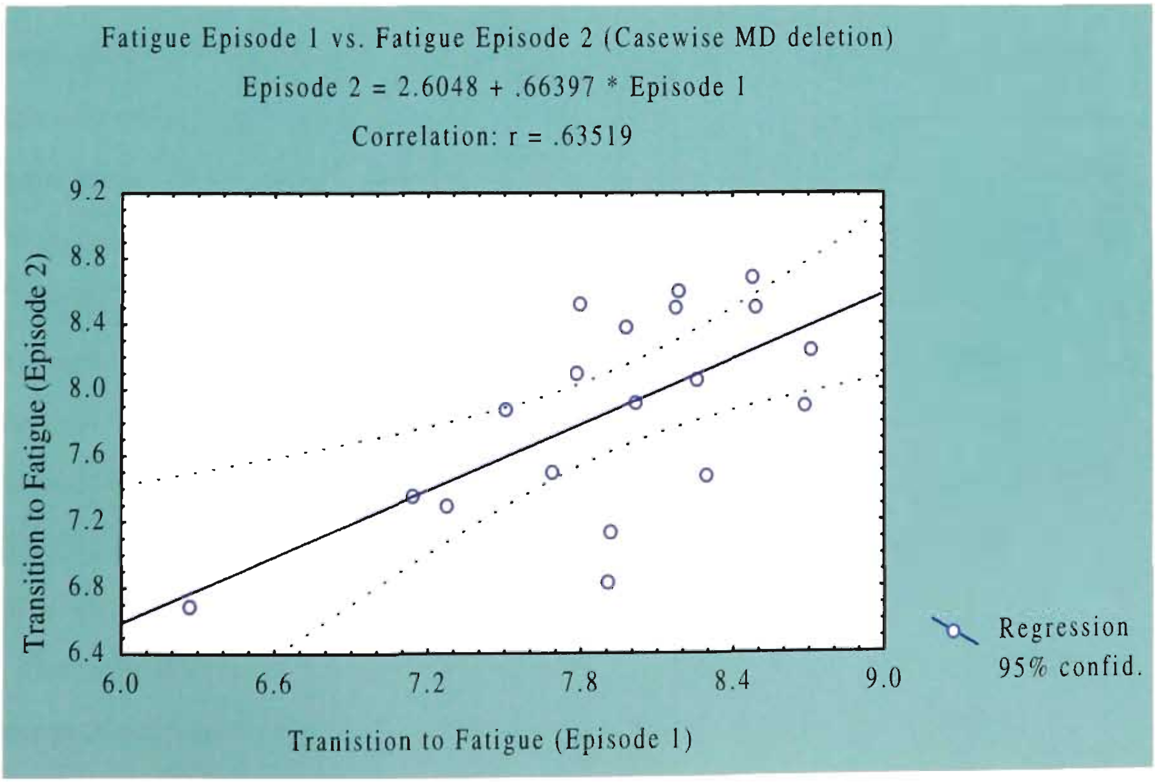
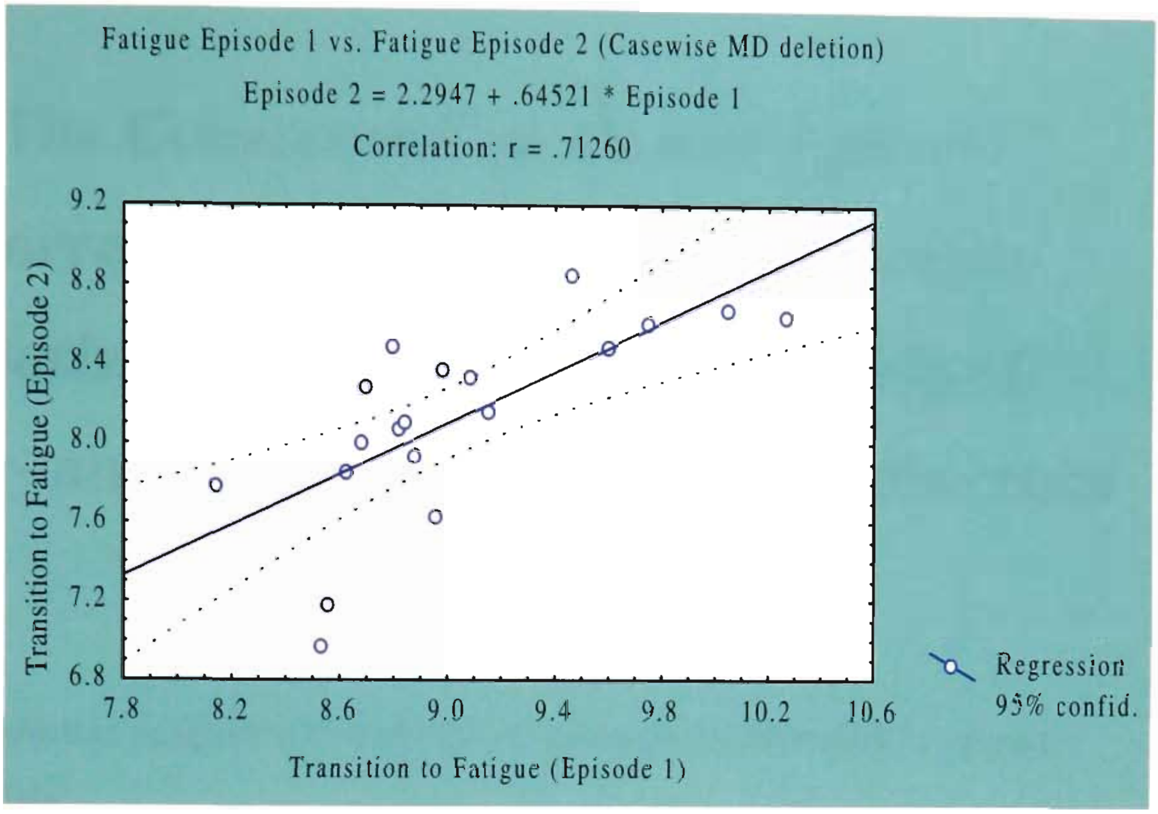


Figure 7.10 Linear regression line and correlation of beta activity during the two episodes of fatigue in professional drivers



7.4 Discussion

At the time of writing there were no other known investigations on the reproducibility of the EEG changes during driver fatigue. In the present research, reproducibility was studied for each of the 19 EEG channels and also separately in an individual site on the brain in two groups of drivers (n=35 non-professional and n=20 professional drivers) during the one session recording. The EEG changes were reproducible in the delta and alpha bands in the entire brain during the transition to fatigue. These changes were also observed in one selected site on the brain i.e. the central site (Cz). This suggests that the EEG of fatigue measured from different sites reflect the response of the entire brain. However, theta and beta activity may be more variable during different periods of transition to fatigue. Significant differences were found in these two bands during two episodes of fatigue. However, these differences were of a small order of approximately 1 μV. The EEG signals were highly correlated over time. Similar findings were observed in the two episodes of fatigue for both professional and non-professional drivers. The only difference was that EEG changes of higher magnitudes were observed in the non-professional drivers compared to the professional drivers, indicating a greater level of fatigue in the previous group (refer to Chapter 6). The next chapter will assess the changes that occur in EEG coherence during driver fatigue.

Chapter Eight

The Coherence Function or Spectral Correlation of Electroencephalography during Driver Fatigue: a case study of inter- and intra-hemispheric EEG coherence during drowsiness

8 Introduction to Spectral Correlation or Coherence Analysis in EEG Signal Analysis

It is of interest to measure the degree to which EEG signals recorded simultaneously from different electrode sites are similar in amplitude fluctuations. The quantitative assessment of such a relationship between EEG signals may be associated with physiological or functional coupling within the brain (Shaw, 1981). The EEG correlation may detect task-induced changes in the EEG related to functional organization in the brain (Shaw, 1981). Several methods for measuring the association between pairs of signals have been used, but the two most accepted methods are the cross-correlation function and the coherence function (Shaw, 1974; Shaw, 1981). The cross-correlation function measures the correlation between the whole pattern of amplitude fluctuations in the two signal epochs being compared (Shaw, 1974). It displays the correlation coefficient as a function of time displacement between signals. On the other hand the coherence function measures the correlation between two signals as a function of the frequency components which they contain (Shaw, 1981). Thus, the coherence function is a correlation spectrum and also known as spectral correlation. The coherence function is a statistical measure used to determine the likelihood of two stochastic signals arising from some common generator process, and the frequency band in which this occurs. Therefore, the coherence measure is conducted on sample epochs of the signals of interest and is therefore a statistical estimate of the true relationship between the signals (Shaw, 1981).

8.1 Use of Spectral Correlation in Drowsiness Research

There have been few comprehensive studies of the spectral correlation in the EEG changes occurring in the drowsy state in normal adults (Boldyreva & Zhavoronkova, 1991; Wada et al., 1996). In contrast to the previous assumption that drowsiness is characterised by the disappearance of alpha activity, some investigators showed that the presence of alpha activity does not always indicate an awake state (Santamaria & Chiappa, 1987a). They have observed a persistence of alpha activity during light drowsiness or transitional phase to fatigue. They also found changes in alpha activity including a decrease in its frequency and a change in its distribution and amplitude. Similarly, in the current research with drowsy drivers, it was found that alpha persists during drowsiness and may also change its distribution (refer to Chapters 3 and 6).

EEG coherence analysis or spectral correlation is a non-invasive measure of functional relationship between brain regions. Coherence of two EEG signals recorded from spatially separated electrodes estimates the similarity of waveform components generated by the mass action of neurons in underlying cortical regions (French & Beaumont, 1984; Shaw, 1981). A number of studies have applied coherence analysis to examine electrophysiological abnormalities in patients with neurological and psychiatric disorders (French & Beaumont, 1984; Michelogiannis, Paritsis, & Trikas, 2000; Nagase, Okubo, Matsuura, Kojima, & Toru, 1992). Previous studies have also used EEG coherence to investigate functional changes occurring during sleep in normal adults (Nielsen, Abel, Lorrain, & Montplaisir, 1990). However, as stated earlier, there have been few studies examining EEG coherence during drowsiness (Boldyreva & Zhavoronkova, 1991; Wada et al., 1996). One study reported a change of coherence during transition from wakefulness to drowsiness (Boldyreva & Zhavoronkova, 1991) while another study also found that light drowsiness could alter both inter- and intrahemispheric coherence (Wada et al., 1996). However, there were no studies found that examined EEG coherence changes during drowsiness in sleep deprived drivers. The present case study was therefore conducted to examine both inter- and intrahemispheric EEG coherence during wakefulness and light drowsiness in truck drivers.

The hypothesis to be tested was:

There will be changes in both inter- and intrahemispheric EEG coherence during transition from awake to light drowsiness in drivers.

8.2 Methods

8.2.1 Subjects

The data of five male subjects used for the coherence analysis were randomly selected from a total of twenty subjects studied in Chapter 6. The n=5 sample consisted of all males, aged between 30-54 years. The details of the five subjects are provided in Table 8.1. The subjects were all professional truck drivers with no history of psychiatric or neurological disease. All subjects were right handed, and agreed to participate in the study with full knowledge of the experimental nature of the research.

Table 8.1 Demographics of the five subjects in this study (n=5)

Variable	**Subject 1**	**Subject 2**	**Subject 3**	**Subject 4**	**Subject 5**
Age	30	49	52	48	54
Weight (kg)	78	87	123	75	83
Height (cm)	176.5	170	189	187	178
Head circumference (cm)	60	60	61	60	61
Handedness	right	right	right	right	right
Pre-study SBP	123	124	144	115	141
Post-study SBP	116	126	149	118	141
Pre-study DBP	82	83	95	86	80
Post-study DBP	83	90	96	84	81
Pre-study HR	68	70	88	64	72
Post-study HR	64	64	84	64	64

Note: SBP= systolic blood pressure (mmHg), DBP= diastolic blood pressure (mmHg), HR= heart rate (beats/minute)

8.2.2 Study protocol

Refer to Chapter 2 for the full details on the procedure, experimental interventions used and statistical analysis employed. The study was conducted in a temperature-controlled laboratory as the subjects performed a standardised sensory motor driver simulator task. The driving task consisted of 5-10 minutes of active driving to familiarise the subject, followed by approximately two hours of driving (speed < 80 km/hr) till the subjects showed physical signs of fatigue.

Nineteen channels of EEG were recorded according to the International 10-20 system (Fisch, 1991b). A monopolar montage was used, that is EEG activity was recorded in relation to an inactive reference site (electrodes placed on ear lobes). Physical signs of fatigue were identified using a video image of the driver's face, linked in real time with the EEG measures (refer to Chapter 2 for details). Approximately 15 minutes of EEG data were recorded during the awake state when the subjects performed an 'alert' driving task. This was followed by at least two hours of a 'passive and monotonous' driving task until the subjects showed physical signs of drowsiness or fatigue. The EEG was recorded during noon between 12:00 and 2:00 pm for each subject.

8.2.3 Data and statistical analysis

The details for data management and statistical analysis are provided in Chapter 2. The video recording was used to select the EEG segments to be analysed for the awake and light drowsy or transition to drowsiness phase (Santamaria & Chiappa, 1987a). The EEG data was digitised at a sampling rate of 256 per epoch. EEG spectra was calculated using fast Fourier transform (Exporter, Lexicor, USA). For each of the five subjects, ten artifact-free epochs were randomly selected and processed for analysis from each of the two functional states i.e. alert and light fatigue. The epochs selected were from sections of alert and transition to fatigue phase based on the video analysis of fatigue. The inter- and intra-hemispheric coherence was computed using spectral analysis software (Exporter, Lexicor, USA). In this study interhemispheric coherence was measured between the following three homologous pairs: F3-F4 (frontal), C3-C4 (central), and O1-O2 (occipital). Intrahemispheric coherence was measured at the centro-occipital region in the left (C3-O1) and right (C4-O2) hemispheres. These EEG sites were chosen to make a comparison with a previous study (Wada et al., 1996) that examined coherence changes in these sites during drowsiness. The EEG was defined in terms of the following four frequency bands including delta (0-4 Hz), theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) (Fisch, 1991b). A total of 10 epochs each for the alert and 10 epochs for the early fatigue state were analysed for the five EEG pairs. Therefore, a total of 100 epochs were analysed for each subject.

