

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

Saroj Kusum Lata Lal (BSc, MAppSc)

Doctor of Philosophy (Science)

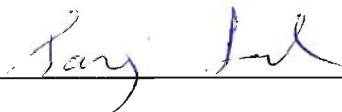
2001

Certificate of Authorship/Originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate



Acknowledgements

I would foremost like to thank the God Almighty, Bhagwan Sri Sathya Sai Baba for his blessings and guidance during the course of my study. I would also like to thank my parents (Mr Dhansukh Lal and Mrs Kusum Lal) and my brother (Shailendra Lal) for their continuous encouragement and strength that they provided during this doctoral research. I would further like to thank my mother for proof correcting the thesis.

I wish to extend my sincere gratitude and acknowledgement to Professor Ashley Craig, for his expertise and guidance throughout the doctoral research and for the preparation of this thesis. I have recently received a National Medical and Health Research (NHMRC) fellowship for further research and would like to thank Professor Craig for his expert assistance and advice. I also extend my appreciation to Associate Professor Les Kirkup and Yvonne Tran for their assistance.

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

Lal, SKL and Craig, A (2001). A critical review of the psychophysiology of driver fatigue. *Biological Psychology*, 55: 173-194.

Lal, SKL and Craig, A. (2000). Electroencephalography activity associated with driver fatigue: implications for a fatigue countermeasure device. *Journal of Psychophysiology* (submitted).

Lal, SKL and Craig, A (2000). Driver Fatigue: electroencephalography and psychological assessment. *Psychophysiology* (submitted).

Conference Papers and abstracts

Lal SKL, Craig A. Psychophysiology of driver fatigue. Proceedings of the Fourth International Conference on Fatigue and Transportation. *Transportation Research*, (2000).

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.

Table of Contents

List of Illustrations-----	xiv
List of Tables-----	xviii
Abstract -----	xxii
Definition of Technical Terms -----	xxiv

Chapter One:

Introduction and Review of the Concepts and Psychophysiology of Fatigue

1. Introduction -----	1
1.1 Definition of Fatigue-----	3
<i>1.1.1 Physical fatigue-----</i>	<i>4</i>
<i>1.1.2 Mental fatigue-----</i>	<i>4</i>
<i>1.1.3 Mental fatigue and boredom-----</i>	<i>4</i>
<i>1.1.4 Fatigue and vigilance-----</i>	<i>7</i>
<i>1.1.5 Fatigue and circadian rhythms-----</i>	<i>7</i>
1.2 Fatigue in Different Workplace Situations -----	8
<i>1.2.1 Shift/night work and fatigue-----</i>	<i>8</i>
<i>1.2.2 Fatigue in aviation -----</i>	<i>9</i>
<i>1.2.3 Driver fatigue -----</i>	<i>9</i>
<i>1.2.3.1 Driver fatigue and arousal-----</i>	<i>11</i>
<i>1.2.3.2 Driver fatigue and psychological determinants-----</i>	<i>12</i>
<i>1.2.3.3 Fatigue and the professional driver -----</i>	<i>12</i>
1.3 Fatigue, Driving and Sleep Disorders-----	14
1.4 Measurement of Fatigue-----	16
<i>1.4.1 Primary task measure-----</i>	<i>16</i>
<i>1.4.2 Secondary task measure -----</i>	<i>16</i>
<i>1.4.3 Objective indicators of fatigue -----</i>	<i>16</i>
<i>1.4.4 Subjective measures of fatigue -----</i>	<i>17</i>
1.5 The Physiological Indicators of Fatigue-----	18
<i>1.5.1 Eye movement as a measure of fatigue-----</i>	<i>18</i>