Statistical analysis was performed using a t-test for dependent samples for comparison of mean values. The significance level was set at $p<0.05$ for all analyses performed. Results are reported as mean and standard deviation of differences.

8.3 Results

8.3.1 Interhemispheric EEG coherence

Table 8.2 shows the average interhemispheric coherence values obtained during alert and transition to fatigue. In the beta frequency band, interhemispheric coherence for F3-F4 electrode pairs was significantly lower during transition to fatigue than during the alert phase ($t=3.06$, $df=4$, $p<0.04$). No other significant differences were found for other frequency bands.

Table 8.2 Average interhemispheric EEG coherence during alert 'a' and transition to fatigue 'f' phase (n=5)

Frequency Bands	F3/F4 a	F3/F4 f	C3/C4 a	C3/C4 f	O1/O2 a	O1/O2 f
Delta	0.91 ± 0.04	0.88 ± 0.06	0.87 ± 0.08	0.83 ± 0.02	0.88 ± 0.10	0.93 ± 0.03
Theta	0.95 ± 0.04	0.91 ± 0.04	0.90 ± 0.05	0.92 ± 0.03	0.94 ± 0.03	0.94 ± 0.03
Alpha	0.89 ± 0.07	0.91 ± 0.03	0.87 ± 0.06	0.87 ± 0.03	0.93 ± 0.04	0.94 ± 0.04
Beta	0.88 ± 0.03	0.83 ± 0.02*	0.82 ± 0.02	0.81 ± 0.06	0.89 ± 0.05	0.90 ± 0.07

Note: values are mean ± SD of coherence values

* $p<0.05$ compared with alert

8.3.2 Intrahemispheric EEG coherence

Table 8.3 shows the average intrahemispheric coherence values obtained in the C3-O1 and C4-O2 sites during wakefulness and light drowsiness. No significant differences were found for any of the frequency bands between the alert and transition to fatigue phases in the two sites. Furthermore, the differences between intrahemispheric coherence values for the left (C3-O1) and right hemispheres (C4-O2) were also examined and were found to be not significantly different. However, during wakefulness and fatigue, mean coherence values in the left hemisphere were consistently higher than those in the right hemisphere.

Table 8.3 Average intrahemispheric EEG coherence during alert 'a' and transition to fatigue 'f' phase (n=5)

Frequency Bands	**C3/O1**		**C4/O2**	
	a	**f**	**a**	**f**
Delta	0.85 ± 0.05	0.87 ± 0.05	0.82 ± 0.05	0.85 ± 0.07
Theta	0.88 ± 0.06	0.88 ± 0.04	0.86 ± 0.06	0.86 ± 0.06
Alpha	0.83 ± 0.08	0.85 ± 0.02	0.86 ± 0.05	0.85 ± 0.04
Beta	0.80 ± 0.04	0.80 ± 0.05	0.80 ± 0.05	0.82 ± 0.06

Note: values are mean ± SD of coherence values

8.4 Discussion

The present study examined inter- and intrahemispheric EEG coherence as a case study in five truck drivers during an alert phase and transition to fatigue phase. The hypothesis was not supported except for the changes in the EEG interhemispheric coherence during the transition from awake to drowsiness in the F3/F4 site in the beta band. In this case interhemispheric coherence was found to be significantly lower during light drowsiness or transition to fatigue than during wakefulness for the beta band. However, there were no other significant differences in beta coherence in the other two homologous sites, that is, C3/C4 and O1/O2. Even though the delta and theta bands showed lower interhemispheric coherence during light drowsiness, the differences were not significant. Others have also observed a lower interhemispheric coherence in the beta band during light drowsiness (Wada et al., 1996).

The hypothesis was also not supported for the intrahemispheric coherence differences. However, the intra-hemispheric EEG coherence was observed to be slightly higher during light drowsiness for the delta, alpha and beta bands, but not significantly. However, others have found that intrahemispheric EEG coherence was significantly higher during light drowsiness for the theta and beta frequency bands

(Wada et al., 1996). Another comparative study of the event related brain potential P300 during wakefulness and light drowsiness found that the P300 increased in its latency and decreased in amplitude during light drowsiness. This study suggests that the brain differs electrophysiologically between these two different states. Considering EEG coherence is assumed to index functional coupling between the brain regions under the recording electrodes (French & Beaumont, 1984; Shaw, 1981), there may be some indications from previous studies (Wada et al., 1996) that during light drowsiness an alteration of functional organization can occur between and within hemispheres. However, the precise mechanism alteration of functional organization remains to be specified.

Previous studies have applied coherence analysis to examine functional changes in EEG during performance of a perceptual or cognitive task. It has been reported that spatial and arithmetic tasks induce an increase in interhemispheric coherence (Shaw, O'Connor, & Ongley, 1977). Interestingly, Busk and Galbraith (1975) have reported that coherence increases with the difficulty of the task, while practice reduces coherence as a result of a decrease in task difficulty. The results of these earlier studies show that EEG coherence changes during mental tasks and light drowsiness and may be an indicator of arousal level. The smaller numbers of subjects reported here as a case study, however, did not support the findings of previous studies.

The present study found that during wakefulness mean values of intrahemispheric EEG coherence were slightly, but not significantly, higher in the left hemisphere (C3-O1) especially for delta and theta bands than in the right hemisphere (C4-O2). Other studies have previously reported higher coherence in the left hemisphere during wakefulness (Boldyreva & Zhavoronkova, 1991; Wada et al., 1996). The results from these studies suggest that there is higher functional connectivity in the dominant hemisphere during wakefulness. A slightly different coherence was observed during light drowsiness in the left and right hemispheres. Others have reported a decrease of coherence in the transitional period from wakefulness to drowsiness, suggesting a reorganisation of cortical-subcortical interactions (Boldyreva & Zhavoronkova, 1991). In the current research, investigating larger numbers of subjects would have provided a much stronger confirmation of the findings of previous studies; however, this was beyond the scope of the current research. The following chapter describes the development of software for an EEG-based fatigue countermeasure device utilising the results reported in Chapters 3 and 6.

Chapter Nine

Feasibility of Technological Countermeasure Software for Detecting Fatigue in Drivers from Electroencephalography Signals

9 Technological Countermeasures for Fatigue/Drowsiness

9.1 Research on Technological Countermeasure to Fatigue

Evidence from the scientific literature suggests reasons exist for giving serious consideration to the implementation of technological countermeasures for driver fatigue. These are:

(1) Fatigue is a persistent occupational hazard for professional or any long-distance drivers who have schedules to maintain and who may be involved in shift-work.

(2) Fatigue impairs cognitive skills; hence it can adversely affect the drivers' ability to assess their level of alertness in order to continue driving safely (Brown, 1997).

Therefore, on-line monitoring of fatigue/drowsiness while driving provides in real time the possibility of detecting potentially dangerous behaviours that are related to fatigue, such as eye-closing, head nodding and deterioration in alertness. To date, most fatigue countermeasure devices measure some physiological response in the driver such as the electroencephalogram, electro-oculogram, respiratory signals, behavioural recordings such as analysis of the video film of driver's face (Artaud, et al., 1994) or changes in the driver's alertness through steering behaviour (Yabuta et al., 1985).

Research has described how the analysis of a driver's breathing regularity can contribute to the prediction of deterioration in alertness (Artaud, et al., 1994), however this approach has still not been confirmed in a real-driving situation. Furthermore, videoing the driver's face has also been reported to have a number of technical hurdles and little is known about the feasibility of this approach (Artaud, et al., 1994). Others have described adaptive driver systems with telemetric applications in the car aimed at supporting the driver such as route guidance, anti-collision, etc (Michon, 1993). These applications can distract the driver by presenting too much information. These types of applications lack driver acceptance because of inadequate warning thresholds (i.e. neither situation-specific nor driver adapted) and there is certainly no guarantee that the systems are designed intelligently to detect fatigue states (Onken & Feraric, 1997). Even though a variety of countermeasures to fatigue have been developed, the effectiveness of these devices in preventing deterioration in driving performance is disappointing (Desmond & Matthews, 1997). This outcome may be attributable to the device's failure to take into account the variation of fatigue effects with changing task demands (Desmond & Matthews, 1997).

Although numerous physiological indicators are available to describe an individual's level of alertness, the EEG signal has been shown in this present research (Chapter 3) and the research of others to be one of the most predictive and reliable (Artaud, et al., 1994). However, very little evidence exists on incorporating EEG signal detection and analysis into a technological countermeasure device for fatigue. Researchers have suggested the possibility of using EEG grouped alpha waves and electrocardiogram in sleep detection systems (Fukuda, et al., 1994; Ninomija et al., 1993). However, evidence does not exist on the implementation of such a device. An automated drowsiness detector based on ongoing EEG was also developed about twenty years ago by Gevins et al. (1977b). However, once again progress on the applicability of the device has not been reported. In spite of this, the same researchers suggest that EEG could be used to create an automated system that continuously tracks and compensates for variations in the alertness of a human operator (Gevins, et al., 1995).

The aims of this study were:

(1) to utilise the EEG changes that occur during driver fatigue (described in Chapters 3 and 6) for the development of software to be incorporated into the development of a fatigue countermeasure device.

(2) to test the ability of such software to detect the transitional phase to fatigue, transitional-post transitional phase and the post-transitional phase in 'offline data analysis'.

The hypotheses generated for this study included:

(1) EEG based fatigue detection software will be capable of categorising the data into the three phases of fatigue i.e. transitional, transitional-post transitional and post-transitional.

(2) The above fatigue states will be identified in the majority of the subjects.

9.2 Methods

9.2.1 Subjects

Ten male subjects who were professional truck drivers were randomly selected from a total of twenty (refer to Chapter 6). All consecutive data and statistical analyses that follow have been performed in this group of 10 subjects.

9.2.2 Study protocol

For the full details on the procedure and experimental interventions refer to Chapter 2. The study was conducted in a temperature-controlled laboratory as the subjects performed a standardised sensory motor driver simulator task. The driving task consisted of 5-10 minutes of active driving to familiarise the subject, followed by approximately two hours of driving (speed < 80 km/hr) till the subjects showed physical signs of fatigue. Simultaneous EEG measures were obtained during the driving task. Nineteen channels of EEG were recorded according to the International 10-20 system (Fisch, 1991b). Physical signs of fatigue were identified using a video image of the driver's face, linked in real time with the EEG measures.

9.2.3 The fatigue anticipating software: towards a technological countermeasure against driver fatigue

The EEG changes that were found during fatigue (reported in Chapters 3 and 6) were used as the basis of developing the fatigue monitoring software. To accomplish this, the EEG changes observed during the alert, transitional, transitional-post-transitional and post-transitional phases of fatigue were used to develop an algorithm that could detect a set of programmed changes that occur during different phases of fatigue. The software was developed using Lab View (version 5.1, National Instruments, USA). The software was designed to detect four different functional states and these are alert, transitional phase (early fatigue stage) of fatigue, the transitional-post transitional phase (medium levels of fatigue) and the post-transitional phase (extreme levels of fatigue) (the phases are described according to (Santamaria & Chiappa, 1987a)). EEG data in the four phases were categorised into four channels represented by colour panels, which were green, yellow, orange and red respectively. As indicated by the colour scale, green is a 'safe' level (alert) and red is a 'dangerous level of fatigue (post-transitional phase). Yellow and orange denote early (transitional phase) and medium (transitional-post transitional phase) level of fatigue, respectively.

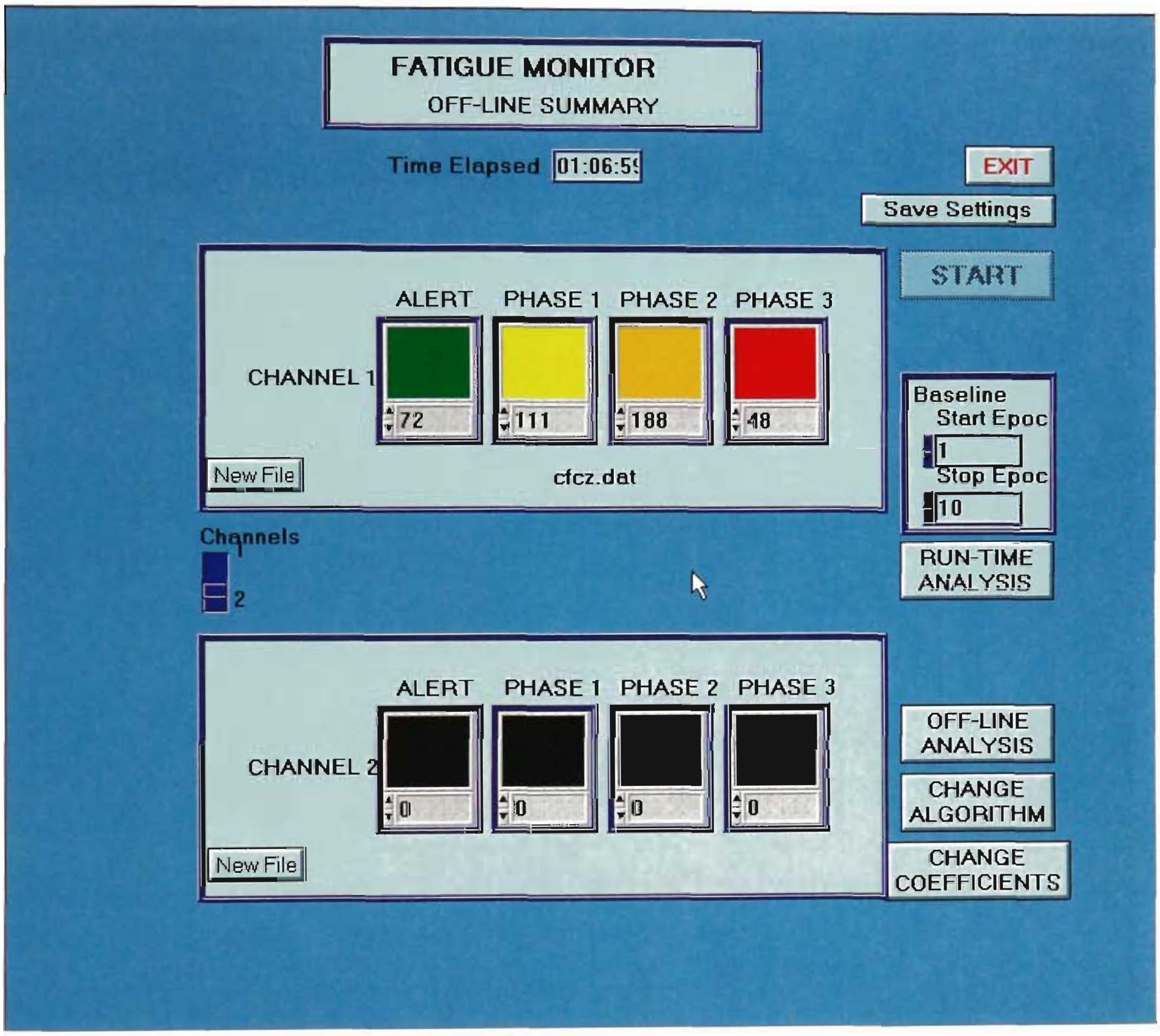
9.2.4 Data and statistical analysis

Different algorithms based on the EEG changes observed during fatigue were developed and tested. The fatigue software is capable of analysing EEG data in real-time as well as it allows off-line analysis of previously acquired data. In real time and off line analysis, the fatigue software is capable of acquiring two channels of EEG data (i.e. data acquired from two different EEG sites on the brain) which has been sampled at 256 Hz during the driving task. For the purposes of this chapter the results of testing the software on previously acquired EEG data (reported in Chapter 6) will be reported and hence only the off-line analysis mode will be referred to.

The software performs a fast Fourier transform for spectral analysis of the acquired EEG data. The EEG is then defined in terms of frequency bands including delta (0-4 Hz), theta (4-8 Hz), alpha (8-13 Hz) and beta (13-20 Hz) (Fisch, 1991b). For each band the software computes the EEG magnitude (μV) which is the sum of all amplitudes of all data points within a band's frequency range.

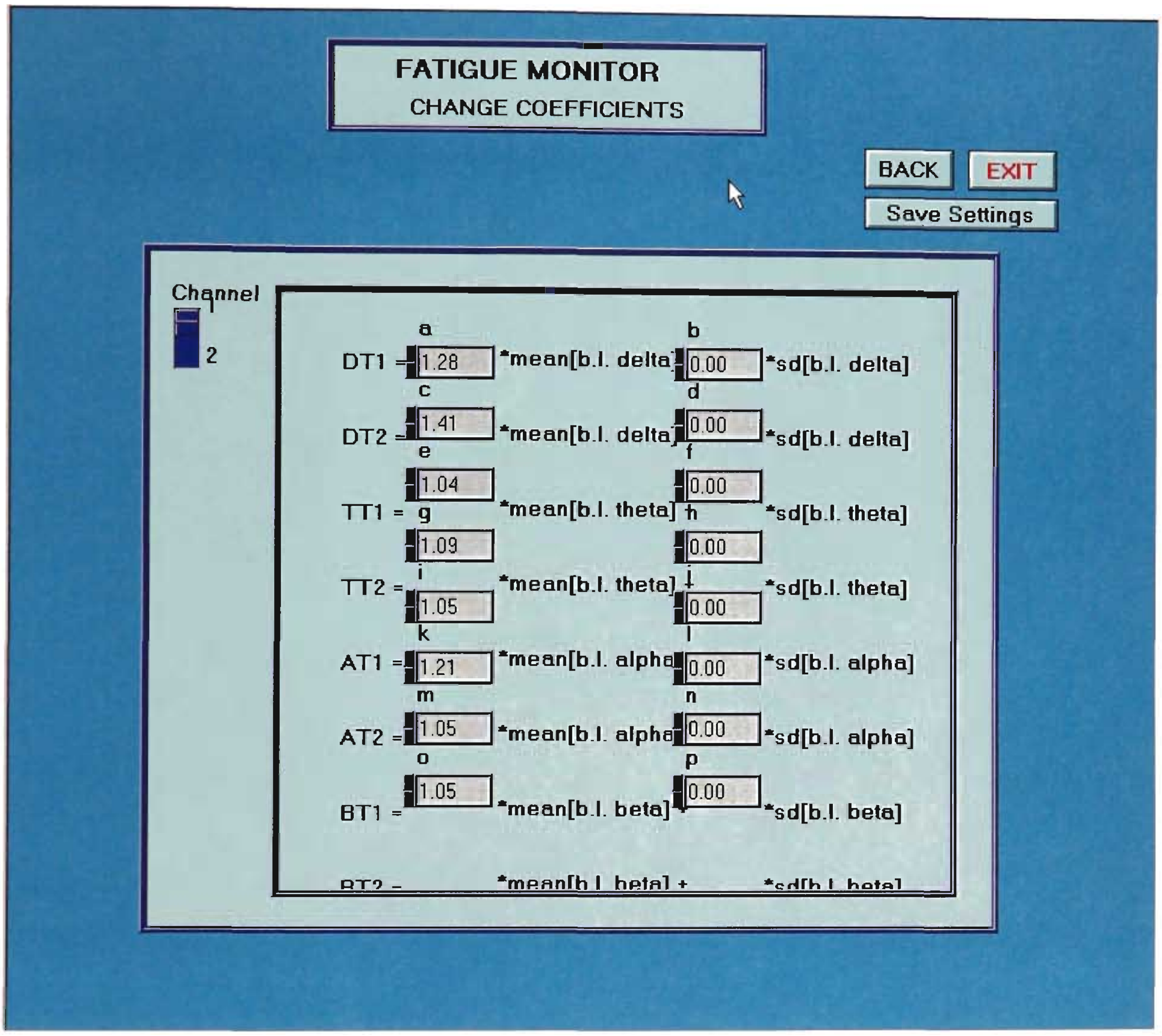
The software computes a baseline mean from a section of data that represents the alert state of the individual. A range of randomly selected epochs, linked in real time to a video recording of the subject's alert state (refer to Chapter 3) were chosen to represent the baseline. The mean and standard deviation of the EEG magnitude in this phase is then computed for all four frequency bands in the alert phase. The software allows a threshold coefficient to be defined for each of the frequency bands in terms of the mean and standard deviations that will determine a particular state of the individual i.e. alert or a fatigue state. For each of the four phases mentioned above, a different set of coefficients decides whether the data will be detected as being in the alert (green), transition to fatigue (yellow), transitional to post-transitional (orange) or post-transitional (red) phase (see Figure 9.1). The coefficient-setting panel is shown in Figure 9.2. A range of EEG magnitude values were programmed into the software in terms of mean and standard deviation for each phase which decides the percentage of data that will be detected as an alert or one of the fatigue phases. Using the AND (&)/OR (|) logic an algorithm is defined for the alert and fatigue states. For example (D & T) & A | B indicates that the state of fatigue is indicated only if the delta and theta and either alpha or beta magnitude is within the defined range (see Figure 9.3). This algorithm can be varied depending on the presence of the different EEG waves in a particular phase.

Figure 9.1 The panel allocation of data into an alert (green), transition to fatigue (yellow), transitional-post transitional phase (orange) and post-transitional phase (red)



Note: Data detection shown in one channel only (detected from one site on the brain, that is, Cz (central)).

Figure 9.2 This panel shows the mean coefficients allocated to detect the alert and fatigue phases by the software



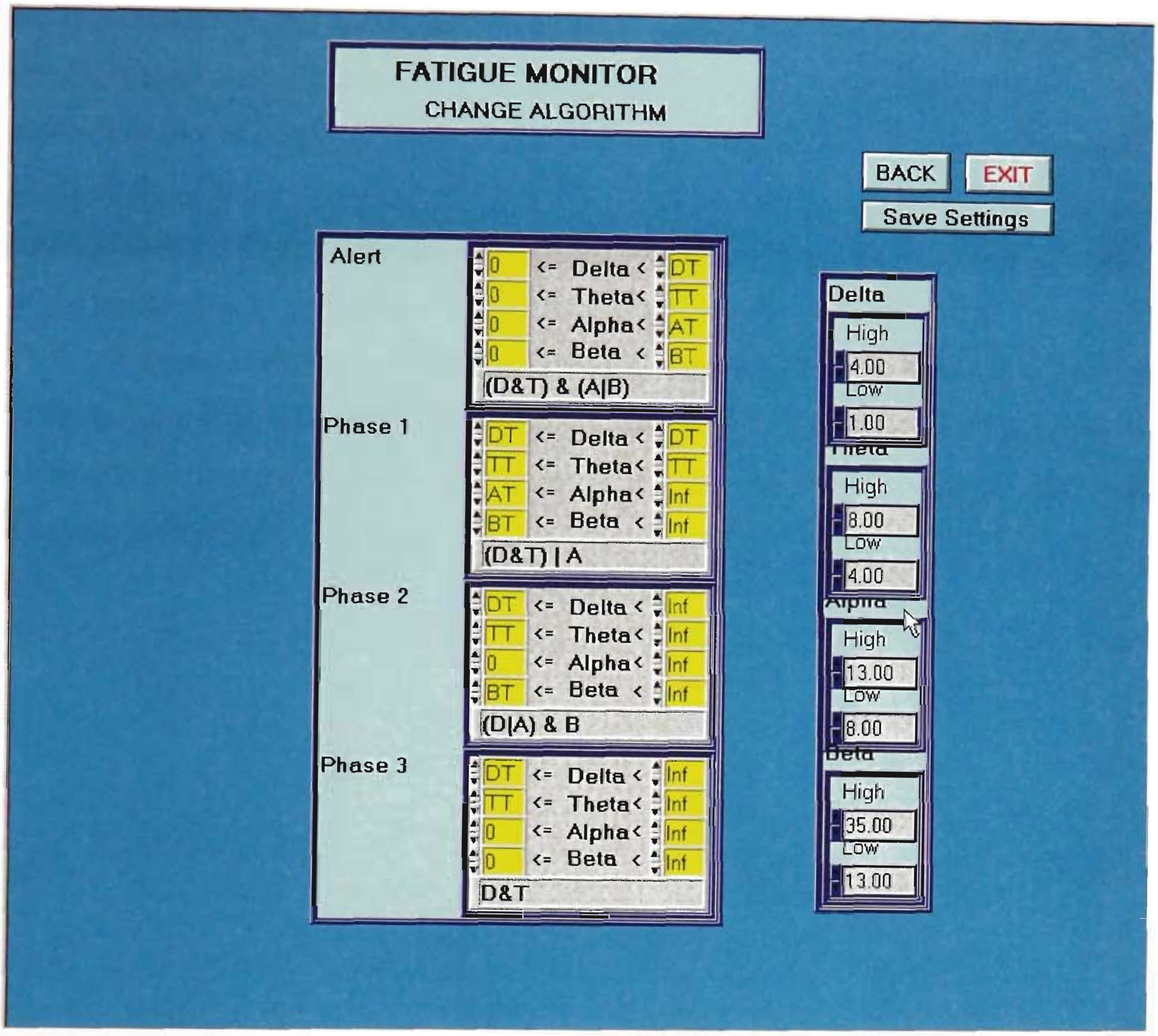
Note: DT= delta threshold, TT= theta threshold, AT= alpha threshold and BT= beta threshold

For example:

DT1= fatigue phase one threshold (transitional)

DT2= fatigue phase second threshold (transitional to post transitional or post transitional)

Figure 9.3 The algorithm panel of the fatigue monitoring software



Note: D= delta, T= theta, A= alpha and B= beta

The bar on the right specifies the frequency range for delta, theta, alpha and beta.

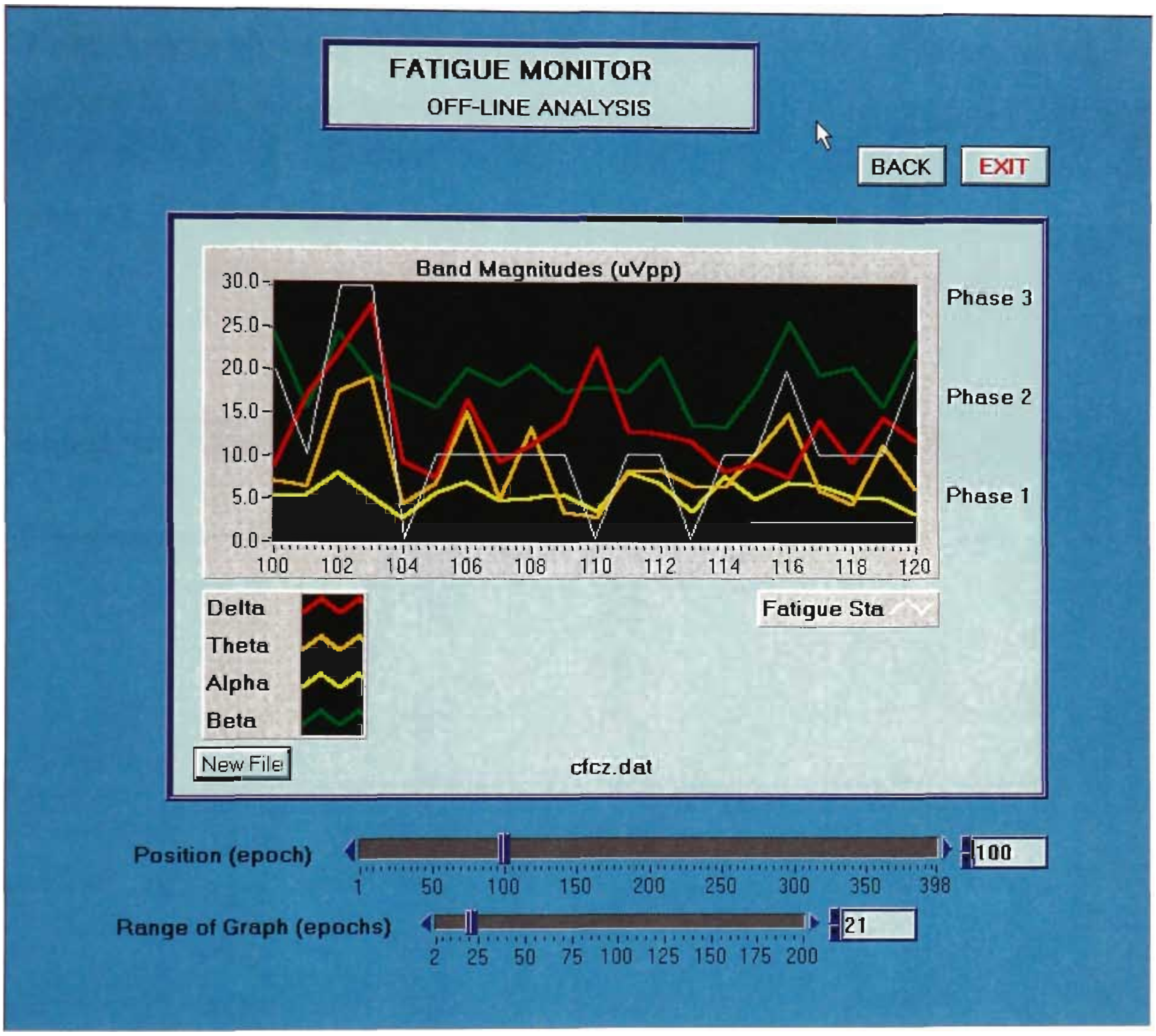
For example a specified algorithm indicates:

(D & T) & (A | B) refers to detect a specific state when delta and theta and alpha or beta are detected using a programmed threshold.