1.5.2	<i>Eye blinks to monitor fatigue</i> -----	18
1.5.3	<i>Heart rate and heart rate variability as an indicator of fatigue</i> -----	19
1.6	Other Methods to Assess Fatigue -----	21
1.6.1	<i>Psychomotor tests to measure fatigue</i> -----	21
1.6.2	<i>Mental tests to assess fatigue</i> -----	21
1.6.3	<i>Questionnaire studies of fatigue</i> -----	21
1.6.4	<i>Video indication of fatigue</i> -----	22
1.6.5	<i>Electroencephalography as an indicator of fatigue, alertness and sleep</i> -----	22
1.7	Fundamentals of Neuroscience -----	24
1.8	The Electroencephalography (EEG) -----	26
1.8.1	<i>EEG recording</i> -----	26
1.8.2	<i>Descriptors of EEG activity</i> -----	27
1.8.3	<i>Description of the EEG frequency</i> -----	29
1.8.4	<i>The effects of the EEG Rhythms</i> -----	31
1.8.4.1	<i>Delta waves</i> -----	31
1.8.4.2	<i>Theta activity</i> -----	31
1.8.4.3	<i>Alpha frequency</i> -----	31
1.8.4.4	<i>Beta waves</i> -----	32
1.8.5	<i>EEG coherence analysis</i> -----	32
1.8.6	<i>EEG signal processing and artifact detection</i> -----	33
1.9	The Electroencephalographic Features of Normal Sleep -----	34
1.9.1	<i>Sleep stages</i> -----	36
1.9.2	<i>Sequential changes and sleep</i> -----	36
1.9.3	<i>Sleep deprivation</i> -----	39
1.10	Electroencephalography of Fatigue and Drowsiness -----	39
1.10.1	<i>Electroencephalography of Fatigue and Drowsiness in Different Environments and Situations</i> -----	41
1.10.2	<i>The electroencephalogram changes and aviation fatigue</i> -----	42
1.10.3	<i>The electroencephalogram changes and driver fatigue</i> -----	42
1.11	Specific Effects of Different Functional States of the Brain on the EEG Activity -----	44

1.11.1	<i>Effects of attention and drowsiness on EEG rhythms</i>	44
1.12	Fatigue Counter Measures	46
1.12.1	<i>Countermeasure using eye activity</i>	47
1.12.2	<i>Countermeasures using neural networks</i>	48
1.12.3	<i>Countermeasures using EEG</i>	48
1.12.4	<i>Other types of countermeasure methods</i>	50
1.12.5	<i>'Break periods' and practical countermeasures</i>	50
1.12.6	<i>Criteria for effective countermeasures</i>	51
1.13	On the Methodology of Fatigue Studies	52
1.14	Aims	53
1.14.1	<i>General Aim</i>	53
1.14.2	<i>Specific Aims</i>	54

Chapter Two:

Procedures Involved in Psychophysiological Assessment of Driver Fatigue

2.	Methods	59
2.1	Justification of Psychophysiological Procedures Used	59
2.2	Experimental Procedure	60
2.2.1	<i>Study protocol</i>	60
2.2.2	<i>Physiological assessment</i>	66
2.2.3	<i>Validation of fatigue</i>	72
2.2.4	<i>Reliability of the video identification of fatigue</i>	72
2.2.5	<i>Psychological assessment</i>	72
2.2.5.1	<i>The State-Trait Anxiety Inventory</i>	73
2.2.5.2	<i>The Profile of Mood States (POMS)</i>	73
2.2.5.3	<i>The Locus of Control of Behaviour</i>	75
2.2.5.4	<i>The Fatigue State Questionnaire</i>	75
2.2.5.5	<i>The fatigue state likert question</i>	75
2.3	Data Acquisition and Statistical analysis	75
2.3.1	<i>Data acquisition</i>	75
2.3.2	<i>Data management, conversion and analysis</i>	76
2.3.3	<i>Statistical and sample power analysis</i>	77

Chapter Three:

Physiology of Fatigue and Drowsiness in Non-Professional Drivers

3.	Fatigue effects in Non-Professional Drivers: electroencephalography and electro-oculogram effects -----	78
3.1	Introduction to the Physiology of Driver Fatigue -----	78
3.2	Methods -----	80
	<i>3.2.1 Subjects</i> -----	<i>80</i>
	<i>3.2.2 Study protocol</i> -----	<i>81</i>
	<i>3.2.3 Data acquisition and analysis</i> -----	<i>82</i>
	<i>3.2.4 Statistical analysis</i> -----	<i>82</i>
3.3	Results -----	83
3.4	Discussion -----	101
	<i>3.4.1 Driver fatigue and physiological effects</i> -----	<i>101</i>
	<i>3.4.2 The methodology used in fatigue studies</i> -----	<i>104</i>