Therefore, the data collected in the ten truck drivers were analysed using offline analysis. Raw EEG time domain ASCII data acquired using a physiological monitor (Neurosearch-24, Lexicor, America), were converted to real text format using a program modified from the Neurosearch-24 software, Lexicor, America (E.exe). Using the previously recorded EEG data from twenty truck drivers (refer to Chapter 6), four test algorithms were developed for the alert and the three fatigue phases. These algorithms identified the proportion of data that was in the alert and fatigue states and allocates them to the colour panels described above. In off-line analysis mode, the data could also be viewed graphically with a line indicating in which panel i.e. alert or one of the fatigue states, a particular epoch had been allocated (see Figure 9.4).

A repeated measures ANOVA was performed to identify if differences existed in the means of the four states. A Scheffé test then identified where the differences existed in the comparison of the means. The significance level was set at $p<0.05$ for all analyses performed.

Figure 9.4 A graphical representation of the data in offline analysis mode using the fatigue monitoring software



Note: The level of the grey line on the graph represents the phase in which the epoch (EEG data point) was detected.

9.3 Results

The results of the off-line analysis using the fatigue detection software on EEG data of the ten truck drivers are shown in Table 9.1. The software categorised the data into an alert, transition to fatigue, transitional- post transitional and a post-transitional phase. Table 9.1 shows the percentage of fatigue status detected in the subjects. The ability of the software to detect fatigue (validated by the video analysis of fatigue, refer to Chapter 3 for details) was demonstrated by the fact that the software detected no false positives. In other words, the software did not detect fatigue when the subject was alert.

Table 9.1 Showing the ability of the fatigue software to detect an alert or a fatigue state in each subject (detection shown as percentage values)

Subject No	Alert	Transition to Fatigue	Transitional-post transitional	Post-Transitional
1	37.2	27.7	22.0	13.1
2	36.3	14.3	29.4	20.0
3	35.9	22.5	23.7	17.9
4	18.9	27.2	27.7	26.1
5	34.3	46.9	12.6	6.2
6	46.5	28.8	16.8	8.0
7	29.6	39.6	16.6	14.2
8	65.9	16.1	9.1	8.9
9	39.7	17.3	13.1	29.9
10	52.0	32.4	6.0	9.6
average ± sd	39.6 ± 12.8	27.3 ± 10.4	17.7 ± 7.8	15.4 ± 8.0

The ANOVA showed that there was an overall difference in the comparison of the means of the four states (F=9.15, df=3, 27, p=0.0002). The post-hoc analysis identified that the percentage of time the subjects were detected to be in the transitional-post transitional and post-transitional fatigue phases were significantly different to the alert phase (p=0.003 and p=0.0009, respectively). The software detected a larger proportion of epochs in the first fatigue state, that is, the transitional phase to fatigue, compared to the other two fatigue phases. That is the subjects' were in the transitional phase of fatigue for a greater proportion of the time than in the transitional-post transitional or the post-transitional phases of fatigue. For almost 40% of the total driving time the subjects were in an alert state, while for the remaining 60% of the time, the software detected the subjects to be in one of the three fatigue states.

9.4 Discussion

9.4.1 The potential of the EEG detecting software

The fatigue detecting software described in this chapter involved the development of algorithms that were designed to detect different states of fatigue i.e. transitional, transitional-post transitional and post-transitional phases of fatigue. The algorithms were based upon EEG changes reported during driver fatigue in Chapter 6. The results of testing the software in offline mode indicates that sleep deprived drivers were in a fatigue state for at least sixty percent of the total time they spent driving in the simulator. The software was capable of detecting the three stages of fatigue; previously validated by video monitoring (refer to Chapter 3). However it should be noted that this is an initial development and these results represent a pilot trial of the first prototype of the software. This software is also unique in the sense that it can detect fatigue based on EEG changes occurring simultaneously in the delta, theta, alpha and beta bands. Furthermore, it has the capability to detect fatigue on an individual basis where an algorithm can be computed based on the individual's EEG changes during fatigue. It can also be programmed to detect fatigue based on the mean changes that occur in a sample.

9.4.2 Future research and development of the fatigue monitoring software

More research is required with the fatigue software to produce a robust and reliable fatigue detecting/alerting system. The need for some future modifications of the software has become apparent in this research. These are (1) In both the real-time and offline analysis mode a 'threshold' algorithm is required which can negate major artifacts in the EEG data that can occur due to coughing, sneezing and any large extraneous movements. For example, individual algorithms need to be incorporated into the software that can detect head and body movements, large muscle potentials and eye-movement potentials referenced against an artifact free calibration period. Such an on-line computer rejection of artifact has been described in previous research (Gevins et al., 1977a) and may form the basis of detecting and eliminating extraneous signals in the fatigue detecting system described in the current research. (2) Currently the software is only capable of specifying two fatigue levels as indicated in the threshold settings panel (refer to Figure 9.2) even though algorithms can be devised to detect three fatigue phases (refer to Figure 9.1). The programming of algorithms can be made simpler by modifying the software to be able to set three threshold coefficients to detect the three fatigue states.

Simultaneous development of the hardware (Biosync, Mind Switch Pty. Ltd., Sydney) is also occurring, which together with the software will form a fatigue monitoring device. The software's ability to allocate the EEG data into the various colour panels could be used in the future to alert drivers of their fatigue status, for example, yellow indicating light fatigue and red indicating extreme fatigue, using varying levels of auditory sounds.

To date few researchers have investigated the use of EEG as a fatigue countermeasure. Ninomija et al. (1993) developed a system which detects sleepy states of drivers using grouped EEG alpha waves and warns them of the dangerous state (Ninomija et al., 1993). They reported an error in their subsystem in the magnitude of 25-35%. In order to improve the reliability of their EEG based system, these researchers suggest that they need to monitor the simultaneous electrocardiogram during driving. The disadvantage apparent in this system is the use of extra electrodes to monitor two separate physiological signals making it more cumbersome than having one recording system to detect fatigue. In progressive research the same investigators further describe the grouped alpha waves detecting system using a convolution with special weighting factors such as moving average methods (Fukuda, et al., 1994). They reported that the system separates grouped alpha waves from various kinds of noise and detects low awakening levels as soon as grouped alpha waves appear. However, this group has not reported the further development of their system in a real field condition. In the current doctoral research it has been found that even though alpha increases during drowsiness, the magnitude of change in the delta and theta waves are larger and easier to detect (refer to Chapters 3 and 6). Furthermore, basing fatigue on one changing EEG variable cannot be as reliable as detecting the simultaneous changes that occur in all the bands. This is the current sophistication of the software described in the current research. Since fatigue is a cortical deactivation that affects all brain waves in one way or the other it can only be beneficial to record and detect changes in all bands in a future EEG based fatigue monitoring device.

As a result of this research other parameters became apparent that need investigation for the feasibility of a fatigue monitoring device in an operational setting. In the laboratory, restrictions on equipment size and weight were of little concern. However, in an applied setting, these restrictions can be important. Furthermore, real time field trials of the fatigue monitoring device are essential. The system also needs to be shown to be reliable. Furthermore, more work needs to be carried out on EEG based electrodes. The electrodes used with the fatigue monitor should be easy to connect as well as be able to monitor EEG changes accurately for long periods. Data reduction should also be quick in real time to defeat the suddenly occurring fatigue states.

Therefore as discussed in the introduction, a valid measure of fatigue such as the EEG seems promising for the development of a fatigue countermeasure device. The fatigue countermeasure device must provide a valid indication of fatigue, rather than some type of performance impairment (Desmond & Matthews, 1997). 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 environment that demands alertness and that involves multiple tasks competing for limited attention resources (Gevins, et al., 1995). With the advances in miniaturisation of equipment, the use of physiological parameters such as the EEG has become more feasible in operational settings (Rokicki, 1995). The use of simple on-line frequency domain procedures to compute EEG alpha, theta, delta and beta bands form the basis of the fatigue detecting software described in this doctoral research. The chapter that follows provides a summary of the current doctoral research. The future prospects for research in the area of driver fatigue are also summarised.

Chapter Ten

Conclusions and Future Directions Evident from a Three Year Investigation of the Psychophysiology of Driver Fatigue/Drowsiness

10 Conclusions from the Review on the Psychophysiology of Driver Fatigue

The literature review on the psychophysiology of driver fatigue and drowsiness revealed that most of the studies conducted in the area suffered from methodological limitations that would potentially confound the results and therefore render the conclusions ambiguous. Study flaws included inadequate number of subjects, lack of validity in identifying fatigue and poor experimental design and data analysis. Furthermore, many 'grey areas' were identified on the psychophysiological and specific electroencephalography (EEG) changes that occur during the onset of driver fatigue, such as:

- Omitting to report sample numbers and sample power reporting EEG changes in inadequate sample numbers.

- Testing EEG in subjects without screening for effects such as psychosis or alcohol abuse which may confound the results.

- Inadequate number of brain sites being tested.

- Use of variable EEG montage.

- Only reporting activity in some bands, when all are influenced by fatigue

The current PhD research was aimed at producing data on the psychophysiology of driver fatigue using a robust experimentally controlled design. An adequate sample size with sufficient statistical power was employed with random allocation of the subjects into the experiment. All experimental interventions were also conducted in a controlled laboratory environment. Furthermore, many factors associated with driver fatigue that lacked investigation or were not adequately examined in previous studies were investigated thoroughly in this doctoral research and included:

- Physiological parameters such as the 19-channel EEG (Fisch, 1991b), three-lead ECG and EOG were assessed.

- a valid indicator of fatigue such as video analysis of the face was used to identify fatigue.

- A thorough investigation of psychological associations with fatigue was conducted. The psychological measures assessed included mood, anxiety, locus of control and self-reported fatigue status.

- A comparison of fatigue in professional versus non-professional drivers.

- A robust validation and reproducibility of fatigue effects was conducted.

- A unique EEG based fatigue countermeasure software which could detect changes in all frequency bands such as delta, theta, alpha and beta was developed and tested for reliability.

10.1 The Electroencephalography and Driver Fatigue

The research found consistent and reliable changes in EEG associated with driver fatigue. These changes were common to all the subjects in the study. Delta and theta activity increased significantly during the transition to fatigue. Alpha and beta activity also increased though by a smaller degree. The result from this research confirms that the increased delta, theta and alpha activity during a monotonous driving task most likely reflects decreased cortical arousal. From the results of the present research, it is most likely that the alpha band is sensitive to changes in alertness while the theta and delta bands are essential for distinguishing lower levels of arousal. The EEG changes associated with fatigue also varied according to the cortical site being assessed. During onset of fatigue, delta and theta activity was mostly evident in the frontal, central and parietal areas of the brain with some anterior alpha and posterior beta. This indicates that various areas of the brain do behave differently during the onset of fatigue and therefore it may be useful to utilise an electrode derivation that spans the whole brain when monitoring the EEG of fatigue such as the 19-channel EEG system. These are novel findings and this research strongly suggests that EEG is a reliable indicator of driver fatigue.

10.2 The Electro-oculogram and Video as an Indicator of Driver Fatigue

The research found that fast eye movements and conventional blinks found during the alert phase were replaced by no eye movements and small fast rhythmic blinks during drowsiness. During deeper drowsiness, slow blinks were evident. These results demonstrate the potential of using EOG to identify the physical onset of fatigue. As stated above, during fatigue eye movement was reduced and mannerisms such as yawning and nodding began to occur. With further progress into fatigue, slow blinks occurred with episodes of eye closure. The video identified that the transition to fatigue is not an immediate process, but that episodes of drowsiness and alert states occur, which was also reflected in the EEG. From this research it can be concluded that video and eye activity changes are also potential indicators of fatigue in drivers.

10.3 The Psychological Associations with Driver Fatigue

It is believed that mood state and anxiety levels could influence fatigue effects during driving. From this research it may be suggested that higher levels of anxiety and negative mood states can influence the ability of a driver detrimentally. Findings of this research suggest that certain personality and temperaments such as mood, anxiety and personal control efficacy may affect driver-related fatigue. However, the psychological investigation in this study was exploratory and therefore further research is required with larger samples to clarify the role of the psychological factors influencing fatigue. This research is one of the first to investigate psychological links to a neurophysiological indicator of fatigue during driving, and as such makes a substantial contribution to the understanding of the psychophysiological changes that are associated with the transition from alert to a fatigue state during driving.

10.4 Heart rate and Heart Rate Variability as an Indicator of Driver Fatigue

The present research found a significant relationship between heart rate variability (HRV) and driver fatigue. HRV is believed to be less susceptible to influences from varying workload and random variation in heart rate, and is therefore a potentially more sensitive indicator of driver fatigue. Fatigue occurring during continuous driving was associated with increased sympathetic activity as well as a simultaneous decrease in the parasympathetic component of the autonomic nervous system. Total HRV was also found to decrease. Therefore, the sympathetic and parasympathetic components of HRV can be used as sensitive and accurate indicators of driver fatigue.