Chapter Four:

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

4.	Fatigue and Psychological Effects -----	106
4.1	Psychological Implications of Fatigue -----	106
4.2	Methods -----	108
	<i>4.2.1 Subjects</i> -----	<i>108</i>
	<i>4.2.2 Study protocol</i> -----	<i>108</i>
	<i>4.2.3 Statistical analysis</i> -----	<i>109</i>
4.3	Results -----	109
4.4	Discussion -----	122

Chapter Five:

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

5.	Introduction -----	126
5.1	The Autonomic Nervous System -----	126
	5.1.1 <i>The sympathetic nervous system</i> -----	127
	5.1.2 <i>The parasympathetic nervous system</i> -----	127
5.2	Physiological and Autonomic Implications of Heart rate and Heart Rate Variability effects during Fatigue and Drowsiness -----	127
	5.2.1 <i>Heart rate variability</i> -----	127
	5.2.2 <i>Heart rate variability as an indicator of fatigue/sleepiness and workload</i> -----	128
	5.2.3 <i>Heart rate variability as an indicator of driver fatigue</i> -----	129
	5.2.4 <i>Relationship between heart rate variability and electroencephalography during fatigue/sleepiness</i> -----	130
5.3	Methods -----	130
	5.3.1 <i>Subjects</i> -----	130
	5.3.2 <i>Study protocol</i> -----	131
	5.3.3 <i>Data acquisition and analysis</i> -----	131
	5.3.4 <i>Statistical analysis</i> -----	132
5.4	Results -----	133
	5.4.1 <i>Fatigue, HR and HRV effects</i> -----	133
	5.4.2 <i>Association between cardiovascular and EEG changes during fatigue</i> -----	135
5.5	Discussion -----	139
	5.5.1 <i>Using spectral analysis of HR to identify autonomic effects during driver fatigue</i> -----	139
	5.5.2 <i>EEG and cardiovascular associations during fatigue</i> -----	140

Chapter Six:

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

6.	Introduction to Fatigue in Professional Drivers -----	143
6.1	Truck Drivers and Fatigue -----	143
6.2	On the Brain Wave Activity of Professional Drivers -----	144
6.3	Methods -----	145
	6.3.1 <i>Subjects</i> -----	145
	6.3.2 <i>Study protocol</i> -----	147
	6.3.3 <i>Statistical analysis</i> -----	147
6.4	Results -----	148
	6.4.1 <i>The physiological response during the driving task in professional truck drivers</i> -----	148
	6.4.2 <i>comparison of the EEG activity in non-professional versus professional drivers</i> -----	158
6.5	Discussion -----	161
	6.5.1 <i>Fatigue effects, cardiovascular variables, age and weight</i> -----	161
	6.5.2 <i>Fatigue effects on EEG in professional drivers</i> -----	162
	6.5.3 <i>A comparison of fatigue effects on EEG in professional and non-professional drivers</i> -----	163

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 -----	165
7.1	The reproducibility of electroencephalography changes during driver fatigue -----	165
7.2	Methods -----	166
	7.2.1 <i>Subjects</i> -----	166
	7.2.2 <i>Study protocol and statistical analysis</i> -----	166
	7.2.3 <i>Data and statistical analysis</i> -----	167
7.3	Results -----	167
	7.3.1 <i>The agreement in EEG response, representative of the whole brain, during the transitional phase</i>	

	<i>to fatigue in non-professional drivers</i> -----	168
7.3.2	<i>The agreement in EEG response in a single site (central site (Cz)) during the transitional phase to fatigue in non-professional drivers</i> -----	172
7.3.3	<i>The agreement in EEG response, representative of the whole brain, during the transitional phase to fatigue in professional drivers</i> -----	173
7.4	Discussion -----	177