Some strong associations were observed between the EEG of drowsiness and the parasympathetic component of HRV, indicating that physiological change occurs simultaneously during fatigue and that one may influence the other. Further investigation in this area can provide useful insights into the physiological interactions that occur during driver fatigue. As indicated in previous research, HRV is thought to precede changes in brain activity (Otzenberger et al., 1997) and therefore it could be used to identify the onset of a fatigue state. Furthermore, since changes in autonomic activity using HRV has clinical significance (Yeragani et al., 1993), it is important to study this variable in the driving context. Further investigations into HRV and fatigue effects could provide information on the medical and health implications of continuous fatigue effects.

10.5 Fatigue Effects in Professional Versus Non-Professional Drivers

Obtaining the EEG data of skilled and unskilled drivers performing a monotonous driving task is extremely valuable for road safety issues. In the present study both professional and non-professional drivers were shown to be prone to experiencing fatigue during continuous driving. However, it was found that non-professional drivers experienced significantly higher levels of fatigue compared to the professional drivers. The primary achievement of this experiment has been the demonstration of clear differences in brain wave activity between those trained to perform monotonous driving and those not trained. In other words, it is more common for untrained drivers to show greater amounts of drowsiness when performing such a monotonous task. However, trained drivers still showed some drowsiness effects. If replicated these findings have important implications for road safety.

10.6 The Reproducibility of Fatigue During Driving

EEG activity during different periods of transition to fatigue was shown to be highly reproducible. While variability was shown in theta and beta responses these differences were small. Delta and alpha activity were found to be more stable during transition to fatigue. The EEG changes were also shown to be reproducible in the whole brain as well as in individual sites on the brain. The reproducibility data also suggested that progressive episodes of fatigue might become more severe in professional drivers compared to non-professional drivers. Even though fatigue effects were shown to be greater in non-professional drivers compared to professional drivers, continuous driving had cumulative fatigue effects in professional drivers. Therefore, fatigue effects may be more dangerous and have greater implications for road safety in professional drivers, who on average drive for longer periods than non-professional drivers.

10.7 Electroencephalography Coherence Analysis During Fatigue

The present study is the first to investigate EEG coherence changes during driver fatigue. Very little significant change in coherence was found. The results did not replicate prior research which found transition to fatigue produces changes in inter- and intrahemispheric EEG coherence when compared with wakefulness, suggesting that an alteration of cerebral functional organization occurs across these two states. It has been reported that EEG coherence can be affected by subject variables such as age, sex and handedness (Boldyreva & Zhavoronkova, 1991; French & Beaumont, 1984; Nielsen et al., 1990; Shaw, O'Connor, & Ongley, 1977). The current case study provides some evidence that the degree of EEG coherence is influenced by arousal levels and therefore has implications for driver fatigue. A larger study of EEG coherence is required in drivers in order to confirm the EEG coherence changes that occur during drowsiness.

10.8 The Prospects of a Fatigue Monitoring and Alerting Software Employing Electroencephalography Changes that Occur During Driver Fatigue

From the literature review conducted during this doctoral research, it is evident that at present no convenient and inexpensive means exist to monitor accurately and reliably driver fatigue. Most of the research conducted in this area has described preliminary or impractical steps towards the development of such technology.

Along these lines, the results of the doctoral research were utilised to develop fatigue monitoring software. While further laboratory and field based research is required to test the reliability and accuracy of the software program, this research is the first investigation of its kind to produce a reliable and valid fatigue monitoring software based upon EEG. The software was capable of detecting fatigue in all the subjects tested with no false positives. It therefore has potential for use as an on-board vehicular fatigue monitoring technology. In the future, such an EEG based enabling technology could be important in the transport, aviation, high risk military and other civilian operational environments that demand sustained wariness and that involves multiple tasks competing for limited attention resources (Gevins, et al., 1995).

In summary, this research has provided important information on the psychophysiology of driver fatigue clarifying some of the 'grey areas' present in the studies to date, and also creating ideas and providing information for future research. Furthermore, the research presented here has been ambitious in steering towards the development of a fatigue countermeasure device. However, technological capabilities of equipment and machines are rapidly approaching, or in some cases have already exceeded, the limits of human capability. The subtle, non-intrusive application of psychophysiological measures to aid in determining human workload, fatigue, and performance is becoming more of a necessity than a scientist's dream. Therefore investigating the psychological profile further and producing a fatigue-anticipating device that can be used in vehicles will lead to better fatigue management and will also benefit society.

10.9 Future Research Prospects on the Psychophysiological Associations with Driver Fatigue

This doctoral research has clarified a number of issues concerning the psychophysiological associations of driver fatigue. It has also provided direction for future research in this area. For example, the pychophysiological associations such as electroencephalography, cardiovascular and eye activity changes should be investigated in large groups of drivers suffering from sleep disorders such as sleep apnoea, narcolepsy and various dyssomnias. A National Medical and Health Research Council Fellowship has been awarded to the doctoral researcher, Saroj Lal with Professor Ashley Craig as a co-investigator in order to investigate this important area of driver fatigue. The findings will be incorporated into the further development of an algorithm for a potential fatigue monitoring device. Field trials should also be conducted to test such fatigue monitoring technology.

The psychological investigation, which was exploratory in this research, should be assessed further with larger samples. This will lead to the identification of any psychological factors that may be associated with fatigue. These psychological and physiological investigations should lead to the development of a psychophysiological model which will assist in the better management of driver fatigue.

References

Adkins, S. (1964). Performance, heart rate, and respiration rate on the day-night continuum. *Perceptual Motor Skills, 18:* 409-412.

Akerstedt, T. (1984). Hormones and sleep. In A.A. Borbély & J.L. Valatx (Eds.), *Experimental Brain Research. Sleep Mechanisms.* (pp. 193-203). Berlin: Springer-Verlag.

Akselrod, S., Gordon, D., Madwed, J.B., Snidman, N.C., Shannon, D.C., & Cohen, R.J. (1985). Hemodynamic regulation: investigation by spectral analysis. *American Journal of Physiology, 249:* H867-H875.

Aldrich, M.S. (1989). Automobile accidents in patients with sleep disorders. *Sleep, 12:* 487-494.

Alloway, C.E.D., Ogilvie, R.D., & Shapiro, C.M. (1997). The alpha attenuation test: assessing excessive daytime sleepiness in narcolepsy-cataplexy. *Sleep, 20 (4):* 258-266.

Andreassi, J.L. (2000a). Eye movements, eye blinks, and behavior. In J.L. Andreassi (Ed.), *Psychophysiology: human behavior and physiological response.* (pp. 265-274). New Jersey: Lawrence Erlbaum Associates, Inc., Publishers.

Andreassi, J.L. (2000b). *Psychophysiology: Human Behavior and Physiological Response.* London: Laurence Erbaum Associates.

Andreassi, J.L. (2000c). The EEG and behavior: sensation, attention, perception, conditioning, and sleep. In J.L. Andreassi (Ed.), *Psychophysiology: human behavior and physiological response.* (pp. 61-84). London: Lawrence Erlbaum Associates.

Appel, M.L., Berger, R.D., Saul, P., Smith, J.M., & Cohen, R.J. (1989). Beat to beat variability in cardiovascular variables: noise or music? *Journal of the American College of Cardiology, 14:* 1139-1148.

Arnold, P.K., Hartley, L.R., Corry, A., Hochstadt, D., & Penna, F. (1997). Hours of work, and perceptions of fatigue among truck drivers. *Accident Analysis and Prevention, 29 (4):* 471-477.

Artaud, P., Planque, S., Lavergne, C., Cara, H., de Lepine, P., Tarrière, C., & Gueguen, B. (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).

Åkerstedt, T. (1988). Sleepiness as a consequence of shift work. *Sleep, 11(1):* 17-34.

Åkerstedt, T., & Gillberg, M. (1981). The circadian variation of experimentally displaced sleep. *Sleep, 4 (2):* 159-169.

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

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. (1982). Sleepiness and shiftwork: field studies. *Sleep, 5:* (Suppl. 2). 95-106.

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

Åkerstedt, T., Torsvall, L., & Gillberg, M. (1987). Sleepiness in shiftwork. A review with emphasis on continuous monitoring of EEG and EOG. *Chronobiology International, 4 (2):* 129-140.

Åstrand, P.O., & Rodahl, K. (1986). *Textbook of work physiology.* New York: McGraw-Hill.

Baharav, A., Kotagal, S., Gibbons, V., Rubin, B.K., Pratt, G., Karin, J., & Akselrod, S. (1995). Fluctuations in autonomic nervous activity during sleep displayed by power spectrum analysis of heart rate variability. *Neurology, 45:* 1183-1187.

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 Transactions on Biomedical Engineering, 39 (12):* 1305-1310.

Barlow, J.S. (1986). Artifact processing (rejection and reduction) in EEG data processing. In F.H. Lopes da Silva, W. Storm van Leeuwen, & A. Remond (Eds.), *Handbook of Electroencephalography and Clinical Neurophysiology.* (pp. 15-65). Amsterdam: Elsevier.

Bartlett, F.C. (1943). Fatigue following highly skilled work. *Proceedings of the Royal Society, B, 131,* 248-257.

Bartley, S.H. (1970). The homeostatic and comfort perceptual systems. *Conference Proceedings, 75,* 157-162.

Basmajian, J.V., & De Luca, C.J. (1985). *Muscles Alive.* Baltimore: Williams and Wilkins.

Bates, R.A., Hilton, M.F., Godfrey, K.R., & Chappell, M.J. (1997). Autonomic function assessment using analysis of heart rate variability. *Control Engineering Practice, 5 (12):* 1731-1737.

Bearpark, H. (1990). *Road safety and pathological sleepiness: the role of sleep apnea* (Rep. No. CR 3/90). Australia: Road Traffic Authority.

Beatty, J., Greenberg, A., Deibler, W.P., & O'Hanlon, J.F. (1974). Operant control of occipital theta rhythm affects performance in a radar monitoring task. *Science, 183:* 871-873.

Bechtereva, N.P. (1981). Neurophysilogical correlates of mental processes in man. In N.P. Bechtereva (Ed.), *Psychophysiology Today and Tomorrow.* (pp. 11-21). New York: Pergamon Press.

Belyavin, A., & Wright, N.A. (1987). Changes in electrical activity of the brain with vigilance. *Electroencephalography and clinical Neurophysiology, 66:* 137-144.

Benson, H., Beary, J.F., & Carol, M.P. (1974). The relaxation response. *Psychiatry, 37:* 37-46.

Berger, H. (1929). *Uber das Elktrenkephalogramm des Menschen. Translated and reprinted in Pierre Gloor, Han Berger on the electroencephalogram of man.* Amsterdam: Elsevier.

Birrell, P. (1990). *Sleep mechanisms and their relevance to driver fatigue.* (Rep. No. CR 2/90). Workshop on driver fatigue: report on proceedings. Australia: Road Traffic Authority.

Bjerner, B., Holm, Å., & Swensson, Å. (1955). Diurnal variation in mental performance. A study of three-shift workers. *British Journal of Industrial Medicine, 12:* 103-110.

Blanc, C., LaFontaine, E., & Medvedeff, M. (1966). Radiotelemetric recordings of the electroencephalograms of civil aviation pilots during flight. *Aerosp Med, 37:* 1060-1065.

Boldyreva, G.N., & Zhavoronkova, L.A. (1991). Interhemispheric asymmetry of EEG coherence as a reflection of different functional states of the human brain. *Biomedical Science, 2:* 266-270.

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. *Physiological Reviews, 69:* 605-670.

Brisley, C.L., & Fielder, W.F. (1983). 'Unmeasurable' output of knowledge/office workers can and must be measured. *IE,* 42-47.

Broadbent, D.E., Broadbent, M.H.P., & Jones, J.L. (1986). Performanec correlates of self-reported cognitive failure and of obsessionality. *British Journal of Clinical Psychology, 25:* 285-299.

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. *Journal of Clinical Neurophysiology, 12 (4):* 372-386.

Brown, I.D. (1997). Prospectus for technological countermeasures against driver fatigue. *Accident Analysis and Prevention, 29 (4):* 525-531.

Brown, I.D., & Eng, C. (1967a). Car driving and fatigue. *Triangle, 8 (4):* 131-137.

Brown, I.D., Simmonds, D.C.V., & Tickner, A.H. (1967b). Measurement of control skills, vigilance, and performance on a subsidiary task during 12 hours of car driving. *Ergonomics, 10 (6):* 665-673.

Brown, I. (1994). Driver fatigue. *Human Factors, 36,* 298-314.

Browne, R.C. (1949). The day and night performance of teleprinter switchboard operators. *Occupational Psychology, 23:* 121-126.

Busk, J., & Galbraith, G.C. (1975). EEG correlates of visual motor practice in man. *Electroencephalography and clinical Neurophysiology, 38:* 415-422.

Cabon, Ph., & Al. (1993). Human vigilance in railway and long-haul flight operation. *Ergonomics, 9:* 1019-1033.

Cacioppo, J.T., & Tassinary, L.G. (1990). *Principles of Psychophysiology.* New York, USA: Cambridge University Press.

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 R.R. Mackie (Ed.), *Vigilance.* (pp. 59-72). New York: Plenum Press.

Cameron, C. (1971). Fatigue problems in modern industry. *Ergonomics, 14 (6):* 713-720.

Cameron, C. (1973). A theory of fatigue. *Ergonomics, 16 (5):* 633-648.

Camkin, H. (1990). *Introduction: fatigue and road safety.* (Rep. No. CR 2/90). Workshop on driver fatigue: report on proceedings. Australia: Road Traffic Authority.

Carskadon, M.A., & Dement, W.C. (1982). The multiple sleep latency test: what does it measure? *Sleep, 5:* S67-S72.

Chrousos, G.P., McCarty, R., Pacák, K., Cizza, G., Sternberg, E., Gold, P.W., & Kvetnanský, R. (1995). Stress: basic mechanisms and clinical implications. *Annals of the New York Academy of Sciences,* (771).