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 -----	178
8.1	Use of Spectral Correlation in Drowsiness Research -----	179
8.2	Methods -----	180
	8.2.1 <i>Subjects</i> -----	180
	8.2.2 <i>Study protocol</i> -----	181
	8.2.3 <i>Data and statistical analysis</i> -----	181
8.3	Results -----	182
	8.3.1 <i>Interhemispheric EEG coherence</i> -----	182
	8.3.2 <i>Intrahemispheric EEG coherence</i> -----	182
8.4	Discussion -----	183

Chapter Nine:

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

9.	Technological Countermeasures for Fatigue/Drowsiness -----	185
9.1	Research on Technological Countermeasure to Fatigue -----	185
9.2	Methods -----	187
	9.2.1 <i>Subjects</i> -----	187

9.2.2	<i>Study protocol</i> -----	187
9.2.3	<i>The fatigue anticipating software: towards a technological countermeasure against driver fatigue</i> -----	187
9.2.4	<i>Data and statistical analysis</i> -----	188
9.3	Results -----	194
9.4	Discussion -----	195
9.4.1	<i>The potential of the EEG detecting software</i> -----	195
9.4.2	<i>Future research and development of the fatigue monitoring software</i> -----	195

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 -----	198
10.1	The Electroencephalography and Driver Fatigue -----	199
10.2	The Electro-oculogram and Video as an Indicator of Driver Fatigue -----	200
10.3	The Psychological Associations with Driver Fatigue -----	200
10.4	Heart rate and Heart Rate Variability as an Indicator of Driver Fatigue -----	201
10.5	Fatigue Effects in Professional Versus Non-Professional Drivers -----	201
10.6	The Reproducibility of Fatigue during Driving -----	202
10.7	Electroencephalography Coherence Analysis during Fatigue ---	202
10.8	The Prospects of a Fatigue Monitoring and Alerting Software Employing Electroencephalography Changes that Occur during Driver Fatigue -----	202
10.9	Future Research Prospects on the Psychophysiological Associations with Driver Fatigue -----	203
	References -----	205
	Appendices -----	231
	Appendix 1 -----	231
	Appendix 2 -----	233

List of Illustrations

Figure 1.1	A theoretical model to illustrate the neuro-physiological mechanism which 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) -----	6
Figure 1.2	General functional areas of the cerebral cortex (adapted from Spence and Mason, 1987)-----	25
Figure 1.3	Frequency bands. Delta, theta, alpha and beta frequency bands, defined by wave frequency (Hz) and length (ms)-----	30
Figure 1.4a	EEG after on-line reduction of muscle artifact contamination-----	35
Figure 1.4b	EEG after on-line reduction of eye artifact contamination -----	35
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, Torsvall, & Gillberg, 1987)-----	38
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)-----	45
Figure 2.1	Fatigue study protocol -----	62
Figure 2.2	Shows fatigue laboratory with car simulator and other equipment--	63
Figure 2.3	The screen as displayed to the subject during active and alert driving-----	64
Figure 2.4	The screen as displayed to the subject during passive driving -----	65
Figure 2.5	The International 10-20 System of Electrode Configuration-----	67
Figure 2.6	Shows the electrodes mounted on the Electro-Cap System™ -----	69
Figure 2.7 a	Shows the equipment and material used in the study with the Electro-Cap System™ a) electrode gel, syringe and blunted needle-----	70
Figure 2.7 b	Shows the equipment and material used in the study with the Electro-Cap System™ b) resistance meter and electrode tester -----	70
Figure 2.8	The Red dot electrodes and connections ‘clips’ used for EOG	

	and ECG recordings-----	71
Figure 3.1	The EEG amplitude response during driver fatigue over all 19 channels -----	86
Figure 3.2	The EEG magnitude response during driver fatigue over all 19 channels -----	87
Figure 3.3	Shows the EEG activity during the alert phase in all 19 channels---	88
Figure 3.4	Shows the EEG activity during the transition to fatigue phase in all 19 channels -----	89
Figure 3.5	Shows the EEG magnitude during alert in the FZ, CZ, PZ, O1 and O2 sites -----	92
Figure 3.6	Shows the EEG magnitude during transition to fatigue phase in the FZ, CZ, PZ, O1 and O2 sites -----	92
Figure 3.7	Shows the EEG power during alert in the FZ, CZ, PZ, O1 and O2 sites-----	93
Figure 3.8	Shows the EEG power during transition to fatigue phase in the FZ, CZ, PZ, O1 and O2 sites-----	93
Figure 3.9	Shows the EEG magnitude spectral activity during an alert state in the FZ, CZ, PZ, O1 and O2 sites-----	94
Figure 3.10	Shows the EEG magnitude spectral activity during transition to fatigue state in the FZ, CZ, PZ, O1 and O2 sites-----	94
Figure 3.11	Shows the topograph of EEG activity in the 1= theta, 2= alpha and 3= beta bands during an alert state-----	96
Figure 3.12	Shows the topograph of EEG activity in the 1= theta, 2= alpha and 3= beta bands during transition to fatigue phase -----	96
Figure 3.13	The EEG amplitude activity during the transitional phase to fatigue in different sites on the brain -----	99
Figure 3.14	The EEG magnitude activity during the transitional phase to fatigue in different sites on the brain -----	99
Figure 4.1	A positive linear regression line of delta amplitude changes with Trait Anxiety -----	112
Figure 4.2	A positive linear regression line of theta amplitude changes with Control Efficacy -----	112
Figure 4.3	A positive linear regression line of alpha amplitude changes with Fatigue-Inertia-----	113

Figure 4.4	A positive linear regression line of beta amplitude changes with pre-study fatigue state-----	113
Figure 4.5	A positive linear regression line of delta magnitude changes with Tension-Anxiety -----	114
Figure 4.6	A negative linear regression line of delta magnitude changes with Vigor-Activity-----	114
Figure 5.1	The correlation and linear regression between LF:HF and alpha amplitude during transition to fatigue -----	138
Figure 5.2	The correlation and linear regression between LF:HF and beta amplitude during transition to fatigue -----	138
Figure 6.1	The delta magnitude (μV) in professional drivers during alert, transition to fatigue, transitional-post-transitional, post-transitional and arousal phases -----	151
Figure 6.2	The theta magnitude (μV) in professional drivers during alert, transition to fatigue, transitional-post-transitional, post-transitional and arousal phases -----	151
Figure 6.3	The alpha magnitude (μV) in professional drivers during alert, transition to fatigue, transitional-post-transitional, post-transitional and arousal phases -----	152
Figure 6.4	The beta magnitude (μV) in professional drivers during alert, transition to fatigue, transitional-post-transitional, post-transitional and arousal phases -----	152
Figure 6.5	Shows an example of the raw EEG activity during the alert phase -	153
Figure 6.6	Shows an example of the raw EEG activity during the transition to fatigue phase -----	154
Figure 6.7	Change in EEG magnitude during the alert phase -----	155
Figure 6.8	Change in EEG magnitude during the transition to fatigue phase---	155
Figure 6.9	The EEG topograph during the alert phase in a subject in the 1= theta, 2= alpha and 3= beta bands-----	156
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-----	157
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 -	157
Figure 7.1	Average EEG magnitude changes during two episodes of	

	transition to fatigue in non-professional drivers (n=35) -----	169
Figure 7.2	Linear regression line and correlation of delta activity during the two episodes of fatigue in non-professional drivers -----	170
Figure 7.3	Linear regression line and correlation of theta activity during the two episodes of fatigue in non-professional drivers -----	170
Figure 7.4	Linear regression line and correlation of alpha activity during the two episodes of fatigue in non-professional drivers -----	171
Figure 7.5	Linear regression line and correlation of beta activity during the two episodes of fatigue in non-professional drivers -----	171
Figure 7.6	Average EEG magnitude changes during two episodes of transition to fatigue in professional drivers (n=20)-----	174
Figure 7.7	Linear regression line and correlation of delta activity during the two episodes of fatigue in professional drivers -----	175
Figure 7.8	Linear regression line and correlation of theta activity during the two episodes of fatigue in professional drivers -----	176
Figure 7.9	Linear regression line and correlation of alpha activity during the two episodes of fatigue in professional drivers -----	176
Figure 7.10	Linear regression line and correlation of beta activity during the two episodes of fatigue in professional drivers -----	177
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) -----	189
Figure 9.2	This panel shows the mean coefficients allocated to detect the alert and fatigue phases by the software-----	190
Figure 9.3	The algorithm panel of the fatigue monitoring software-----	191
Figure 9.4	A graphical representation of the data in offline analysis mode using the fatigue monitoring software -----	193