Colquhoun, W.P., Rutenfranz, J. (1980). *Studies of shiftwork.* London: Taylor and Francis.

Corlett, E., & Mahadeva, K. (1970). A relationship between freely chosen working pace and energy consumption curves. *Ergonomics, 13 (4):* 517-524.

Costa, G. (1993). Evaluation of workload in air traffic controllers. *Ergonomics, 36:* 1111-1120.

Craig, A., Davies, D.R., & Matthews, G. (1987). Diurnal variation, task characteristics, and vigilance performance. *Human Factors, 29:* 675-684.

Craig, A.R., Franklin, J.A., & Andrews, G. (1984). A scale to measure locus of control of behaviour. *British Journal of Medical Psychology, 57:* 173-180.

Czeisler, C.A., Zimmerman, J.C., Ronda, J.M., Moore-Ede, M.C., & Weitzman, E.D. (1980). Timing of REM sleep is coupled to the circadian rhythm of body temperature in man. *Sleep, 2 (3):* 329-346.

Daniel, R.S. (1967). Alpha and theta EEG in vigilance. *Perceptual and Motor Skills, 25:* 697-703.

Darrow, C.W. (1947). Psychological and psychophysiological significance of the electroencephalogram. *Psychological Review, 54:* 157-168.

Davies, D.R. (1965). Skin conductance, alpha activity and vigilance. *American Journal of Psychology, 78 (2):* 304-306.

Davies, D.R., & Parasuraman, R. (1982). *The psychology of vigilance.* London: Academic Press.

Davis, H., Davis, P.A., Loomis, A.L., Harvey, E.N., & Hobart, G. (1938). Human brain potentials during the onset of sleep. *Journal of Neurophysiology, 1:* 24-38.

De Waard, D., & Brookhius, K.A. (1991). Assessing driver status: a demonstration experiment on the road. *Accident Analysis and Prevention, 23 (4):* 297-307.

Dement, W., & Kleitman, N. (1957). Cyclic variations in EEG during sleep and their relation to eye movements, body motility, and dreaming. *Electroencephalography and clinical Neurophysiology, 9:* 673-690.

Desmond, P.A., & Matthews, G. (1997). Implications of task-induced fatigue effects for in-vehicle countermeasures to driver fatigue. *Accident Analysis and Prevention, 29 (4):* 515-523.

Dinges, D.F. (1995). An overview of sleepiness and accidents. *Journal of Sleep Research, 4:* ((Suppl 2)). 4-14.

Doghramji, K., Mitler, M.M., Sangal, R.B., Shapiro, C., Taylor, S., Walsleben, J., Belisle, C., Erman, M.K., Hayduk, R., Hosn, R., O'Malley, E.B., Sangal, J.M., Schutte, S.L., & Youakim, J.M. (1997). A normotive study of the maintenance of wakefulness test. *Electroencephalography and clinical Neurophysiology, 103 (5):* 554-562.

Du, W.; Leong, H.; Gevins, A.S. (1994). Ocular artifact minimization by adaptive filtering. *Seventh IEEE SP Workshop on Statistical Signal and Array Processing*. Quebec City, CA: 26-29.

Duffy, F.H. (1986). *Topographic mapping of brain electrical activity.* Boston: Butterworths.

Dureman, E.I., & Bodén, Ch. (1972). Fatigue in simulated driving. *Ergonomics, 15:* 299-308.

Egelund, N. (1982). Spectral analysis of heart rate variability as an indicator of driver fatigue. *Ergonomics, 25 (7):* 663-672.

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

Erwin, C.W., Somerville, E.R., & Radtke, R.A. (1984). A review of electroencephalographic features of normal sleep. *Journal of Clinical Neurophysiology, 1(3):* 253-274.

Falls Church, V.A. (Ed) (1985). *Transportation research marketing*. American Automobile Association Foundation for Traffic Safety. A report on the determination and evaluation of the role of fatigue in heavy truck accidents. USA.

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.

Finkelman, J.M. (1994). A large database study of the factors associated with work-induced fatigue. *Human Factors, 36 (2):* 232-243.

Fisch, B.J. (1991a). *Spehlmann's EEG Primer.* Amsterdam: Elsevier Science B.V.

Fisch, B.J. (1991b). *Spehlmann's EEG Primer, Second revised and enlarged edition.* Amsterdam, The Netherlands: Elsevier Science B.V.

Fisher,S.; Goodhall,J.; Wark,L. (1994). Effects of new technology in cars on driver attitudes and behaviour. *Paper presented at the 23rd IAAP International Congress of Applied Psychology*. Madrid, Spain.

Folkard, S. (1987). Irregular and abnormal hours of work (special issue). *Ergonomics, 30:* 1227-1409.

Folkard, S., Dirkx, J., Härmä, M., Knauth, P., Koller, M., Smith, P., Wedderburn, A. (1993). Night and shiftwork (special issue). *Ergonomics, 36:* 1-322.

French, C.C., & Beaumont, J.C. (1984). A critical review of EEG coherence studies of hemisphere function. *International Journal of Psychophysiology, 1:* 241-254.

Fruhstorfer, H., Langanke, P., Meinzer, K., Peter, J.H., & Pfaff, U. (1977). Neurophysiological vigilance indicators and operational analysis of a train vigilance monitoring device: a laboratory and field study. In R.R. Mackie (Ed.), *Vigilance.* (pp. 147-162). New York: Plenum Press.

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 D.J. Oborne & J.A. Lewis (Eds.), *Human Factors in Transport Research.* (pp. 117-125). London: Academic Press.

Furlan, R., Guzzetti, S., Crivellaro, W., Dassi, S., Tinelli, M., Baselli, G., Cerutti, S., Lombardi, F., Pagani, M., & Malliani, A. (1990). Continuous 24-hour assessment of the neural regulation of systemic arterial pressure and RR variabilities in ambulant subjects. *Circulation, 81 (2):* 537-547.

Gaillard, A.W.K. (1993). Comparing the concepts of mental load and stress. *Ergonomics, 36:* 991-1005.

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. *Human 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. *Aviation, Space, and Environmental Medicine, 64:* (3). 189-195.

George, C.F., Nickerson, P.W., Hanly, P.J., Millar, T.H., & Kryger, M.H. (1987). Sleep apnoea patients have more automobile accidents. *Lancet, ii:* 447.

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. *Biological Psychology, 40:* 169-186.

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. *Electroencephalography and clinical Neurophysiology, 76:* 339-350.

Gevins, A.S., & Morgan, N.H. (1988). Applications of neural-network (NN) signal processing in brain research. *IEEE Transactions on Acoustics, Speech and Signal Processing, 36 (7):* 1152-1161.

Gevins, A.S., Yeager, C.L., Zeitlin, G.M., Ancoli, S., & Dedon, M.F. (1977a). On-line computer rejection of EEG artifact. *Electroencephalography and clinical Neurophysiology, 42:* 267-274.

Gevins, A.S., Zeitlin, G.M., Ancoli, S., & Yeager, C.L. (1977b). Computer rejection of EEG artifact. II. Contamination by drowsiness. *Electroencephalography and clinical Neurophysiology, 42:* 267-274.

Gillberg, M., Kecklund, G., & Åkerstedt, T. (1996). Sleepiness and performance of professional drivers in a truck simulator- comparisons between day and night driving. *Journal of Sleep Research, 5:* 12-15.

Gloor, P. (1976). Generalized and widespread bilateral paroxysmal abnormalities. In A. Remond (Ed.), *Handbook of Electroencephalography and Clinical Neurophysiology.* (pp. 11B52-11B87). Amsterdam: Elsevier.

Gogolitsin, Y.L., & Kropotov, Y.D. (1981). Application of the post stimulus-time histogram to the analysis of discharge patterns in neuronal populations of the human brain during intellectual-amnestic activity. In N.P. Bechtereva (Ed.), *Psychophysiology Today and Tomorrow.* (pp. 23-31). New York: Pergamon Press.

Graeber, R.C. (1988). Aircrew fatigue and circadian rhythmicity. In E.L. Weiner & D.C. Nagel (Eds.), *Human factors in aviation.* (pp. 305-344). San Diego: Academic Press.

Grandjean, E. (1970). Fatigue. *American Industrial Hygiene Association Journal, 31:* 410-411.

Grandjean, E. (1979). Fatigue in industry. *British Journal of Internal Medicine, 36,* 175-186.

Grandjean, E. (1988). *Fitting the task to the man.* London: Taylor and Francis.

Griffiths, R.R., Evans, S.M., Heishman, S.J., Preston, K.L., Sannerud, C.A., Wolf, B., & Woodson, P.P. (1990). Low-dose caffeine discrimination in humans. *Journal of Pharmacology and Experimental Therapeutics, 252:* 970-978.

Hamelin, P. (1987). Lorry driver's time habits in work and their involvement in traffic accidents. *Ergonomics, 30:* 1323-1333.

Haraldsson, P.-O., Carenfelt, C., Laurell, H., & Törnros, J. (1990). Driving vigilance simulator test. *Acta Otolaryngol.(Stockh.), 119:* 136-140.

Harris, W. (1977). Fatigue, circadian rhythms and truck accidents. In R.R. Mackie (Ed.), *Vigilance: theory, operational performance and physiological correlates.* (pp. 133-147). New York: Plenum Press.

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* (Rep No. 1727-2). California: Human Factors Research Inc.

Harris, W.C., Hancock, P.A., Arthur, E.J., & Caird, J.K. (1995). Performance, workload, and fatigue changes associated with automation. *The International Journal of Aviation Psychology, 5 (2):* 169-185.

Harrison, Y., & Horne, J.A. (1996). Occurrence of 'microsleeps' during daytime sleep onset in normal subjects. *Electroencephalography and clinical Neurophysiology, 98:* 411-416.

Hartley, L.R., & Arnold, P.K. (1994). Indicators of fatigue in truck drivers. *Applied Ergonomics, 25:* (3). 143-156.

Haslam, D.R. (1982). Sleep loss, recovery sleep, and military performance. *Ergonomics, 25 (2):* 163-178.

Haworth, N. (1990). *Current countermeasures and areas for countermeasures development* (Rep. No. CR 3/90). Workshop on driver fatigue: report on proceedings. Australia: Road Traffic Authority.

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

Haworth, N.L., Triggs, T.J., & Grey, E.M. (1988). *Driver fatigue: concepts, measurement and crash countermeasures.* Canberra, Australia: Federal Office of Road Safety.

Heller, W., Nitschke, J.B., Etienne, M.A., & Miller, G.A. (1997). Patterns of regional brain activity differentiate types of anxiety. *Journal of Abnormal Psychology, 106 (3):* 376-385.

Hiroshige, Y., & Dorokhov, V.B. (1997). Hemispheric assymetry and regional differences in electroencephalographic alpha activity at the wake-sleep transition. *Japanese Psychological Research, 39(2):* 75-86.

Horne, J.A. (1992). Stay awake, stay alive. *New Scientist, 133:* 20-24.

Horne, J.A., & Reyner, L.A. (1995a). Driver sleepiness. *Journal of Sleep Research, 4:* (suppl 2). 23-29.

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

Horne, J.A., & Reyner, L.A. (1995c). Sleep related vehicle accidents. *British Medical Journal, 310:* 565-567.

Horne, J.A., & Wilkinson, S. (1985). Chronic sleep reduction: daytime vigilance performance and EEG measures of sleepiness, with particular reference to "practice" effects. *Psychophysiology, 22:* 69-78.

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. *Aviation, Space, and Environmental Medicine, 49(10):* 1197-1202.

Hoyos, C.G. (1988). Mental load and risk in traffic behavior. *Ergonomics, 31:* 571-584.

Idogawa, K. (1991). On the brain wave activity of professional drivers during monotonous work. *Behaviormetrika, 30:* 23-34.

Implementation Task Force. (1994). *The national road safety action plan.* Australia.

Ivanitsky, A.M. (1980). The physiology of brain signal evaluation and the psychology of perception. In N.P. Bechtereva (Ed.), *Psychophysiology Today and Tomorrow.* (pp. 191-200). New York: Pergamon Press.

Jaffe, R.S., Fung, D.L., & Behrman, K.H. (1993). Optimal frequency ranges for extracting information on autonomic activity from the heart rate spectogram. *Journal of Autonomic Nervous System, 46:* 37-46.

Janati, A., Kidawi, S., & Nowack, W.J. (1986). Episodic anterior drowsy theta in adults. *Clinical Electroencephalography, 17:* 135-138.

Jasper, H.H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and clinical Neurophysiology, 10:* 371-375.

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

Kahn, E.M., Weiner, R.D., Brenner, R.P., & Coppola, R. (1988). Topographic maps of brain electrical activity- pitfalls and precautions. *Biological Psychiatry, 23:* 628-636.

Kales, A., Caldwell, A.B., & Cadieux, R.J.e.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, 1991-1998.

Kiroy, V.N., Warsawskaya, L.V., & Voynov, V.B. (1996). EEG after prolonged mental activity. *International Journal of Neuroscience, 85:* 31-43.

Kishida, K. (1973). Temporal change of subsidiary behavior in monotonous work. *Journal of Human Ergology, 2:* 75-89.

Knowles, W.B. (1963). Operator loading tasks. *Human Factors,* 155-161.

Kogi, K., & Ohta, T. (1975). Incidence of near accidental drowsing in locomotive driving during a period of rotation. *Journal of Human Ergology, 4:* 65-76.

Kumashiro, M. (1995). Practical measurement of psychophysiological functions for determining workloads. In J.R. Wilson & E.N. Corlett (Eds.), *Evaluation of human work.* (pp. 864-887). London: Taylor and Francis.

Lal, S.K.L., & Craig, A. (2000a). A critical review of the psychophysiology of driver fatigue. *Biological Psychology, 55:* 173-194..

Lal, S.K.L., & Craig, A. (2000b). Driver Fatigue: psychophysiological effects. *Proceedings of the 4th International Conference on Fatigue and Transportation.* Perth, Australia.

Lal, S.K.L., & Craig, A. (2000c). Psychophysiological effects associated with Drowsiness: driver fatigue and electroencephalography. *International Journal of Psychophysiology, 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. *Psychophysiology, 35 (4):* 405-412.

Lauber, J.K., & Kayten, P.J. (1988). Sleepiness, circadian dysrhythmia, and fatigue in transportation system accidents. *Sleep, 11 (6):* 503-512.

Leger, D. (1994). The cost of sleep-related accidents: a report for the national commission on sleep disorders research. *Sleep, 17 (1):* 84-93.

Lehmann, D., Grass, P., & Meier, B. (1995). Spontaneous conscious covert cognition states and brain electric spectral states in canonical correlations. *International Journal of Psychophysiology, 19:* 41-52.

Lemke, M. (1982). Correlation between EEG and driver's actions during prolonged driving under monotonous conditions. *Accident Analysis and Prevention, 14:* 7-17.

Lisper, H.-O., Laurell, H., & Stening, G. (1973). Effects of experience of the driver on heart rate, respiration rate and subsidiary reaction time in a three hours continuous driving task. *Ergonomics, 16:* 501-506.

Loomis, A., Harvey, E., & Hobart, G. (1937). Cerebral states during sleep as studied by human brain potentials. *Journal of Experimental Psychology, 21:* 127-144.

Lorist, M.M., Snell, J., Kok, A., & Mulder, G. (1994). Influence of caffeine on selective attention in well-rested and fatigued subjects. *Psychophysiology, 31:* 525-534.

Lubin, A., Johnson, L.C., & Austin, M.T. (1969). Discriminating among states of consciousness using E.E.G. spectra. *Agressologie, 10:* 593-602.

Luczak, H., & Laurig, W. (1973). An analysis of heart rate variability. *Ergonomics, 16 (1):* 85-97.

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* (Rep. No. 1765-F). Coleta, CA: Human Factors Research Inc.

Makeig, S., & Inlow, M. (1993). Lapses in alertness: coherence of fluctuations in performance and EEG spectrum. *Electroencephalography and clinical Neurophysiology, 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.

Makeig, S., & Jung, T. (1996). Tonic, phasic, and transient EEG correlates of auditory awareness in drowsiness. *Cognitive Brain Research, 4:* 15-25.

Malliani, A., Pagani, M., Lombardi, F., & Cerutti, S. (1991). Cardiovascular neural regulation explored in the freqency domain. *Circulation, 84 (2):* 482-492.

Markand, O.N. (1990). Alpha rhythms. *Journal of Clinical Neurophysiology, 7(2):* 163-189.

Mascord, D.J., & Heath, R.A. (1992). Behavioral and physiological indices of fatigue in a visual tracking task. *Journal of Safety Research, 23:* 19-25.

Matousek, M., & Petersen, I.A. (1983). A method for assessing alertness fluctuations from EEG spectra. *Electroencephalography and clinical Neurophysiology, 55:* 108-113.

Matthews, G., & Desmond, P.A. (1995). Stress as a factor in the design of in-car driving enhancement systems. *Le Travail Humain, 58 (2):* 109-129.

Maycock, G. (1996). Sleepiness and driving: the experience of UK car drivers. *Journal of Sleep Research, 5:* 229-237.

McDonald, N. (1980). Fatigue, safety, and the industrialisation of heavy goods vehicle driving. In D.J. Oborne & J.A. Lewis (Eds.), *Human Factors in Transport Research.* (pp. 134-142). London: Academic.

McDonald, N. (1984). *Fatigue, Safety and the Truck Driver.* London: Taylor and Francis.

McNair, D.M., Lorr, M., & Droppleman, L.F. (1971). *Edits Manual. Profile of mood states.* San Diego, CA: Educational and Industrial Testing Service.

Michelogiannis, S., Paritsis, N., & Trikas, P. (2000). EEG coherence during hemispheric activation in schizophrenics. *European Archives of Psychiatry and Clinical Neuroscience, 241:* 31-34.

Michon, J.A. (1993). *Generic intelligent driver support.* London: Taylor and Francis.

Miller, J.C., & Mackie, R.R. (1980). Effects of irregular schedules and physical work on commercial driver fatigue and performance. In D.J. Oborne & J.A. Levis (Eds.), *Human factors in transport research.* (pp. 127-133). New York: Academic Press.

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

Mitler, M.M., Carskadon, M.A., Czeisler, C.A., Dement, W.C., Dinges, D.F., & Graeber, R.C. (1988). Catastrophes, sleep, and public policy: concensus report. *Sleep, 11:* 100-109.

Moglia, A., Mauri, M., Alfonsi, E., Coblesano, V., Lozza, A.S.E., & Bono, G. (1997). Neurophysiological and neuropsychological monitoring of fatigue during extreme environmental conditions. *Electromyography and clinical Neurophysiology, 37:* 67-72.

Moore-Ede, M.C., Sulzman, F.M., & Fuller, C.A. (1982). *The clocks that time us. Physiology of the circadian timing system.* Cambridge, MA: Harvard Univ. Press.

Morrel, L.K. (1966). EEG frequency and reaction time- a sequential analysis. *Neuropsychologia, 4:* 41-48.

Morris, T.L., & Miller, J.C. (1996). Electrooculographic and performance indices of fatigue during simulated flight. *Biological Psychology, 42:* 343-360.

Nagase, Y., Okubo, Y., Matsuura, M., Kojima, T., & Toru, M. (1992). EEG coherence in unmedicated schizophrenic patients: topographical study of predominantly never medicated cases. *Biological Psychiatry, 32:* 1028-1034.

Naitoh, P. (1975). Sleep deprivation in humans. In P.H. Venables & M.J. Christie (Eds.), *Research in Psychophysiology.* (pp. 153-180). New York: Wiley.

Nelson, T.M., Carlson, D., & Nilsson, T. (1982). *Development of fatigue under various conditions of comfort and work demand* (Rep. No. 55-23017). Edmonton, Alberta: Workers Health, Safety and Compensation.

Nielsen, T., Abel, A., Lorrain, D., & Montplaisir, J. (1990). Interhemispheric EEG coherence during sleep and wakefulness in left- and right handed subjects. *Brain Cognition, 14:* 113-125.

Nilsson, T., Nelson, T.M., & Carlson, D. (1997). Development of fatigue symptoms during simulated driving. *Accident Analysis and Prevention, 29 (4):* 479-488.

Ninomija, S.P., Funada, M.F., Yazu, Y., Ide, H., & Daimon, N. (1993). Possibility of ECGs to improve reliability of detection system of inclining sleep stages by grouped alpha waves. *IEEE,* 1410-1411.

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

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 R.R. Mackie (Ed.), *Vigilance.* (pp. 189-202). New York: Plenum Press.

Okogbaa, O., Shell, R., & Filipusic, D. (1994). On the investigation of the neurophysiological correlates of knowledge worker mental fatigue using the EEG signal. *Applied Ergonomics, 25,* 355-365.

Onken, R. & Feraric, J.P. (1997). Adaptation to the driver as part of a driver monitoring and warning system. *Accident Analysis and Prevention, 29 (4):* 507-513.

Otzenberger, H., Simon, C., Gronfier, C., & Brandenberger, G. (1997). Temporal relationship between dynamic heart rate variability and electroencephalographic activity during sleep in man. *Neuroscience Letters, 229:* 173-176.

Parasuraman, R., Warm, J.S., & See, J.E. (1998). Brain systems of vigilance. In R. Parasuraman (Ed.), *The attentive brain.* (pp. 221-256). London: The MIT Press.

Parkes, A.M., & Coleman, N. (1990). Route guidance systems: a comparison of methods of presenting directional information to the driver. In E.J. Lovesey (Ed.), *Contemporary Ergonomics.* (pp. 480-485). London: Taylor and Francis.

Polich, J. (1987). Task difficulty, probability and inter-stimulus intervals and determinants of P300 from auditory stimuli. *Electroencephalography and clinical Neurophysiology, 68:* 311-320.

Potts, G.R. (1951). *A study of long haul truck operations.* (p 85). Research Reports on Human Factors in Highway Transport Safety. Boston: Havard School of Public Health, Mass.

Poulton, E.C., Hunt, G.M., Carpenter, A., & Edwards, R.S. (1978). The performance of junior hospital doctors following reduced sleep and long hours of work. *Ergonomics, 21:* 279-295.

Raggat, P.T.F., & Morrissey, S.A. (1997). A field study of stress and fatigue in long-distance bus drivers. *Behavioral Medicine, 23:* 122-129.

Rechtschaffen, A., Kales, A., & (eds). (1968). *A manual of standardized terminology, techniques and scoring system for sleep stages of human subjects.* Bethesda: U.S. Department of Health, Education and Welfare-Neurological Information Network.

Regina, E.G. (1974). Effects of caffeine on alertness and simulated automobile driving. *Journal of Applied Psychology, 59:* 483-489.

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

Rizzoni, D., Castellano, M., Beschi, M., Muiesan, M.L., Bettoni, G., Porteri, E., & Agabiti-Rosei, E. (1991). Plasma norepinephrine and spectral analysis of the heart rate during cardiopulmonary receptor stimulation in normal and hypertensive subjects. *Journal of Hypertension, 9:* (suppl 6). S84-S85.

Rokicki, S.M. (1995). Psychophysiology measures applied to operational test and evaluation. *Biological Psychology, 40:* 223-228.

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. *Human Factors, 36 (2):* 327-338.

Roth, B. (1961). The clinical and theoretical importance of EEG rhythms corresponding to states of lowered vigilance. *Electroencephalography and clinical Neurophysiology, 13:* 395-399.

Rutenfranz, J., Knauth, P., & Colquhoun, W.P. (1976). Hours of work and shiftwork. *Ergonomics, 19:* 331-340.

Sadasivan, P.K., & Dutt, D.N. (1994). Minimization of EOG artifacts from corrupted EEG signals using a neural network approach. *Computers in Biological Medicine, 24,* 441-449.

Saito, S. (1992). Does fatigue exist in a quantitative measurement of eye movements? *Ergonomics, 35 (5/6):* 607-615.

Samel, A., Wegmann, H., Vejvoda, M., Drescher, J., Gundel, A., Manzey, D., & Wenzel, J. (1997). Two-crew operations: stress and fatigue during long-haul night flights. *Aviation, Space, and Environmental Medicine, 68 (8):* 679-687.

Santamaria, J., & Chiappa, K.H. (1987a). *The EEG of drowsiness.* New York: Demos Publications.

Santamaria, J., & Chiappa, K.H. (1987b). The EEG of drowsiness in normal adults. *Journal of Clinical Neurophysiology, 4:* 327-382.

Sasaki, T., Iwasaki, K., Oka, T., Hisanaga, N., Ueda, T., Takada, Y., & Fujiki, Y. (1999). Effect of working hours on cardiovascular-autonomic nervous functions in engineers in an electronic manufacturing company. *Industrial Health, 37 (1):* 55-61.

Saul, J.P., Berger, R.D., Albrecht, P., Stein, S.P., Chen, M.H., & Cohen, R.J. (1991). Transfer function anlysis of the circulation: unique insights into cardiovascular regulation. *American Journal of Physiology, 261:* H1231-H1245.

Schacter, D.L. (1976). The hypnagogic state: a critical review of the literature. *Psychological Bulletin, 83:* 452-481.

Schacter, D.L. (1977). EEG theta waves and psychological phenomena: a review and analysis. *Biological Psychology, 5:* 47-82.

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.

Second International Conference in Transportation (1996). Management of fatigue in the road transport industry. Fremantle, Australia: Recommendations from the Second International Conference on Fatigue in Transportation.

Shagass, C., Straumanis, J.J., & Overton, D.A. (2000). Correlations between psychiatric diagnosis and some quantitative EEG variables. *Neuropsychobiology, 5:* 16-26.

Shaw, J.C. (1974). An introduction to correlation and its use in signal analysis. *The Proceedings of the Electrophysiological Technologists Association.* 191-200.

Shaw, J.C. (1981). An introduction to the coherence function and its use in EEG signal analysis. *Journal of Medical Engineering and Technology, 5 (6):* 279-288.

Shaw, J.C., O'Connor, P., & Ongley, C. (1977). The EEG as a measure of cerebral functional organization. *British Journal of Psychiatry, 130:* 260-264.

Sheer, D.E. (1988). *A working cognitive model of attention to fit in the brain and in the clinic.* New York: Academic Press.

Simonov, P.V., & Frolov, M.V. (1985). Blink reflex as a parameter of human operator's functional state. *Aviation, Space, and Environmental Medicine, 56:* 783-785.

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

Skelly, J.J., Purvis, B., & Wilson, G. (1988). Fighter pilot performance during airborne and simulator missions: physiological comparisons. *Conference Proceedings,* 23/1- 23/16.

Skipper, J.M., & Wierwille, W.W. (1986). Drowsy driver detection using discriminant analysis. *Human Factors, 28:* 527-540.

Smith, M. (1981). Occupational stress: an overview of psychosocial factors. In G. Salvendy & M. Smith (Eds.), *Machine pacing and occupational stress.* (pp. 13-19). London: Taylor and Francis.

Spence, A.P., & Mason, E.B. (1987). The central nervous system. In A.P. Spence & E.B. Mason (Eds.), *Human Anatomy and Physiology.* (pp. 112-389). California: The Benjamin/Cummings Publishing Company, Inc.

Spielberger, C.D., Gorsuch, R.L., Lushene, R., Vagg, P.R., & Jacobs, G.A. (1983). *State-Trait Anxiety Inventory.* Palo, Alto, CA: Consulting Psychologists Press.

Stein, A.C. (1995). Detecting fatigued drivers with vehicle simulators. In L. Hartley (Ed.), *Fatigue and Driving- driver impairment, driver fatigue and driving simulation.* (pp. 131-148). London: Taylor and Francis.

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

Steriade, M., Gloor, P., Llinas, R.R., Lopes da Silva, F.H., & Mesulam, M.M. (1990). Basic mechanisms of cerebral rhythmic activities. *Electroencephalography and clinical Neurophysiology, 76:* 481-508.

Sterman, M.B., Schummer, G.J., Dushenko, T.W., & Smith, J.C. (1988). Electroencephalographic correlates of pilot performance: simulation and in-flight studies. *NATO/AGARD Conference Proceedings*, 31/1-31/16.