List of Tables

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)-----	23
Table 1.2	Levels of consciousness in terms of psychological states and EEG (adapted from Cacioppo & Tssinary, 1990 -----	30
Table 1.3	Classification of fatigue/drowsiness EEG and arousal EEG -----	41
Table 1.4	Summary of major published fatigue, drowsiness and related studies -----	55
Table 1.5	Psychophysiological findings and relevant conclusions of the above studies-----	57
Table 3.1	Shows the demographics of the subjects in the study (n=35 non-professional drivers)-----	83
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 -	84
Table 3.3	The average change in EEG amplitude and magnitude from the alert baseline during drowsiness-----	91
Table 3.4	Average EEG amplitude and magnitude in different sites on the brain during transition to fatigue-----	97
Table 3.5	The video and EOG indicators of fatigue -----	100
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-----	110
Table 4.2	Showing all significant correlation between the average EEG changes across the entire brain and psychological variables -----	111
Table 4.3	Non-significant correlation between the average EEG changes across the entire brain and psychological variables -----	116
Table 4.4a	Multiple regression analysis of psychological association with EEG delta amplitude changes-----	117
Table 4.4b	Multiple regression analysis of psychological association with EEG theta amplitude changes-----	117

Table 4.4c	Multiple regression analysis of psychological association with EEG theta amplitude changes-----	118
Table 4.4d	Multiple regression analysis of psychological association with EEG beta amplitude changes -----	118
Table 4.4e	Multiple regression analysis of psychological association with EEG delta magnitude changes -----	118
Table 4.4f	Multiple regression analysis of psychological association with EEG delta magnitude changes -----	119
Table 4.4g	Multiple regression analysis of psychological association with EEG delta magnitude changes -----	119
Table 4.4h	Multiple regression analysis of psychological association with EEG delta magnitude changes -----	120
Table 4.4i	Multiple regression analysis of psychological association with EEG delta magnitude changes -----	120
Table 4.5	The self-rated fatigue state questionnaire: scored according to number (percentage) of subjects responding in each category-----	121
Table 5.1	Spectral Power of Heart Rate Variability-effect of fatigue (beats/min ² /Hz) -----	133
Table 5.2	A comparison of the fatigue phases to the alert baseline using post-hoc comparison of the means (Scheffé test)-----	134
Table 5.3	Associations between HR variability and EEG amplitude changes -----	136
Table 5.4	Associations between HR variability and EEG magnitude changes -----	137
Table 6.1	Shows the demographics of the subjects in the study -----	146
Table 6.2	Mean cardiovascular effects before and after the driving task -----	149
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 -----	149
Table 6.4	The changes in EEG magnitude in truck drivers during drowsiness compared to the alert baseline -----	150
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-----	158
Table 6.6	The average changes in EEG magnitude in non-professional (np) and professional (p) drivers during drowsiness from the alert baseline -----	159
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 -----	160
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 -----	161
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. $0.05/4$) -----	168
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. $0.05/4$)-----	169
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. $0.05/4$) -----	172
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. $0.05/4$)-----	173
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. $0.05/4$)-----	174
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. $0.05/4$) ----- 175

Table 8.1 Demographics of the five subjects in this study----- 180

Table 8.2 Average interhemispheric EEG coherence during alert ‘a’ and transition to fatigue ‘f’ phase ----- 182

Table 8.3 Average intrahemispheric EEG coherence during alert ‘a’ and transition to fatigue ‘f’ phase ----- 183

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) ----- 194

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-oculogram (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-oculogram (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.