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

Stoohs, R.A., Bingham, L., Itoi, A., Guilleminault, C., & Dement, W.C. (1995). Sleep and sleep disordered breathing in commercial long-haul truck drivers. *Chest, 107 (5):* 1275-1282.

Stoohs, R.A., Guilleminault, C., Itoi, A., & et al., (1994). Traffic accidents in commercial long-haul truck drivers: the influence of sleep disordered breathing and obesity. *Sleep, 17:* 619-623.

V.J. Storie. (1984). Involvement of goods vehicles and public service vehicles in motorway accidents. Vol. 1113. U.K.: Department of the Environment/ Department of Transport, Transport and Road Research Laboratory.

Standing Committee on Communication, Transport and the Arts. The Parliament of the Commonwealth of Australia. (2000). *Beyond the midnight oil: an inquiry into managing fatigue in transport.* Canberra: CanPrint Communications Pty Limited.

Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996). *Circulation, 93(5):* 1043-1065.

Time. (1995). Time Magazine article. Time Australia Magazine Pty Ltd. 71.

Torello, M.W. (1989). Topographic mapping of EEG and evoked potentials in psychiatry: Delusions, illusions, and realities. *Brain Topography, 1 (3):* 157-174.

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. *Electroencephalography and clinical Neurophysiology, 66:* 502-511.

Torsvall, L., & Åkerstedt, T. (1988). Extreme sleepiness: quantification of EOG and spectral EEG parameters. *International Journal of Neuroscience, 38:* 435-441.

Torsvall, L., Åkerstedt, T., Gillander, K., & Knutsson, A. (1989). Sleep on the Night Shift: 24-Hour EEG monitoring of spontaneous sleep/wake behavior. *Psychology, 26 (3):* 352-358.

Townsend, R.E., & Johnson, L.C. (1979). Relation of frequency-analyzed EEG to monitoring behavior. *Neurophysiology, 47:* 272-279.

Ugajin, H., Ikeda, T., & Yoneyama, S. (1989). Workload management for workers on irregular shifts. In A. Coblentz (Ed.), *Vigilance and performance in automatized systems.* (pp. 191-199). Boston: Kluwer.

Vidacek, S., Radosevic-Vidacek, B., Kaliterna, L., & Prizmic, Z. (1993). Individual differences in circadian rhythm parameters and short-term tolerance to shiftwork: a follow-up study. *Ergonomics, 36 (1-3):* 117-123.

Vincent, K.J., Thornton, D.C., & Moray, N. (1987). Spectral analysis of sinus arrhythmia: a measure of mental effort. *Human Factors, 29:*171-182.

Vivoli, G., Bergomi, M., Rovesti, S., Carrozzi, G., & Vezzosi, A. (1993). Biochemical and haemodynamic indicators of stress in truck drivers. *Ergonomics, 36 (9):* 1089-1097.

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

Wada, Y., Nanbu, Y., Koshino, Y., Shimada, Y., & Hashimoto, T. (1996). Inter- and intrahemispheric EEG coherence during light drowsiness. *Clinical Electroencephalography, 27(2):* 84-88.

Walter, D.O., Rhodes, J.M., & Adey, W.R. (1967). Discriminating among states of consciousness by EEG measurements. A study of four subjects. *Electroencephalography and clinical Neurophysiology, 22:* 22-29.

Walter, W.G. (1953). *The living brain.* New York: Norton.

Weitzman, E.D., & Hellman, L. (1974). Temporal organization of the 24-hour pattern of the hypothalamic-pituitary axis. In M. Ferin, F. Halberg, R.M. Richart, & R.L. Vandewiele (Eds.), *Biorhythms and Human Reproduction.* (pp. 371-395). New York: Wiley.

Weitzman, E.D., Czeisler, C.A., Zimmerman, J.C., & Ronda, J.M. (1980). Timing of REM and stages 3+4 sleep during temporal isolation in man. *Sleep, 2 (4):* 391-407.

Welford, A.T. (1968). *Fundamentals of skill.* London: Methuen.

Wessely, S., & Powell, R. (1989). Fatigue syndromes: a comparison of chronic 'postviral' fatigue with neuromuscular and affective disorders. *Journal of Neurology, Neurosurgery, and Psychiatry, 52:* 940-948.

Wiener, E.L. (1984). Vigilance and inspection. In J.S. Warm (Ed.), *Sustained attention in human performance.* (pp. 207-246). New York: John Wiley.

Wierwille, W.W., & Ellsworth, L.A. (1994). Evaluation of driver drowsiness by trained raters. *Accident Analysis and Prevention, 26 (5):* 571-581.

Wierwille, W.W., Rahimi, m., & Casali, J.G. (1985). Evaluation of 16 measures of mental workload using a simulated flight task emphasizing mediational activity. *Human Factors, 27:* 489-502.

Wilkinson, R.T., Tyler, P.D., & Varey, C.A. (1975). Duty hours of young hospital doctors: effects on the quality of work. *Journal of Occupational Psychology, 48:* 219-229.

Williamson, A.M., Feyer, A., & Friswell, R. (1996). The impact of work practices on fatigue in long distance truck drivers. *Accident Analysis and Prevention, 28 (6):* 709-719.

Wisner, A. (1981). Organizational stress, cognitive load, and mental suffering. In G. Salvendy & M. Smith (Eds.), *Machine pacing and occupational stress.* (pp. 37-44). London: Taylor and Francis.

Wright, Jr.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. (1985). The development of drowsiness warning devices. *Proceedings of the Tenth International Technical Conference on Experimental Safety Vehicles* (Rep. No. section 4, pp. 282-288). Washington, DC: U.S. Department of Transportation.

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

Yeragani, V.K., Srinivasan, K., Vempati, S., Pohl, R., & Balon, R. (1993). Fractal dimension of heart rate time series: an effective measure of autonomic function. *Journal of Applied Physiology, 75:* 2429-2438.

Zulley, J., & Campbell, S.S. (1985). Napping behavior during "spontaneous internal desynchronization": sleep remains in synchrony with body temperature. *Human Neurobiology, 4:* 123-126.

Zulley, J., Wever, R., & Aschoff, J. (1981). The dependence of onset and duration of sleep on the circadian rhythm of rectal temperature. *Pfluegers.Arch., 391:* 314-318.

Appendices

Appendix 1

Fatigue Questionnaire

The following are a number of statements to assess fatigue (modified from Wessely and Powell, 1989) are given below.

The subjects had to respond to each question by entering a 0,1 or 2. Subjects responded to each question on the basis of how they felt presently as compared to the last month. The response was 1= same as usual, 2= worse, 3= much worse than usual. The physical and mental factors of the fatigue questionnaire are stated below.

Physical Fatigue

```
0---------------------1----------------------2
 same as usual          worse                  much worse than usual
```

1 I get tired easily

TIRED #

2 I need to rest more

NEED #

3 I feel sleepy or drowsy

DROWSY #

4 I can no longer start anything

START #

5 I am always lacking in energy

ENERGY #

6 I have less strength in my muscles

STRENGTH #

7 I feel weak

FEEL #

8 I can start things without difficulty, but get weak as I go on

START #

Mental Fatigue

1 I have problems concentrating

HAVE #

2 I have problems thinking clearly

THINK #

3 I make more slips of the tongue, or have problems finding the correct word

CORRECT #

4 I have problems with eyestrain

WITH #

5 I have problems with memory

BRAIN #

Appendix 2

These software macros were written using Epi Info, Version 5.00 (Public Domain Software for Epidemiology and Disease Surveillance, World Health Organization, Switzerland, 1990). The macros were compiled and executed using statistical package for interactive data analysis V6.0 (SPIDA, Australia). The macros were used to score the psychological questionnaires used in this doctoral research.

Macros 1

```
! Macros study1.txt
! Study1 questionnaire macros
! Written by Saroj Lal for doctoral research, 24/2/98
! outputs results to study1.out
! This section calculates the Speilberger Trait scores
%out study1
"Results for study1.rec psychological questionnaire"
"-----------------------------------------------------"
%lines 2
"Speilberger Trait"
%lines 2
$st:=import("c:\psycqest\study1.wks",typ=1)
$1 :=$st[1,?]`
%lab $st $1
%lines 2
$desc:=desc ($st,data=1)
%lines 2
$rows:=$desc[1;2]
!  Put real data (rows 2-X) into $st by taking rows 2-X+1
$st:=$st[2,,$rows+1]
%lines 2
$temp:=5-$st[;4,6,9,10,13,16,17,19,22]
assign($st,(1,,$rows);(4,6,9,10,13,16,17,19,22),$temp)
$st2:=$st[1,,$rows;4,,23]
```

```
$st2sum:=sum.row($st2)
%lines 2
"Average score for Trait Anxiety"
%lines 2
desc ($st2sum)
%lines 2
"Locus of Personal Control"
%lines 2
$pc:=$st
%lines 2
$descpc:=desc($pc,data=1)
%lines 2
$rowspc:=$descpc[1;2]
$temp2:=5-$pc[;24,28,30,31,36,38,39]
assign ($pc,(1,,$rowspc);(24,28,30,31,36,38,39),$temp2)
$cont:=$pc[1,,$rowspc;24,,40]
$contsum:=sum.row($cont)
$contsum
%lines 2
"Average score for Locus of Personal Control"
desc ($contsum)
%out
!analysis complete
```

Macros 2

```
! Macros study2.txt
! Study2 questionnaire macros
! Written by Saroj Lal for doctoral research, 24/2/98
! outputs results to study2.out
! This section calculates the Speilberger Trait scores
%out study2
"Results for study2.rec psychological questionnaire"
"-----------------------------------------------------"
%lines 2
"POMS"
%lines 2
$study2:=import("c:\psycqest\study2.wks",typ=1)
$1 :=$study2[1,?]`
%lab $study2 $1
%lines 2
$desc:=desc ($study2,data=1)
%lines 2
$rows:=$desc[1;2]
!  Put real data (rows 2-X) into $study2 by taking rows 2-
X+1
$study2:=$study2[2,,$rows+1]
%lines 2
"Tension-Anxiety"
%lines 2
$ta:=$study2[;5,13,19,23,25,29,30,37,44]
assign($ta,(1,,$rows);5,4-$study2[;25])
$tasum:=sum.row($ta)
$tasum
desc ($tasum)
%lines 2
"Depression-Dejection"
%lines 2
$ee:=$study2[;8,12,17,21,24,26,35,38,39,47,48,51,61,64,65]
```

```
$eesum:=sum.row($ee)
$eesum
desc($eesum)
%lines 2
"Anger-Hostility"
%lines 2
$ah:=$study2[;6,15,20,27,34,36,42,45,50,55,56,60]
$ahsum:=sum.row($ah)
$ahsum
desc($ahsum)
%lines 2
"Vigor-Activity"
%lines 2
$va:=$study2[;10,18,22,41,54,59,63,66]
$vasum:=sum.row($va)
$vasum
desc($vasum)
%lines 2
"Fatigue-Inertia"
%lines 2
$fi:=$study2[;7,14,32,43,49,52,68]
$fisum:=sum.row($fi)
$fisum
desc($fisum)
%lines 2
"Confusion-Bewilderment"
%lines 2
$cb:=$study2[;11,31,40,53,57,62,67]
assign($cb,(1,,$rows);5,4-$study2[;57])
$cbsum:=sum.row($cb)
$cbsum
desc($cbsum)
%lines 2
"Total POMS"
$total:=$tasum,$eesum,$ahsum,4-$vasum,$cbsum
```

```
$moodsum:=sum.row($total)
$moodsum
desc($moodsum)
%lines 2
"Average score for State Anxiety"
%lines 2
$satemp:=5-$study2[;69,70,73,76,78,79,83,84,87,88]
assign($study2,(1,,$rows);(69,70,73,76,78,79,83,84,87,88),
$satemp)
$sa:=$study2[1,,$rows;69,,88)
$sasum:=sum.row($sa)
$sasum
desc($sasum)
%lines 2
"Fatigue Likert"
%lines 2
$fa:=$study2[;89]
$fa
desc($fa)
%out
!analysis complete
```

Macros 3

```
! Macros study3.txt
! Study3 questionnaire macros
! Written by Saroj Lal for doctoral research, 2/3/98
! outputs results to study3.out
! This section calculates the Speilberger Trait scores
%out study3
"Results for study3.rec psychological questionnaire"
"-------------------------------------------------"
%lines 2
"State anxiety"
%lines 2
$study3:=import("c:\psycqest\study3.wks",typ=1)
$1 :=$study3[1,?]`
%lab $study3 $1
%lines 2
$desc:=desc ($study3,data=1)
%lines 2
$rows:=$desc[1;2]
!  Put real data (rows 2-X) into $study3 by taking rows 2-
X+1
$study3:=$study3[2,,$rows+1]
%lines 2
"Average score for State Anxiety"
%lines 2
$satemp:=5-$study3[;4,5,8,11,13,14,18,19,22,23]
assign($study3,(1,,$rows);(4,5,8,11,13,14,18,19,22,23),$sa
temp)
$sa:=$study3[1,,$rows;4,,23)
$sasum:=sum.row($sa)
$sasum
desc($sasum)
%lines 2
"Fatigue Likert"
%lines 2
```

```
$fa:=$study2[;24]
$fa
desc($fa)
%out
!analysis complete
```

Macros 4

```
! Macros study4.txt
! Study4 questionnaire macros
! Written by Saroj Lal for doctoral research, 2/3/98
! outputs results to study4.out
! This section calculates the Speilberger Trait scores
%out study4
"Results for study4.rec psychological questionnaire"
"-------------------------------------------------"
"Fatigue questionnaire"
%lines 2
$study4:=import("c:\psycqest\study4.wks",typ=1)
$1 :=$study4[1,?]
%lab $study4 $1
%lines 2
$desc:=desc ($study4,data=1)
%lines 2
$rows:=$desc[1;2]
! Put real data (rows 2-X) into $study4 by taking rows 2-
X+1
$study4:=$study4[2,,$rows+1]
%lines 2
"Average Physical Fatigue"
%lines 2
$pf:=study4[;4,,11]
$pf
desc($pf)
%lines 2
"Average Mental Fatigue"
%lines 2
$f:=study4[;12,,16]
$f
desc($f)
%out
!analysis complete
```